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A Modelling Framework for Multisectoral Energy Collaboration in Multi-Voltage Networks: Enhancing System Performance Through Shared Storage and Energy Exchange

Full Name of Student: *Tomás Ribeiro Cardoso*

Core Provider: *Hanze University of Applied Sciences*
Zernikeplein 7, 9747 AS, Groningen, The Netherlands

Specialisation: *Grid integration, University of Zaragoza*
C. de Pedro Cerbuna, 12, 50009 Zaragoza, Espanha

Host Organization: *New Energy Coalition*
Nijenborgh 6, 9747 AG Groningen, Netherlands

Academic Supervisor: *Dr. Folkert Faber*

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Executive Summary

In line with the goals of the Paris Climate Agreement, and the urgent grid congestion challenges in the Netherlands caused by the rapid energy transition, there is a growing need for grid flexibility solutions and improved coordination between distributed energy generation and consumers.

This research proposes an investigation into the performance enhancement in a multisectoral energy collaboration between a 50-house low-voltage residential network and a medium-voltage industrial park with four companies, allowing the shared use of their renewable generation and storage assets. Within the context of the REFORMERS project, the study explores the economic and performance benefits for both regions, as well as their impact on public grid interactions and dependency.

The study models four progressive simulation stages to assess the effects of network collaboration via direct energy exchange and shared storage on key energy performance indicators and potential grid congestion relief. While the last stage focuses on exploring the fulfilment of the REFORMERS project performance goals. The methodology integrates real and estimated data on infrastructure, demand, and generation, implemented in PowerFactory to simulate the system's behaviour under multiple configurations.

Results demonstrate that enabling energy exchange between residential and industrial networks yields modest collective performance improvements of 0,71% for self-sufficiency and 1,36% for self-consumption. The shared BESS integration led to a more substantial impact, improving the system performance by 6,99% to self-sufficiency and by 14,17% to self-consumption. Both multisectoral energy exchange and shared BESS integration showed benefits during grid-congestion hours, highlighting a 25% grid imports reduction from the shared BESS contributions. Economically, the shared BESS reduces the community costs by 9,38%, outperforming the individual BESS, and delivers greater value when shared with residential users, due to the higher electricity prices.

The study also identifies key limitations, such as BESS-constrained maximum power and, especially, the strong seasonal solar intermittency, which prevented the system from achieving performance targets of 75% self-consumption and a positive net annual energy balance, highlighting the need for the integration of seasonal storage or complementary renewable energy sources.

The study demonstrates both performance and economic benefits while envisioning a scenario where industrial areas collaborate with residential zones to optimize renewable energy assets usage, providing a practical solution for collective batteries integration for residential areas, addressing spatial limitations by situating BESS in industrial areas within urban energy ecosystems.

Acknowledgement

I will dedicate this section to express my gratitude for all parts that helped me during this long academic journey. I could go further back on the years, but I will keep it short and restrain it to the last 1,5 years.

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Hope all the readers enjoy this thesis, as much as I liked to make it.

Tomás Cardoso

November 30, 2025

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List of Abbreviations:

Abbreviation	**Definition**
BESS	*Battery Energy Storage System*
CBS	*Chamber of Commerce and Statistics Netherlands*
DEGO	*Energy Transition Data Facility for the Built Environment*
DER	*Distributed Energy Resources*
DoD	*Depth of Discharge*
DSO	*Distribution System Operator*
EMS	*Energy Management System*
EV	*Electric Vehicle*
KPI	*Key Performance Indicator*
LAN	*Dutch National Grid Congestion Action Program*
LES	*Local Energy System*
LV	*Low Voltage*
MV	*Medium Voltage*
NAEB	*Net Annual Energy Balance*
NEC	*New Energy Coalition*
PED	*Positive Energy District*
PoC	*Point of Connection*
PP	*Percentage Points*
PV	*Photovoltaic*
PVGIS	*Photovoltaic Geographical Information System*
REFORMERS	*Regional Ecosystems FOR Multiple Energy Resilient Systems*
REV	*Renewable Energy Valley*
RS	*Research Stage*

1. Introduction

1.1. Problem Background

In response to climate change and in pursuit of the goals set by the Paris Climate Agreement, Distributed Energy Resources (DER) have emerged as a way to involve citizens in renewable energy production [1]. However, the large increase in energy transactions driven by the integration of new loads such as Electric Vehicles (EV), heat pumps, and the electrification of industries has outpaced the capacity of the existing grid, limiting its ability to ensure the safe and reliable transfer of electricity [2]. Consequently, in 2024, the Netherlands saw 10.000 users and 7.500 generation projects remain in a waiting list for new grid connections due to lack of grid capacity [2].

In the Netherlands, the first signs of grid congestion occurred in 2018 [3], due to the large increase in the electricity demand and the Photovoltaic (PV) generation triggered by subsidies that created "extra pressure on an already overburdened grid" [3]. Consequently, grid congestion has emerged as a critical barrier to scaling up renewable energy and electrifying sectors essential for achieving national and EU climate targets [4].

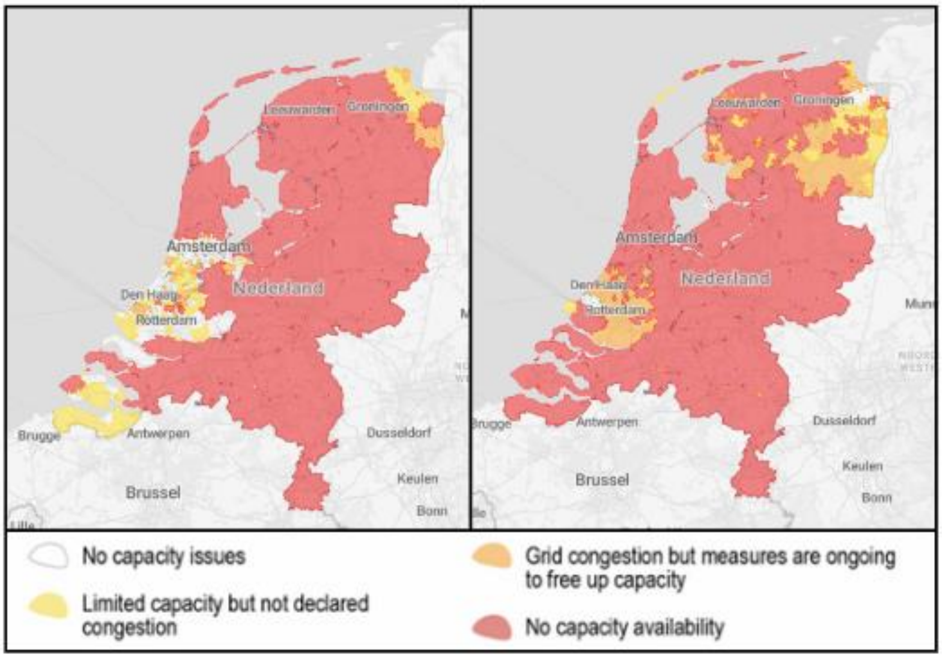

Figure 1 - Grid congestion map for consumption (right) and feed-in (left) in the Netherlands, 2025 (Electricity grid Capacity map)

The Dutch energy policy report from the International Energy Agency (IEA) [2] highlight that for a successful energy transition, the Netherlands depend on optimizing the use of the existing grid capacity through smart solutions, where the coordination across government, industry, and neighborhoods plays an important role.

Measures from Zsuzsanna Pató [3] suggest limiting consumers feed-in and demand, as well as introducing shared grid connections to facilitate the establishment of energy hubs, areas with locally coordinated energy use and generation.

The combination between the grid congestion challenges and the phase-out of the net metering made the development of Local Energy Systems (LES) more urgent [5]. In these systems, citizens have an active role in reducing electricity demand from the utility grid [6] *by generating and trading locally generated renewable energy, while contributing to the grid by reducing the feed-in to the grid [7].*

In the same report [2], the IEA introduces Battery Energy Storage Systems (BESS) as part of the solution to grid congestion challenges. They can be deployed at the utility scale, for system balancing and ancillary services, at the household level, to optimize individual self-consumption and reduce individual cost, and at the community level, where the coordinated operation stores surplus generation, reducing grid imports, and mitigating congestion [2],[7].

Under the proposed solutions, the effective impact from LES highly depend on multiple factors such as the consumers' power profiles, the amount of renewable energy sources and existence of storage systems [8]. To assess the outputs from the LES, literature indicates the following Key Performance Indicators (KPI): (i) community electricity costs, (ii) community self-sufficiency and (iii) self-consumption indexes [6].

Another performance metric introduced by Gabaldón, A (2021) [9] is the (iv) Net Annual Energy Balance (NAEB). It defines a district as energy neutral if, over the course of a year, it requires no net energy imports [10]. Achieving a zero balance is one of the criteria for classifying a community as a Positive Energy District (PED) [11] , a concept central to meeting Europe's climate and energy goals and advancing toward net-zero carbon emissions.

1.2. Research gap and project contribution

Although DER technologies are already mature, their practical applications in different system configurations for LES remain largely unexplored. Existing studies on LES integrating BESS have frequently limited their use to individual consumer [6],[12] or underexplore scenarios involving the shared use among consumers of same typology [13],[14]. Gasca (2025) [8] has advanced this discussion by introducing the concept of combining diversified consumer profiles and BESS solutions, but it is primarily a theoretical optimization-based framework and independently managed BESS. Therefore, there remains a notable gap in the literature regarding real case studies that demonstrate and validate the operation of LES integrating consumers of different typologies sharing a BESS.

To address this gap, this research investigates the potential benefits from a multisectoral energy collaboration between a residential neighbourhood and a light industrial park. In a first stage, by interconnecting these two regions, the study focuses on the benefits of bidirectional energy exchange involving members with high degree of heterogeneity. Building on this interconnected model, a second stage examines the integration of a shared BESS to assess its impact on the collective performance of the LES.

The study was developed in collaboration with the New Energy Coalition (NEC) as part of the Regional Ecosystems FOR Multiple Energy Resilient Systems (REFORMERS) project. REFORMERS is creating the first European Renewable Energy Valley (REV), defined as a LES that fully covers its energy needs (electricity, heat, and fuels) on an annual basis through renewable energy production [9]. This model is designed for replication across Europe, contributing to energy independence, grid stability, climate neutrality, and the engagement of local communities.

Within this context, this work examines a pilot case, interconnecting a low-voltage (LV) residential network with a medium-voltage (MV) industrial network in the region of Heiloo, *the Netherlands. The system comprises 50 households and 4 businesses, representing a scaled-down model of the larger REFORMERS project, which aims to connect 1500 households and industrial businesses.*

By analyzing this smaller-scale case, the project represents an innovative step, directly contributing to the broader REFORMERS' objectives. Seeking to provide a deeper understanding in the multisectoral collaboration, while demonstrating the potential benefits to the current congestion challenges faced at the point of connection (PoC), highlighting the impacts on the systems KPI, and supporting the achievement of the community's energy targets.

The following points summarize the expected contributions of this research to the academic literature:

1. *Quantify the performance benefits from multisectoral energy exchange and shared BESS integration, by analyzing the enhancement in the collective self-consumption (%), self-sufficiency (%), NAEB (MWh) and community costs.*
2. *Addressing grid congestion challenges, providing insights into how the energy collaboration supports the relief of regional grid constraints.*
3. *Evaluating the role of multisectoral collaboration by examining how the shared use of generation and storage assets can support community energy goals, while reducing the total capacity of assets required.*

1.3. Research question and objectives

To the purpose of this work, the research project aims to answer the following question:

"How does the collaboration between low-voltage residential and medium-voltage industrial networks and the integration of a shared battery affect the overall system performance and the planning of a local energy system?"

To address the main research question, the study defines the following research objectives:

1. *Quantifying the energy exchange between the networks, contribution to the KPIs increase and grid congestion relief resulting from the networks' energy collaboration.*
2. *Quantify the impact of integrating a shared BESS on the LES's KPIs and evaluating the impact of shared BESS storage size and location on the system's outcomes.*
3. *Assess the feasibility and amount of required energy generation and storage assets required to meet 75% self-consumption and a net positive annual energy balance, for both split and interconnected configurations, highlighting the differences in the amount and type of required infrastructure.*
4. *Quantify the impacts on the community costs from the multisectoral energy exchange and integration of the shared BESS.*

1.4. Structure of the Thesis

This thesis is organised into six chapters, each representing a key stage of the scientific process followed to address the central research question. The structure is as follows:

The first chapter “Introduction” presents the background and motivations for the carried research project, presenting the challenges posed to the energy transition. It identifies the research gap and clarifies the specific contributions of this work. The main research question and research objectives are formulated to guide the research work.

The second chapter “State of Art” summarizes current literature relevant to the project. It examines the theoretical framework required for the understanding of the discussed concepts and obtained results during the work, highlighting key scientific findings on the different topics. Additionally, the chapter explores frameworks for multi-sectoral collaboration and addresses the technical and regulatory aspects for the collaboration between MV and LV networks. Together, these elements establish the conceptual groundwork for evaluating the relevance of the proposed research work.

The third chapter “Methodology” outlines the methodological approach adopted in the research, detailing data collection procedures, and the different stages of research. The chapter also links each stage to the research objectives, defining the expected outcomes and contributions of each project phase. The methodology mentions the included modeling assumptions, datasets, and KPIs.

The fourth chapter “Results” presents the simulation outcomes based on the previously defined KPIs. It analyses the system’s performance across different scenarios, their impact on the grid, and provides economic insights by assessing community costs reductions and the investment required for the additional proposed assets.

The fifth chapter “Discussion” interprets and critically evaluates the results obtained from the simulations. It links the findings to the research objectives and the wider body of literature, highlighting both alignments and divergences.

The final chapter “Conclusions” highlights the insights gained throughout the study. It summarizes the key findings, answers the research question, and provides recommendations for future research.

2. State of the Art

This chapter introduces key concepts relevant to the research. Its objective is to introduce to the reader the foundational principles and current scientific findings in the field, which will later serve as a comparative basis in the Discussion chapter against the results obtained from the simulation model. The main topics discussed in this chapter are: (i) the fundamentals of LES, (ii) the importance of BESS, (iii) Multi-Sector Energy Collaboration, and (iv) the Energy collaboration between MV and LV networks.

2.1. Fundamentals of the LES

LES are decentralized energy networks integrating renewable energy generation, storage, and controllable demand within a defined geographical area [15], aiming to optimize the balance between local energy supply and demand, thereby reducing reliance on external grid [16].

Advanced LES also promote multi-vector integration, by coupling electricity, heat, and mobility, which further enhances operational flexibility [17]. These systems enable communities to participate actively in the energy transition and support grid congestion relief [18].

2.1.1 Composing elements of a LES

LES incorporate various actors and technologies to support efficient local energy production, management, and consumption. Participants include traditional consumers, who only use energy, and prosumers, who both produce and consume. This collective model improves local balancing and broadens participation, especially for those unable to install their own systems [19].

The key technological components integrated in LES are:

Distributed Energy Resources (DER): Primarily solar Photovoltaic (PV), due to affordability and scalability, though small wind, biomass, or hydropower may be used [19].

Energy storage systems: Essential to mitigate renewable intermittency, increase self-consumption, and reduce external grid dependence [8].

Flexible loads: Controllable demand loads, such as EV charging [20].

Digital infrastructure: Smart meters and Energy Management Systems (EMS) facilitate real-time monitoring, energy trading, and user engagement through dynamic pricing[16].

In this research, these elements are applied to the developed model that integrates rooftop PV, individual and collective BESS, EVs, and a centralized EMS, which will be further explored in this chapter.

2.1.2 Main challenges in integration of Distributed Energy Resources

The widespread integration of solar PV systems presents several challenges for distribution networks, particularly during periods of high solar production and low demand.

One of the main challenges is PV curtailment, the share of onsite electricity generation that is neither self-consumed nor sold to the grid [21]. In grids dominated by independent prosumers, the inability to redistribute excess PV production reduces the renewable system's potential, lowering the economic returns for PV owners [22].

The report by Pato (2024) [3] points to the grid challenges in the Netherlands, where net metering schemes, where surpluses from PV would later compensate grid-imported energy on the energy bills. As a consequence, the schemes offered little incentive for users to align their consumption with generation, leading to increased pressure on the grid and unintentionally contributing to grid congestion. In response, Dutch grid operators have started restricting new PV connections due to infrastructure capacity limitations [3].

For this purpose, Massano (2025) [23] highlights an increasing need for flexibility solutions to reduce strain on the transmission grid, suggesting approaches such as energy communities to enhance local self-consumption and storage systems like BESS, to further contribute to grid stability. Solutions that will be further explored in this chapter and studied during this work.

2.2. The importance of BESS

Current literature identifies BESS as a critical element to enhancing the flexibility of modern LES, reducing the grid congestion by offsetting the energy imports from the utility grid, particularly during the peak demand periods [2],[7]. In pursuit of reduced energy prices, new business models for BESS have been developed for prosumers and grid operators, such as the peer-to-peer energy trading [7].

Despite an 89% cost reduction in the past decade, BESS's costs still represent a significant investment, especially for residential users [7]. Their strategic deployment and management are therefore critical for maximizing their technical and economic benefits. BESS can be implemented in centralized or decentralized configurations, each with distinct roles and operational dynamics.

Introduced by M.V. Gasca [8], a centralized EMS manages an entire energy community as a single unified entity. It coordinates all energy exchanges with the external power grid by aggregating the total production and consumption of all members. The goal is to minimize the net community costs by maximizing the consumption of the locally produced energy.

In the study from Mohanty (2024) [24], centralized storage solutions for local energy initiatives are presented as community-level batteries, typically installed near residential and industrial areas. These systems enable greater self-consumption and lower electricity costs for consumers, and they also support the utility grid by reducing peak demand and facilitating participation in demand response programs. Moreover, the coordination of storage systems combined with flexible loads has been identified as a key factor in maximizing storage benefits [25].

Decentralized BESS, on the other hand, are installed at the household-level and are directly controlled by the end-user [26], primarily used to increase the prosumer self-consumption. When studying the integration of 1258 kilowatt-hours (kWh) in distributed storage among 262 houses, Qiao & Yang (2017) [12] reported a 16,8% reduction in user electricity costs. However, since each household BESS operates independently, the impact on the local grid is found limited.

The benefits from the integration of centralized BESS are explored in the study from Albouys-Perrois [13], which integrated a 700 kWh shared BESS in an association of 100 houses, integrating a total of 175 kilowatt-peak (kWp) of PV generation. Results found a reduction in the annual grid imports in approximately 87 Megawatt-hours (MWh), reducing the grid exports by 80%, and increasing the system self-consumption by 42% and self-sufficiency by 20%. Other studies, such as Zakeri (2021) [26], compare the benefits of centralized BESS coordination, finding up to 2% more annual electricity bill savings than under fully decentralized control.

When studying the benefits of peak shaving, Wagter (2023) [14] found in a residential grid a reduction of the peak load of 20% compared with the scenario without shared BESS. Whereas Li Y (2022) [27], when applying a shared BESS into a commercial park, found a 26,6% peak reduction, demonstrating the peak-shaving capacity by the centralized control.

Addressing the identified research gap, this thesis proposes the integration of a centralized, building-integrated shared BESS within a residential-industrial network, serving both sectors through centralized operation. Departing from conventional models that treat residential and industrial applications separately, this study investigates a shared BESS constrained by real-world technical limitations. This approach aims to assess system-level performance gains enabled by multisectoral energy collaboration.

2.3. Multi-Sector Energy Collaboration

The concept of multi-sector energy collaboration, one of the central subjects on this thesis, is introduced in the 2024 ReInvent report [28], as the end-use sector coupling, consisting of an energy exchange collaboration between different types of end-user's typologies including residential, commercial and Industrial on a decentralized level, more commonly as energy communities as a collective self-consumption models, aiming to maximize local resource efficiency and improve system flexibility.

Although most CSC studies focus on residential collectives and load diversification [13], [8],[12], the integration of diverse user types introduces complementary consumption patterns that improve system-wide performance, as shown in studies from Gasca (2025)[8], Belmar (2023)[6], and Schram (2023)[29]. In these studies, heterogeneous demand smooths aggregated load curves, enhances the match between local generation and consumption, reducing energy waste and grid dependence.

A case study by Belmar (2023) [6] conducted in Portugal, achieved the best overall results in one scenario integrating different participant types, including up to 42% savings in community electricity costs and an increased self-sufficiency of 12,5%. Underlining the shape and timing of participant load profiles as key factors to improve collective performance.

Gasca (2025) [8] demonstrated that energy communities combining both residential and commercial users can achieve higher levels of self-sufficiency, improved energy efficiency, and cost reductions, particularly when 50–75% of participants act as prosumers. Moreover, the study notes that while diversity enhances collective performance, it can reduce individual savings in heterogeneous communities, especially without intelligent control and fair governance mechanisms, it can lead to unequal benefits among participants.

In the same study from Gasca (2025) [8], 4 communities' configurations are explored, where the first 3 groups are categorized by the consumers typologies and a fourth group is created with a linear combination of consumers typologies, resulting in a heterogenous configuration. Illustrated in Figure 2, the findings support the conclusion from Belmar (2023) [6], as the bill savings per user tend to saturate with the aggregation size, with the highest savings observed in Group 4.

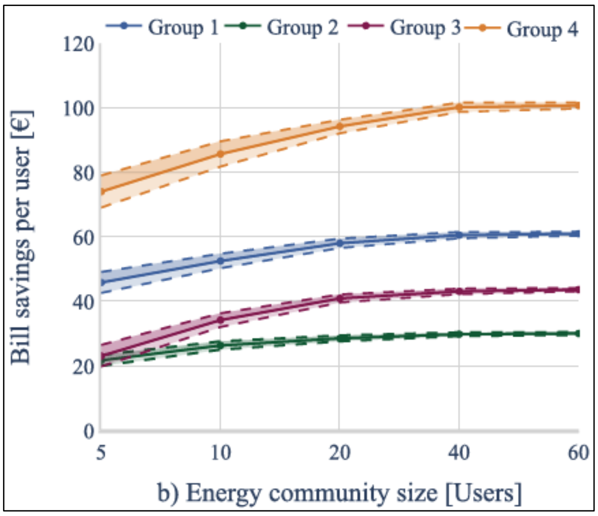

Figure 2 - Relation between user bill savings and community size [9].

This thesis contributes to the existing scientific literature by modelling and quantifying the operational and economic impacts of the industrial and residential networks collaboration within a real-world pilot system. It integrates sector-specific load profiles and PV generation data to assess the potential for energy exchange, while offering insights in seasonal and hourly tendencies.

2.4. Energy collaboration between MV and LV networks

The ability of energy communities to share locally generated electricity depends heavily on how their members are interconnected. Minuto and Lanzini (2025)[30] identified the following approaches:

1. *Private network connection (behind-the-meter): Members are connected via a private network and share a common PoC to the public grid. Energy is exchanged internally within the network before interacting with the wider grid.*
2. *Public grid connection (virtual energy exchange): Members remain individually connected to the public grid, and energy exchanges occur virtually, using metering schemes that simulate a shared PoC for members' coordination.*

In the Interreg project [31] reports that these challenges are intensified by the fact that Dutch legislation currently forbids the development of private interconnections, making the physical multisector energy sharing legally complex.

Although interconnections between LV and MV networks offer potential benefits, it requires addressing several technical challenges:

Bidirectional metering: Advanced smart meters with two-way communication are essential to enable real-time data exchange and precise measurement of energy flows of DER [32].

System coordination: Poorly designed interconnections with low coordination, rather than solving, may aggravate congestion [33].

Control strategies: For a centralized control of shared assets, digital upgrades to the grid are often needed to enable energy balance and improve system stability [34].

Dimovski et al. (2023) [35] reinforce that minimizing energy exchanged with the external grid can significantly reduce MV-level congestion. However, this requires integrated planning, precise control, and effective communication infrastructure.

Despite growing interest in LES and collective self-consumption, non-technical barriers remain substantial. The report [28] ,highlights key limitations such as:

1. *High upfront investment costs.*
2. *Uncertain long-term business models.*
3. *Fragmented and inflexible tariff structures.*
4. *Limited mechanisms to value flexibility and energy sharing.*

The upcoming Energy Law in the Netherlands, expected for 2026, aims to better align national legislation with the Renewable Energy Directive (RED III) [36]. This new framework introduces a formal right to energy sharing and promotes the development of multisectoral energy communities capable of operating across different voltage levels, as already applied in countries such as Belgium [5].

However, the success of collective self-consumption depends not only on technical innovation but also on a coherent and supportive regulatory environment [29]. The CEER (2024) report [5] highlights that complex licensing procedures, fragmented tariff structures, and limited mechanisms for data exchange remain key barriers to scaling energy sharing. Addressing these challenges through simplified administrative processes and harmonised governance frameworks will be essential to unlock the full potential of LV–MV energy collaboration, supporting grid flexibility, renewable integration, and greater energy autonomy at the community level.

3. Research methodology

This chapter details the methodology used to address the research question, beginning with data collection on load demand, PV generation, and infrastructure, while distinguishing the real and estimated data used. The chapter then details the methodology for KPI calculation and the simulation models applied at different research stages, along with the expected outcomes from each model. Finally, it presents the economic analysis of energy collaboration and shared BESS integration, followed by the validation process used to assess the model's consistency under variations in the estimated input data.

3.1. Data collection for simulation models' development

This section outlines the data collection process used to construct the simulation model. The modeling framework integrates measured and estimated data, which are categorized into three key components: (1) electricity demand and PV generation profiles for the industrial park, (2) electricity demand and PV generation data for the residential neighborhood, and (3) grid infrastructure characteristics. Each subsection details the sources, assumptions, and processing methods applied to prepare the input data for the system under study.

3.1.1 – Electricity demand profiles and PV generation at the Industrial Park

The industrial park comprises four companies: a packaging company, a retail store, a joinery workshop, a wood workshop, all connected to the same MV network. Power demand profiles at 15-minute resolution were developed for all entities for the year 2023. For the packaging company, both measured electricity demand and PV generation data were provided by REFORMERS project partners. While for the remaining, demand profiles were estimated. Additionally, for the retail store which also operates as a prosumer, PV generation was also estimated.

To allow the power-flow analysis of the system, energy measurements (kWh), were converted to power, kilowatt (kW), using Equation (1):

$$P(t)(kW) = E_{demand}(t)(kWh) * \frac{60\ (min)}{time\ resolution\ (\min)} \quad (1)$$

The estimated electricity demand profiles were based on the known contracted power, combined with standardized load profiles from Liander Open Data [37]. This dataset compiles normalized electricity demand profiles based on 2023 quarterly measurements from large consumers. Each profile corresponding to a sectoral activity (SBI code), defined by the Chamber of Commerce and Statistics Netherlands (CBS).These profiles were scaled to each company's contracted power to generate 15-minute resolution demand estimates, using the data summarized in Table 1.

Table 1- Load profiles, SBI codes, and contracted power for the companies with estimated consumption.

Company	*Description*	*Contracted Power (kW)*	*SBI code*	*Normalized Profile from Liander Database*
Retail Store	*Retail store of building materials*	*51*	*4752*	*KO_OVERIG*
Carpentry Workshop 1	*Manufacture of wood furniture*	*75*	*4332*	*KO_INDUSTRY*
Carpentry Workshop 2	*Installation of joinery work*	*89*	*3109*	*KO_INDUSTRY*

The industrial prosumers operate rooftop PV systems with the installed capacities (kWp) indicated in Table 2.

Table 2 - PV installed capacities for prosumer companies.

Company	PV installed capacity (kWp)
Packaging Company	97
Retail Store	417

For the retail store, the PV output was estimated by scaling the PV power measurements, using Equation (2).

$$P_{PV_{retail\ store}}(t) = P_{PV_{Packaging\ company}}\ (kW) * \frac{PV_{installed\ Capacity_{Retail\ Store}}\ (kWp)}{PV_{installed\ Capacity_{Packaging\ Company}}\ (kWp)} \quad (2)$$

This approach is justified by the similarity in panel orientation, as both installations are on flat roofs, where standard assumptions on proportional inverter losses were assumed.

In alignment with the REFORMERS project and to support the site's energy transition, the packaging company will integrate an EV truck, along with the shared BESS integrated during the second stage of the research.

The EV model was indicated by the REFORMERS project partners to be a Mercedes eActros electric truck [38] operating from 8:00 to 18:00 and scheduled to start charging between 18:00 and 20:00 at a rated power of 50 kW. While the shared BESS consists of two CELL POWER "CESS 233-100" lithium iron phosphate units, each with a storage capacity of 233 kWh and an Alternating current (AC) output maximum rated power of 100 kW, operating at a depth of discharge (DoD) of 90%. Therefore, totaling in a storage capacity of 466 kWh and 200 kW rated power. The indicated cost per storage unit was 85667€. The complete list of the technical specifications is provided in Appendix 1.

3.1.2 – Electricity demand profiles and PV generation in residential grid

The residential model includes a total of 50 households located in the southern area of Plan Oost, Heiloo. This number was defined by two key constraints: (1) the limited size for simulation models under the PowerFactory academic license and (2) alignment with the first implementation phase of the REFORMERS project, during which these 50 homes were selected to receive smart meters.

Due to data privacy regulations and the unavailability of smart meter data available at the time of the research, energy consumption profiles were estimated. The estimations were derived from postcode-level energy grid import/export data using aggregated statistics from the Energy Transition Data Facility for the Built Environment (DEGO) database [39]. The consumption profiles were made using a standardized Dutch residential load curve developed by the company HET NORMO [40] (central data exchange entity in the Dutch energy market) that includes weekday/weekend and seasonal consumption variations.

The considered neighbourhood includes four postcode areas within the defined project boundary, comprising 50 houses, 10 of which are equipped with individual BESS and EVs, designated as smart houses. These are grouped into two clusters of five, whose locations coincide with the postcode boundaries and the spatial extent of the project area.

Figure 3 shows the neighborhood segment considered, defined by the red boundary line, while the smart house clusters are indicated by red dots.

Figure 3 - Map of the analysed neighbourhood.

Using DEGO database [39], the average annual household electricity imports and exports for 2023 were obtained for each postcode area. Table 3 summarizes these values, with colour highlights corresponding to the postcode zones represented in Figure 3.

Table 3 – Households annual total grid imported and exported energy per postcode

Postcode	Annual total household grid imported energy (kWh)	Annual total household grid exported energy (kWh)
1851GD	1476	3000
1851GB	890	1982
1851EH-EJ	1053	2501
1851EG	1345	2349

As these values are measurements from energy exchange with the grid, they do not account for on-site self-consumption. Therefore, it was required to reconstruct the residential electricity demand and PV generation profiles to capture the complete energy dynamics from the households.

For this purpose, a stepwise methodology was employed. The residential demand profiles were derived using an annual total household demand based 15-minute resolute Normalized standard Dutch electricity curve from HET NORMO [41], and a 15-minute resolute normalized PV generation profile, generated by the Photovoltaic Geographical Information System (PVGIS) tool [42] considering the region's 2023 PVGIS–SARAH3 meteorological data. Due to lack of data, the generation curve was calculated for 1 kWp, assuming optimal values of 37º tilt facing south, based on findings from Bas van Aken [43].

Using both normalized curves, various combinations of annual total household demand and installed PV capacity were tested until annual total imports and exports matched the reference data, using Equations (3) and (4).

$$Total\ electricity\ \ export\ (kWh) = \sum_t \left(PV_{generated}(t) - P_{Demand}(t)\right)\ \ ,\ PV_{generated} \geq P_{Demand} \quad (3)$$

$$Total\ electricity\ usage\ (kWh) = \sum_t \left(P_{Demand}(t) - PV_{generated}(t)\right)\ ,\ PV_{generated} \leq P_{Demand} \quad (4)$$

Table 4 presents the final values for annual total electricity consumption, PV installed capacity, and the resulting annual total grid imported and exported energy per house.

Table 4 - Estimated annual total grid import and export values, and annual total household electricity consumptions and PV installed capacities used.

Postcode	Electricity export (KWh)	Electricity usage (kWh)	Total eletricity consumption (kWh)	PV installed capacity (kWp)
1851GD	1429,08	3149,65	4000	2,00
1851GB	893,18	1909,69	2500	1,25
1851EH-EJ	1059,64	2401,04	3100	1,50
1851EG	1350,01	2401,04	3100	1,80

Although not all houses are equipped with PV, it was necessary to assume PV installation for all 50 households, allowing the aggregated power demand and PV generation to more closely align with the actual statistics.

The smart house models each includes an individual BESS AlphaESS SMILE-G3-BAT-9.3S [44], corresponding to the units being deployed within the REFORMERS project. Each features a usable capacity of 9.3 kWh, and AC output power up to 5 kW. A 90% DoD was applied to ensure consistency in the BESS settings, allowing a consistent comparison of their contributions. In the simulation environment, the BESS is treated as an ideal component with 100% round-trip efficiency due to the use of the software's BESS template.

The EV was modeled as the Tesla Model Y, identified as the most adopted EV in the Netherlands in 2024 [45]. According to the specifications [46], the EV has a storage size of 80 kWh and an AC charge power of 11.5 kW, which was used in the model to simulate the worst-case grid impact scenario, with charging starting times randomized between 16:00 and 19:00 to reflect typical household arrival patterns. The complete list of the technical specifications for both BESS and EV are provided in Appendix 1.

3.1.3 - Infrastructure data for the networks and shared BESS

The development of a consistent simulation model required a representation of the local grid infrastructure, including voltage levels, transformers, cables, and companies' grid connections capacities. Due to lack of real data, only critical information such as MV cable type and grid-connection limits for industrial users was used from internal project documentation, estimating the rest of the network components based on others research.

The voltage levels are known for the local grid, setting 230/400 Volts LV and 10 kilovolts MV. Based in the research [47], two types of transformers were used, 630 kVA designated for industrial loads, and 400 kVA for residential loads.

The MV network uses XLPE-insulated underground 240 mm² aluminium cables, consistent with the known configuration of the existing grid. The LV residential network, uses XLPE-insulated underground 150 mm² aluminium cables, mentioned by Bhattacharyya (2008) [47] as the "commonly used" in the Dutch grid. To maintain consistency across the network, in the LV industrial level XLPE-insulated underground 3×240 mm² copper cables are used, following the industrial network design presented in [48]. In this case, copper was adopted to ensure sufficient current-carrying capacity in accordance with the applied transformer and the maximum power limits of each company grid-connection.

Since the full network and all loads are not modelled, the infrastructure limitations are primarily found in the companies' grid connections integrating new PV or shared BESS units, their selection is further explained in the report. Table 5 indicates the technical maximum active power allowed by the companies' grid connections.

Table 5 – Maximum active power allowed in the Companies' grid connections.

Companies Grid Connection Power Capacity	
Company	Active Power (kW)
Packaging Company	147
Carpentry Workshop 1	94
Carpentry Workshop 2	94

This approach offers a conservative representation of the grid. Relying only on public grid assumptions could compromise the reliability of results, especially during the integration of new energy assets, such as the shared BESS and PVs. Applying known local limits enhances the model's operational validity.

3.2. Description and PowerFactory Simulation Models

This section presents the simulation framework developed to assess the performance of LES under various configuration scenarios. The models simulate power flows based on the data inputs and assumptions detailed in Section 3.1. This section begins by introducing the simulation environment, followed by a description of the KPIs, and finally outlining the four research stages, detailing each configuration and its expected outcomes, while linking each stage to the corresponding research objectives.

3.2.1. General introduction to DigSILENT PowerFactory

Using the data mentioned in the previous Chapter, the simulation models were then developed using PowerFactory, a leading software for smart grid simulation [49]. Through yearly quasi-dynamic simulations, discrete power flow calculations are performed allowing more detailed study of the system's response and energy exchanges within the system. Key considerations include the 3-phase stable network and a model centralized EMS, introduced in Section 2.2 , that by not considering electricity dynamic prices, it minimizes the imports from external grid, aligning with the project goals.

3.2.2. Comparison metrics and KPIs

The analysis of the simulations' results focusses on comparing and discussing the obtained KPIs and energy exchanges for the different scenarios studied. Moreover, the reduction of annual peak import/export power with the grid, annual total grid imports reduction, and potential relief during hours of likely grid congestion are also mentioned. This section presents the methodology applied to calculate the following KPIs:

1- *Self-sufficiency index: Represents the portion of the total energy consumed on an yearly basis* $(Consumption_{total})$ *that derives from local generation, energy exchange, and storage* $(Consumption_{local})$.

$$Self-sufficiency\ (\%) = \frac{Consumption_{local}\ (kWh)}{Consumption_{total}\ (kWh)} * 100 \qquad (5)$$

2- *Self-consumption index: Represents on a yearly basis the share of the locally produced energy* $(Production_{local})$ *consumed in the producing system* $(Consumption_{local})$.

$$Self-consumption\ (\%) = \frac{Consumption_{local}(kWh)}{Production_{local}(kWh)} * 100 \qquad (6)$$

3- *Net Annual Energy Balance (NAEB): Represents difference between the total energy consumed (kWh) from the external grid* $(demand_{external\ grid})$ *and the amount of PV generated excess energy (kWh) injected to the grid* $(Surplus\ injected_{external\ grid})$.

$$\text{NAEB}\ (kWh) = Surplus\ injected_{external\ grid} - demand_{external\ grid} \qquad (7)$$

4- *Community electricity costs: Community costs are the annual total electricity costs of the LES's participants. This KPI is later discussed during the economic considerations, Section 3.3.*

In Equation (8), the $PV_{consumed}$ *(kW) is calculated considering the possible charge of the shared BESS, not considered as consumption [50], and the PV exported into the grid,* PV_{excess} *(kW).*

$$PV_{consumed}\ [t] = PV_{total\ generation}\ [t] + BESS_{community_{Charge}}[t] + BESS_{Individual_{charge}}[t] - PV_{excess}\ [t] \quad (8)$$

Where $PV_{total\ generation}$ *(kW) is the total generated PV, while* $BESS_{community_{Charge}}$ *(kW) and* $BESS_{Individual_{charge}}$*, represent the shared and individual BESS charge power (kW), which the model considers negative values. Note that in the scenarios that don't include the shared BESS, the variable is not considered in the formulas.*

Following the work from Zepter (2022) [50], the calculation of the local energy consumption accounts for the losses from the exchanged energy and shared BESS. Using the simulated power flow results for cables and transformers, it is possible to estimate for each instant the share of total losses on the grid corresponding to the shared energy, represented by share factor k, calculated using Equation (9).

$$k\ [t] = \frac{BESS_{community_{discharge}}\ [t] + PV_{consumed}\ [t]}{BESS_{community_{discharge}}[t] + PV_{consumed}\ [t] + Grid_{imports}\ [t]} \in [0,1] \qquad (9)$$

Equation (10) derives the proportional renewable power lost in the local grid, $\mathrm{P}_{\mathrm{renewable}_{\mathrm{losses}}}$ *(kW), found using the share factor k and the total grid losses in each instance ,* $Grid_{losses}$.

$$\mathrm{P}_{\mathrm{renewable}_{\mathrm{losses}}}\ [t]\ (kW) = k[t] * Grid_{losses}[t] \quad (10)$$

Equation (11) obtains the local power consumption, considering the contribution from PV generation ,$PV_{consumed}$ *, individual BESS,* $BESS_{Individual_{discharge}}$ *,and shared BESS,* $BESS_{community_{discharge}}$ *, and the proportional renewable losses,* $\mathrm{P}_{\mathrm{renewable}_{\mathrm{losses}}}$.

$$Consumption_{local}\ [t]\ (\mathrm{kW}) = PV_{consumed}\ [t] + BESS_{Individual_{discharge}}[t] + BESS_{community_{discharge}}[t] - \mathrm{P}_{\mathrm{renewable}_{\mathrm{losses}}}[t] \quad (11)$$

The yearly consumption of locally produced energy is obtained in Equation (12), summing all the instants in the year and converting the 15-min power to energy.

$$Consumption_{local}\ (MWh) = \frac{\sum Consumption_{local}(t) * 0{,}25}{1000} \quad (12)$$

3.2.3. Description and expected outcomes from each research stage

A. Research Stage 1 – Baseline Assessment of Split Residential and Industrial Networks

The first research stage (RS1) starts by analyzing the residential and industrial distribution networks operating independently, reflecting the current state of the networks and setting the base case for this research.

The industrial MV network model uses the data introduced in Section 3.1.1. Although the real layout was applied, the lengths of the MV cables were estimated based on the known spatial configuration from the DSO's grid layout database [51], by measuring the distances between the nearest MV substation and the MV terminals within the industrial zone. In contrast, the LV cable lengths were assumed to be the physical distances between the companies' buildings, due to the lack of detailed connection data. Figure 4 shows a simplified schematic of the industrial network, where the metering point with the external grid is labeled 'M'

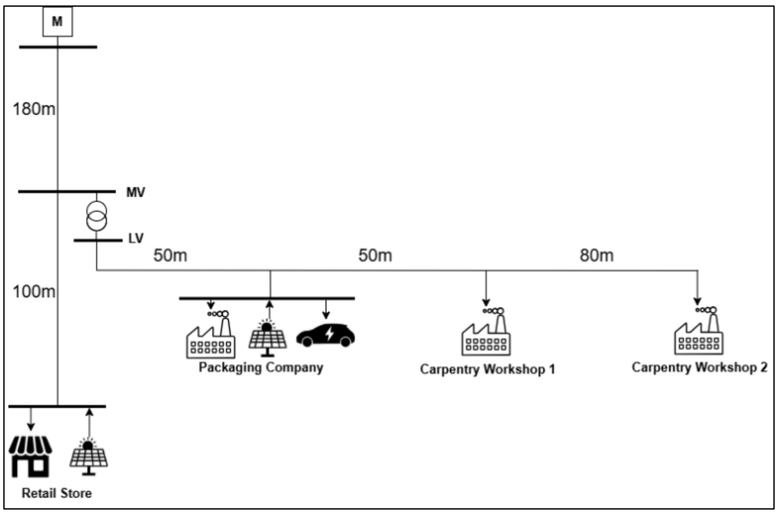

Figure 4 - Simplified diagram of Industrial Park network.

The residential network was modeled using the data described in Section 3.1.2. In this case, the cables between the 3 parallel streets were measured, using the same DSO database [51]. While the distance between houses was assumed 12 m between households was applied, following the approach from [47].

Figure 5 presents a simplified schematic of the residential network, where smart houses are marked with an 'S', and the metering point with the external grid is labeled 'M'.

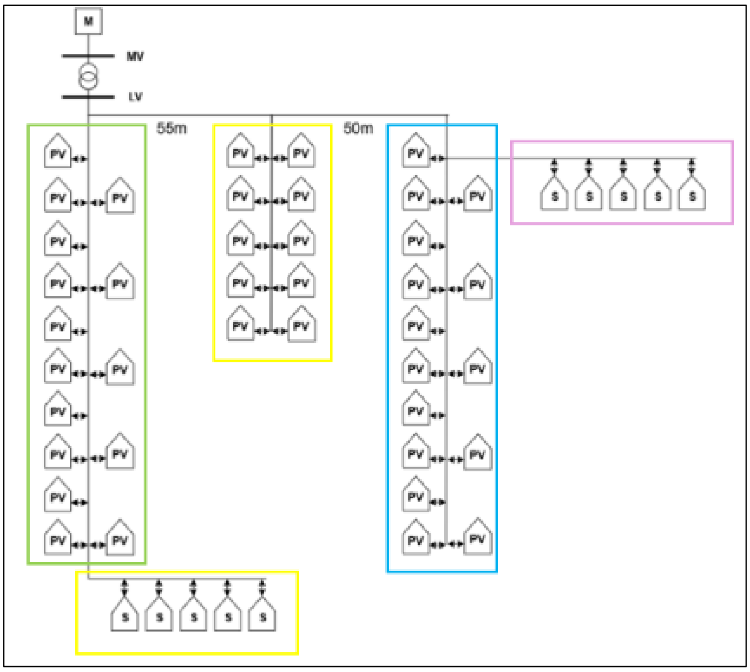

Figure 5 - Simplified diagram of residential network.

The EVs present in both networks were modeled using a dedicated EV template in the simulation software. This template configures each vehicle to initiate charging daily within the time window mentioned in Section 3.1.2, continuing until the battery reaches full capacity. As individual BESS operate by a decentralized EMS, managing the power flow in the smart house PoC.

RS1 establishes the baseline energy behaviour of the residential and industrial systems, defining the reference annual KPIs against which all subsequent scenarios are evaluated. It also analyses monthly KPIs to capture temporal and seasonal performance variations across the networks. Additionally, the stage explores potential complementarities that may arise from interconnection. A sensitivity analysis is conducted to assess how varying the number of residential units influences the effectiveness of multisectoral energy exchange.

B. Research Stage 2 – New interconnected system allowing energy exchange

The second research stage (RS2) investigates the benefits from interconnecting the residential and industrial areas to enable direct energy exchange through an MV link between the residential transformer and an industrial MV distribution box.

In the interconnected network, all loads were connected to a common PoC measuring the interactions with the external grid. The link between the two regions uses the same cable as the industrial MV grid, ensuring that both energy surpluses and energy drawn from the public *grid can be transferred safely. The cable's length was estimated by measuring the physical distance between the two terminals using the DSO geographical database [51] and assuming a route close to existing cables.*

Figure 6 illustrates a simplified diagram of the new interconnected network.

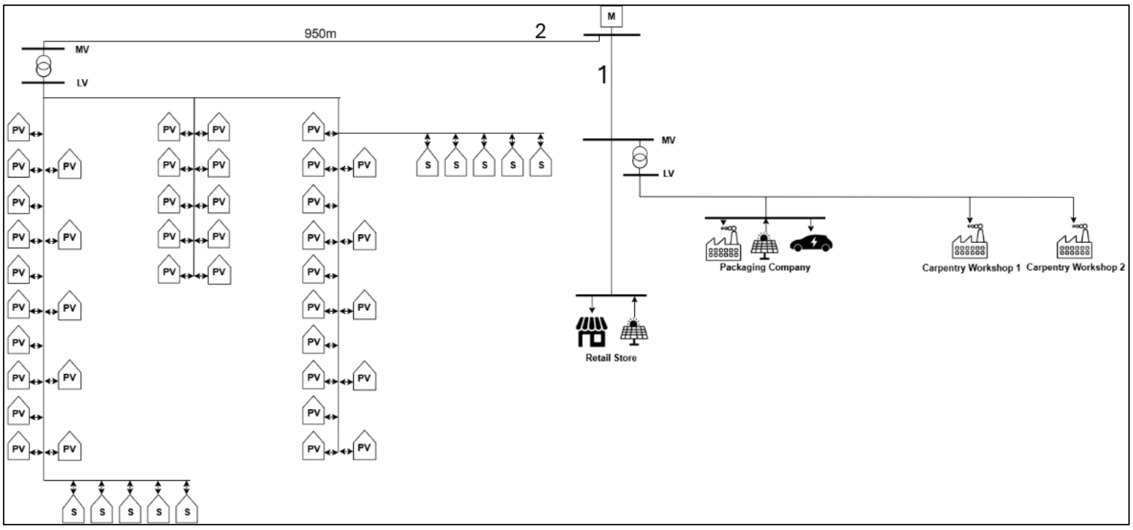

Figure 6 - Simplified diagram of the interconnected networks system.

The main goal of this study is to quantify the energy exchanged between the two regions, the impact of the interconnection on the system's KPIs, and interactions with the external grid.

Equations (13) and (14) define the logic behind the direct energy exchange, where line 1 and 2 measure, respectively, the total imports and exports from the industrial and residential networks, measuring negative when the region is exporting PV surpluses.

$$IF(Line\ 2 < 0\ and\ Line\ 1 > 0): \quad P_{Residential\ to\ Industrial} = Min(\ |P_{Line2}|\ ;\ P_{Line1}\ ) \quad (13)$$

$$IF(Line\ 1 < 0\ and\ Line\ 2 > 0): \quad P_{Industrial\ to\ Residential} = Min(\ P_{Line2}\ ;\ |P_{Line1}|\ ) \quad (14)$$

The first research objective is addressed by comparing the outcomes of the RS1 and RS2. The comparison will highlight the amount and timing of the energy exchanged between the two sectors, particularly during peak and off-peak demand periods, and consequent effect on the KPIs.

C. Research Stage 3 – Analysis of the Interconnected Network with Shared BESS

The third research stage (RS3) builds on the interconnected configuration from RS2, now incorporating the shared BESS described in Section 3.1.1. The BESS is modeled using the simulation software's predefined storage template and is physically located at the industrial park with the objective of evaluating its impact on the system's performance.

A simplified schematic of the simulation setup for this stage is presented in Figure 7.

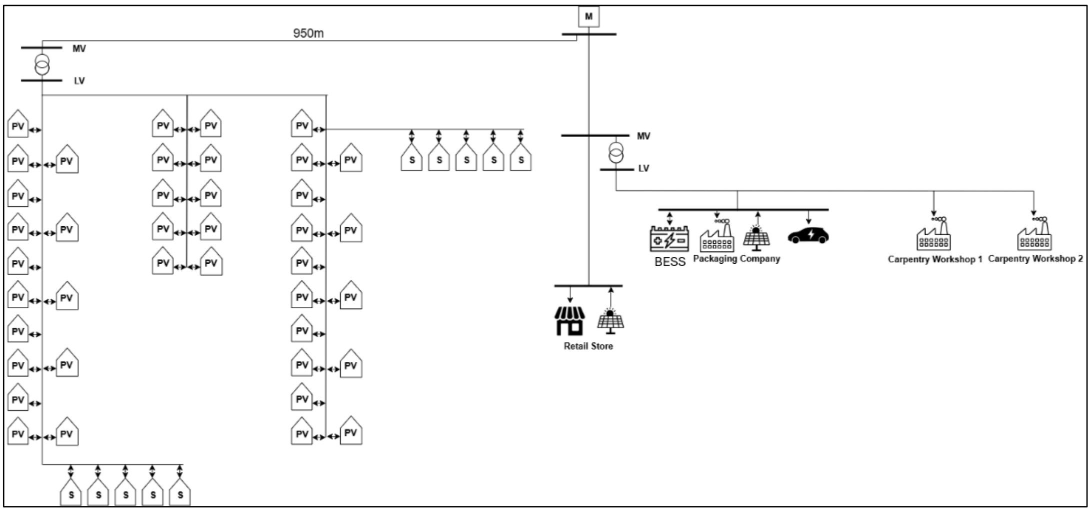

Figure 7 - Simplified diagram of system integrating shared BESS.

The BESS is centrally controlled at the PoC of the interconnected system. In line with the project's perspective, during discharge, the model prioritizes first fulfilling the industrial demand due to the proximity to the loads and energy physical flow. Whereas during charge the BESS uses the PV surpluses measured at the PoC. The BESS EMS logic is defined by Equations (15), (16) and (17).

$$IF\ (P_{POC} < 0):\quad \mathrm{P}_{\mathrm{BESS}_{\mathrm{charge}}} = \mathrm{Min}(\mathrm{P}_{\mathrm{MAX}_{\mathrm{BESS}}}\ ;\ \mathrm{P}_{\mathrm{POC}}) \qquad (15)$$

$$IF\ (P_{POC} > 0\ and\ SOC_{BESS} > 10\%\ ):\quad \mathrm{P}_{\mathrm{BESS}_{\mathrm{discharge}}} = \mathrm{Min}(\mathrm{P}_{\mathrm{MAX}_{\mathrm{BESS}}}\ ;\ \mathrm{P}_{\mathrm{POC}}) \quad (16)$$

$$IF\left(\mathrm{P}_{\mathrm{BESS}_{\mathrm{discharge}}} > 0\right):\ \mathrm{P}_{\mathrm{Discharge}_{\mathrm{Residential}}} = \mathrm{P}_{\mathrm{BESS}_{\mathrm{discharge}}} - P_{Demand_{Industrial}} \quad (17)$$

The BESS, when not fully utilized to meet industrial demand, can provide additional support to the residential network while also being capable of discharging whenever power is required by only one of the interconnected regions. During the charge, both regions contribute to charge the shared BESS, maximizing the BESS system contribution. However, as mentioned in Section 3.2.1, as the model minimizes the energy imports from the grid, the BESS can only be charged with PV surpluses.

Results from RS3 are compared against RS1 to assess improvements on the reference KPIs and compared with RS2 to isolate the specific impact of the shared BESS on system performance. Addressing the second research objective by quantifying the BESS's contribution to performance gains, while also analysing possible contributions to grid congestion mitigation, reduction of annual peak export and import values, and decreased reliance on the external grid. The impact of storage capacity is assessed through a sensitivity analysis, in which additional units of the same BESS model are incrementally added to the initially deployed system. Additionally, the influence of BESS location is evaluated by adjusting its maximum power output, simulating both a lower-capacity and a higher-capacity grid connections.

D. Research Stage 4 – Technical assessment for target KPIs fulfilment

The final research stage (RS4) focuses on assessing the feasibility of achieving the REFORMERS project's energy targets of 75% self-consumption rate and a positive NAEB. The two main technical conditions considered to validate the practical possibility are (i) the availability of rooftop space and (ii) the companies' grid connections capacity to integrate the additional PV.

According to Liander's database [37], approximately 50% of the residential buildings already have PV installations. Therefore, the maximum technically feasible PV capacity is assumed to be twice the current installed capacity. On the industrial side, internal REFORMERS project data confirms the two PV-integrated companies' rooftops are fully utilized. As a result, only the remaining companies can accommodate limited additional PV installations while ensuring to not exceed the power limits of their grid connections, indicated in Section 3.1.3.

In this scenario, both split and interconnected systems are simulated under the condition of achieving the energy targets. The results compare the type and size of additional assets required in each configuration, providing insight into how multisectoral collaboration can reduce infrastructure needs and facilitate the attainment of community energy goals, addressing the third research objective.

3.3. Economic Considerations

A simplified economic assessment is included to evaluate the financial viability of the proposed system configurations. Using the baseline scenario from RS1 as a reference, the analysis compares community cost savings and investment requirements across the subsequent research stages. For each stage, annual community electricity costs are calculated using the average 2023 electricity prices reported by CBS [52], shown in Table 6.

Table 6 - Electricity prices for household and non-household loads.

2023 Average Electricity Prices (€/kWh)	
Households up to 5MWh/year	*Non-households up to 2000 MWh/year*
0,316	*0,279*

Investment costs are considered when new infrastructure is implemented, RS3 and RS4. The cost estimates are based on component prices derived from the REFORMERS project. The BESS module cost corresponds to the specific unit described in Section 3.1.1, whereas PV system costs are calculated using Canadian Solar CS6K-260 modules [53], priced at €95 per module [54].

Due to the complexity of estimating the interconnection required infrastructure and additional investment costs such as additional cables, labor work, operational costs and assets degradation, these were excluded from the analysis considering only the PV and BESS prices. The goal is to estimate annual savings and assess the economic benefit from each configuration. A simplified payback period is calculated by dividing the total additional assets costs by their contribution to the community costs reduction.

3.4. Validation process

The validation process aims to confirm the reliability of both the data sources and the simulation model developed in this research.

First, the residential demand and PV generation profiles were validated by comparing the modeled net grid imports and exports with actual aggregated values indicated by DEGO [39]. This estimation approach was then reviewed with energy analysts from the NEC and stakeholders to confirm their suitability for the residential area studied.

For the industrial network, the estimated profiles were validated through a sensitivity analysis. This method consists of varying annual consumption values (±50%) and observing the impact on the KPIs. The goal was to demonstrate that small deviations in input data do not significantly affect the overall results of the study.

Through this process, the model's assumptions and input data will be critically assessed to validate the accuracy of the simulation outcomes and support the reliability of the research conclusions.

4. Results

This chapter analyses the outcomes from the simulation models developed to evaluate the performance of the LES. It starts by evaluating the current configuration of the region and gradually incorporates the energy collaboration and shared BESS. At the end of the chapter, a simplified economic assessment is presented to compare the financial feasibility of the different configurations, followed the validation process, where variation of the input data assesses the reliability of the models' outcomes.

Research Stage 1 – Baseline Assessment of Split Networks

A. Residential Network

The first part of this section analyzes the simulation's results for the 50 houses located in the southern section of Plan Oost, grouped by postcode and connected the same MV/LV transformer. The residential network model is shown in Appendix 2.

Figure 8 shows the demand and PV generation profiles by postcode during the peak demand week, with each curve's colour corresponding to the postcode colour defined in Table 3. The smart houses (including EV and individual BESS) are labeled SH, while T17 and T2 represent two households respectivily in postcodes 1851GB and 1851EG.

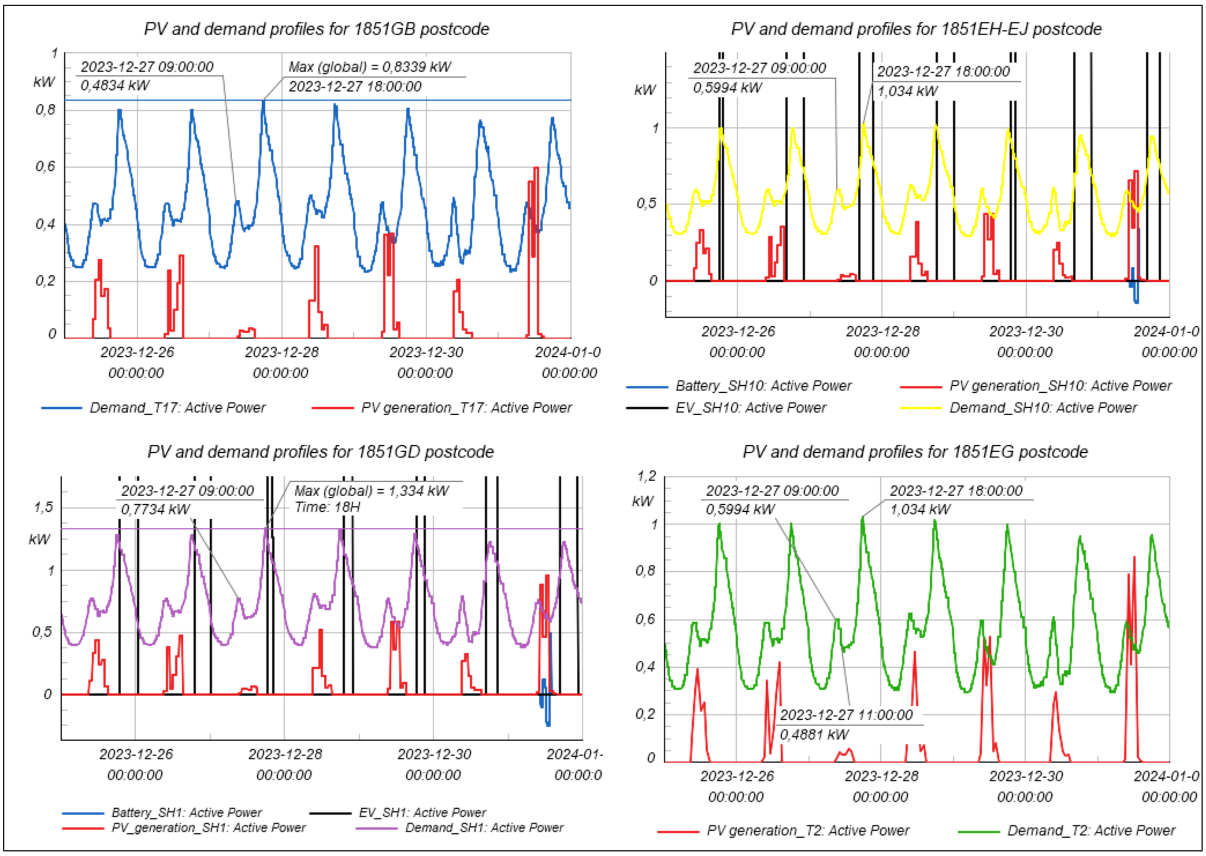

Figure 8 - Consumption and PV generation profiles for each postcode during a winter week.

Using the same consumption profile across all postcodes results in a consistent peak electricity demand occurring at 18:00, decreased during the weekends. The smart houses exhibit distinct EV charging profiles, with randomized initial states of charge resulting in varied charging durations, observable through the timing of start and stop charging marked by the black lines. Additionally, the PV generation shows frequently not enough to meet household demand, therefore causing an underuse of individual BESS.

Figure 9 illustrates a summer week in which household electricity demand is at its seasonal minimum. The same color-coding scheme is used to distinguish the demand and generation curves corresponding to each postcode.

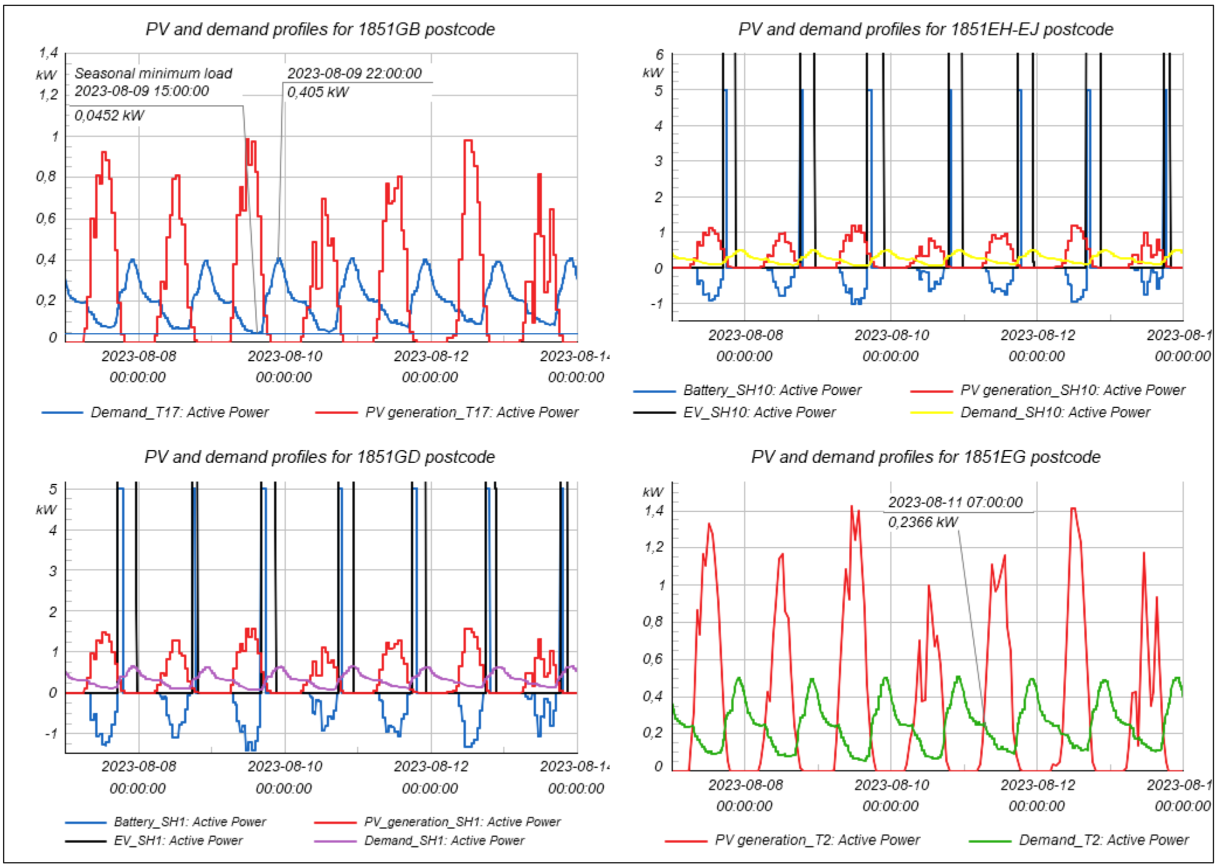

Figure 9 - Consumption and PV generation profiles for each house postcode during a summer week.

The results show frequent daytime PV surpluses during the summer period, shown in peak summer to start at 7:00 ,which can be stored by the houses with individual BESS while the others export to grid. Charging is constrained by the available surplus, while discharging occurs during evening hours, mainly to offset the increased load from EV charging as the profiles show a late summer demand peak at 22:00. This behavior is controlled by the individual BESS's decentralized EMS, which aims to fulfill the grid imports measured at the house's PoC. The postcodes' consumption profiles show reduced peak demand and flattened consumption curves, reflecting the seasonal variation in electricity usage.

Figure 10 illustrates the aggregated PV generation and household demand curves for the residential network, and the total power losses occurring across the network due to cables and transformers.

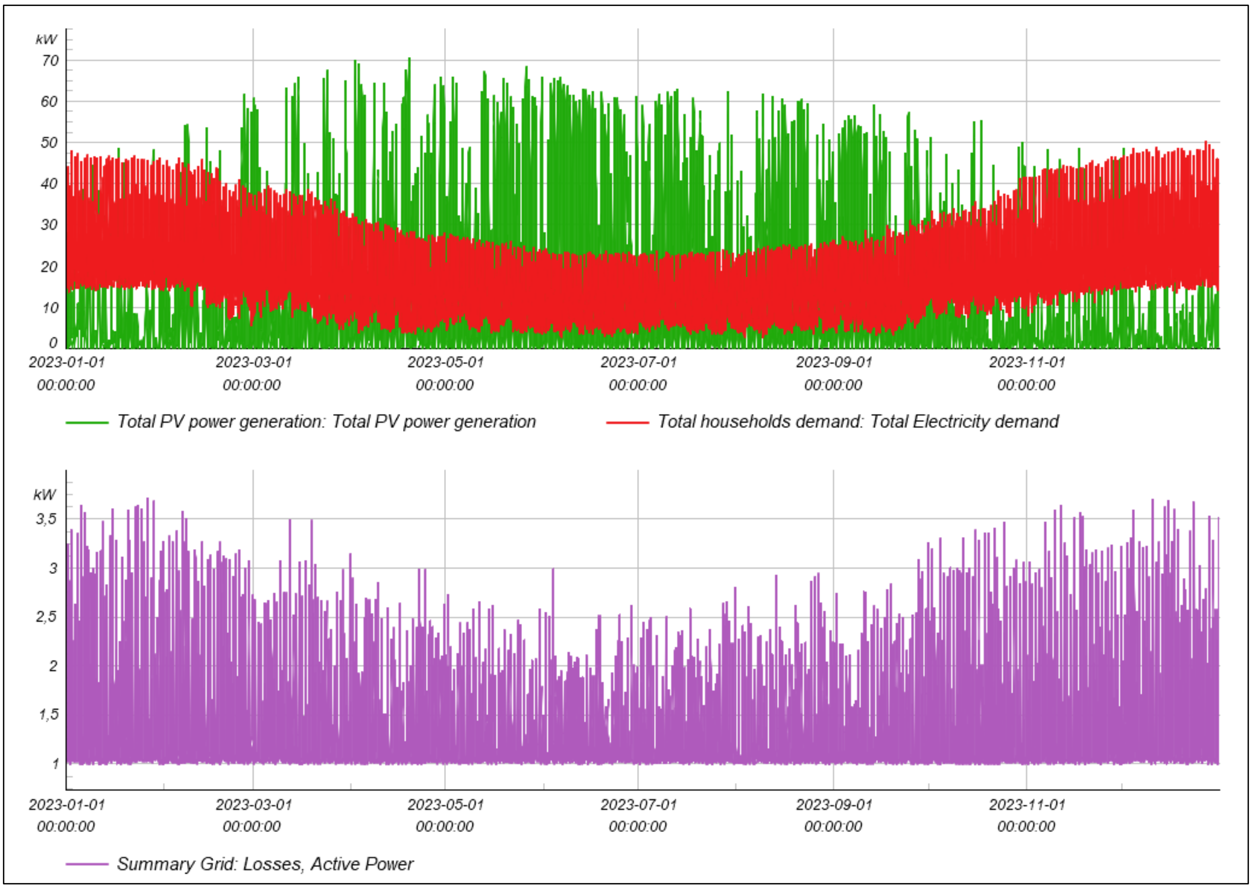

Figure 10 - Residential network's total households demand, PV generation and grid losses.

Results show large variations in the PV generation, caused by the northern latitude of the region, while increased distributed generation during summer shows lower network losses due to less total power beings transported in cables and transformer, highlighting the network's efficiency benefits from the integration of DER .

The main residential network annual parameters are summarized in Table 7.

Table 7 – Main annual basis results for residential network.

Results	*Value*	*Unit*
Total electricity demand	*298,250*	*MWh*
Total Renewable generation (PV)	*84,061*	*MWh*
Total electricity demand from grid	*266,268*	*MWh*
Local energy consumption	*40,003*	*MWh*
Contributions from individual BESS	*11,560*	*MWh*
Total PV excess exported to grid	*42,683*	*MWh*
Total energy losses in network	*10,954*	*MWh*

From these parameters and deriving from the formulas introduced in Section 3.2.2, the resultant KPIs are shown in Table 8.

Table 8 - KPIs found for residential network.

Residential network's KPIs (Annual Basis)	
Self-consumption (%)	*47,59*
Self-sufficiency (%)	*13,41*
Net Annual Energy Balance (MWh)	*-223,585*

To provide deeper insight, Figure 11 presents the monthly evolution of the self-consumption and self-sufficiency throughout the year.

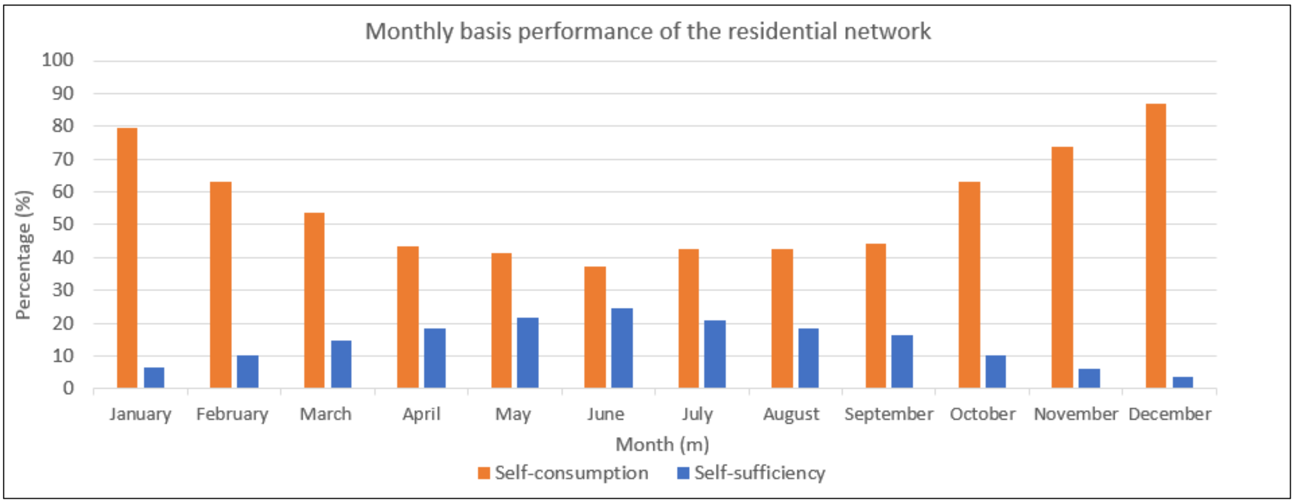

Figure 11 - Monthly basis KPIs for residential network.

In winter months, the system exhibits low self-sufficiency and high self-consumption due to limited PV generation and higher household demand, also causing a poor individual BESS utilization as PV surpluses are minimal, seen in Figure 8. In contrast, the summer profiles with higher PV output and reduced demand lead to greater contribution from household BESS. These conditions improve self-sufficiency, however the excessive PV generation without storage decreases the self-consumption.

B. Industrial Network

This section presents the performance results of the industrial park operating independently, before the integration of any storage units. The simulation model diagram used to represent the industrial network configuration is shown in Appendix 2.

Similarly with the residential network, the load profiles are analyzed first, however due to different demand profiles, the selected weeks are based on the maximum winter, and the minimum summer aggregated businesses demand, shown in Appendix 3. Considering summer season from April to September and winter season from October to March.

Figure 12 presents the businesses' demand profiles during the respective winter week.

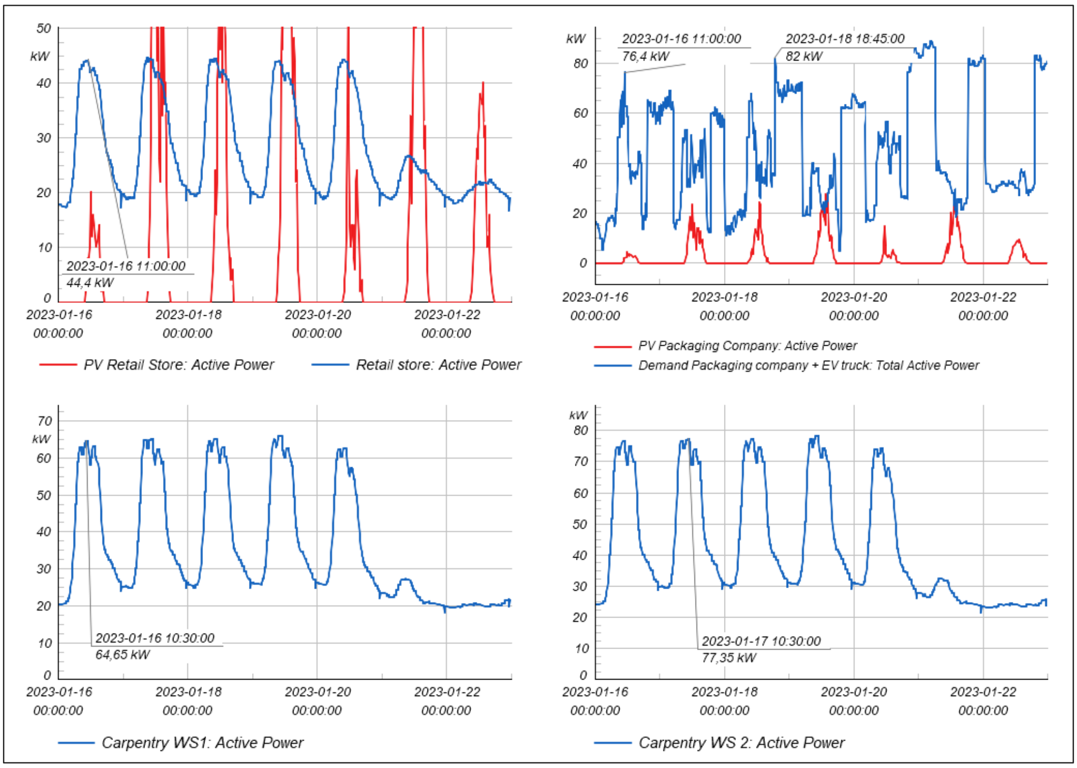

Figure 12 - Businesses demand and PV profiles during a winter week.

Figure 13 presents the businesses' demand profiles during the respective summer week.

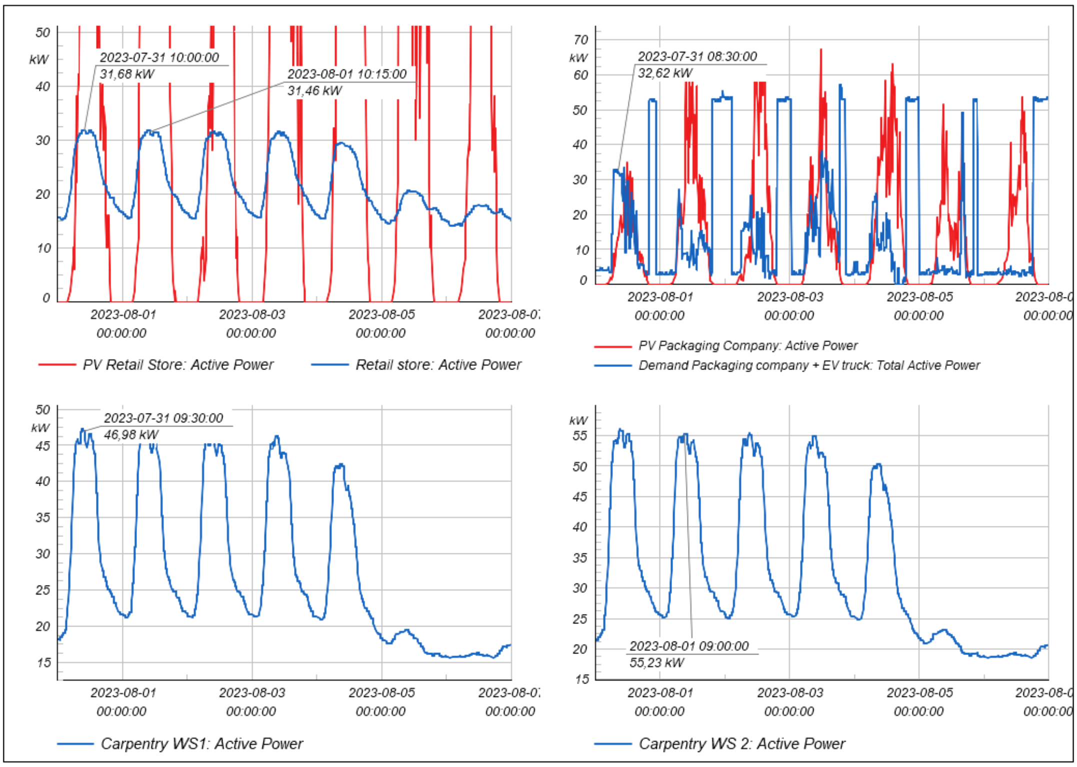

Figure 13 - Businesses demand and PV profiles during a summer week.

The demand curves exhibit the operational characteristics of each company, while the packaging company consistently shows a double-peak profile from the daytime operations and EV truck charging.

The difference between the retail store and the carpentry workshops is marked in the shape of their demand curves, reflecting distinct usage patterns, while showing a significant PV generation largely contributing to the industrial loads in both winter and summer seasons. During winter businesses demands peak around 11:00, while during summer they anticipate to approximately 9:00. While during weekends, demand drops significantly offering surplus-sharing potential to the residential network after interconnection.

Figure 14 displays the industrial park's PV generation and demand curves, which, similarly to the residential side, reveal strong seasonal fluctuations on the local solar generation.

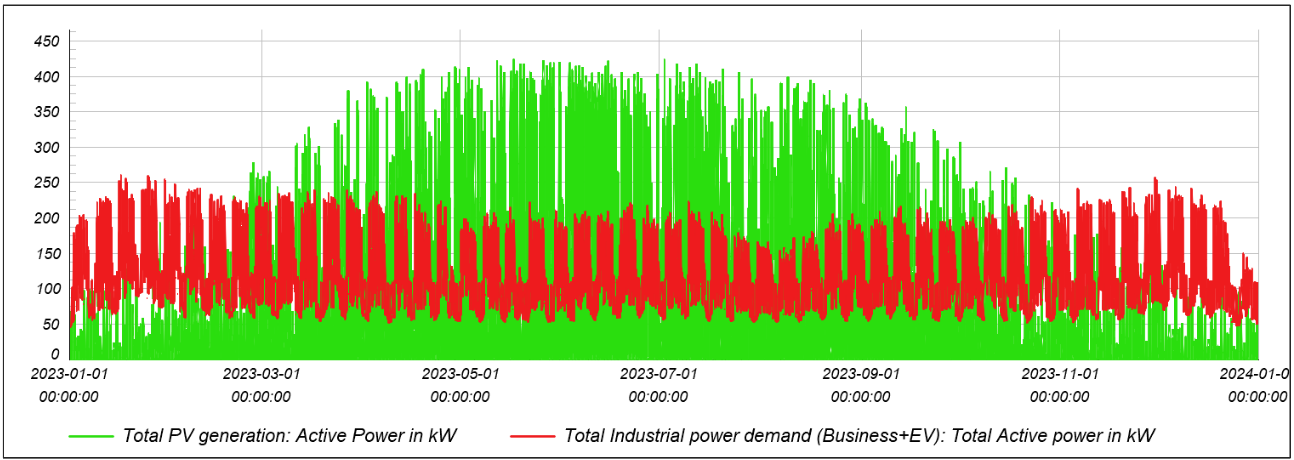

Figure 14 - Consumption and PV generation annual profiles in the Industrial Park.

Following the analysis of the operational curves, the annual performance results for the industrial park are presented below in Table 9.

Table 9 – Main annual basis results for industrial network.

Results	value	unit
Total electricity demand	975,924	MWh
Total renewable generation (PV)	533,538	MWh
Total electricity demand from Grid	679,512	MWh
Local energy consumption	307,058	MWh
Total PV excess exported to grid	221,678	MWh
Total energy losses in network	15,449	MWh

The simulation yields the following annual KPIs, summarized in Table 10.

Table 10 - KPIs found for the Industrial network.

Industrial network's KPIs (Annual basis)	
Self-consumption (%)	57,55
Self-sufficiency (%)	31,46
Net Annual Energy Balance (MWh)	-457,834

As with the residential network, monthly variations in self-consumption and self-sufficiency are depicted in Figure 15.

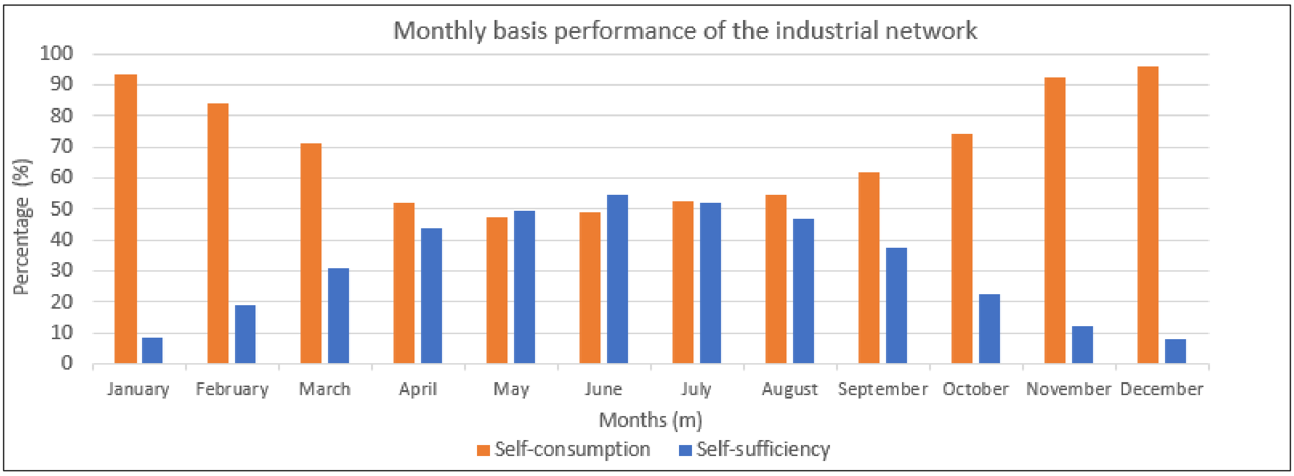

Figure 15 - Monthly basis KPIs for the industrial network.

The industrial park demonstrates greater seasonal resilience, due to a closer alignment between load demand and PV generation profiles, which mitigates the impact of seasonal fluctuations on overall performance.

C. Combined performance of the split networks

To allow the comparison with the subsequent interconnected scenarios. The analysis of the combined networks included combining both main results, while excluding any potential energy exchange, defined in Equations (13) and (14) for the grid interactions, revealing an annual maximum export of 404,7 kW and import of 336,7 kW, illustrated in Appendix 4.

To identify the hours of higher grid dependence, Figure 16 presents the hourly distribution of combined annual total imported and exported energy.

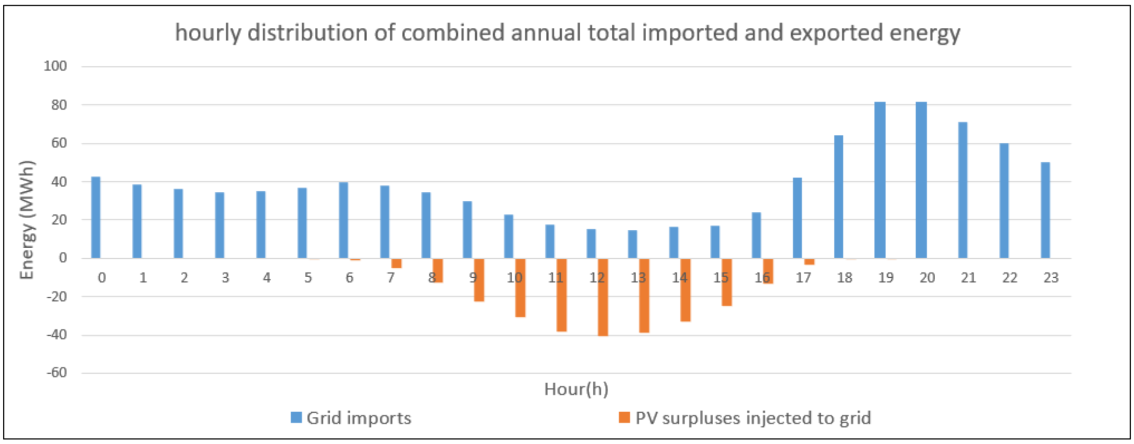

Figure 16 - Hourly distribution of combined annual total imported and exported energy.

The combined load profiles indicate a system's consumption increase from 17:00, reflecting the increased residential evening demand peaking at 18:00 in winter, and peaking between 19:00 and 20:00, reflecting overlap of EVs charge, starting between 16:00 and 19:00, and EV truck starting between 18:00 and 20:00. Although these values don't represent the external grid congestion, they indicate the hours of most probable congestion in the grid due to higher demand.

The collective performance of the split networks is summarized in Table 11, where combined results and consequent collective KPIs are presented for the baseline scenario.

Table 11 – Networks combined results and collective KPIs before energy collaboration.

Results	*value*	*unit*
Total Grid usage	*945,780*	*MWh*
Total PV excess exported to grid	*264,361*	*MWh*
Local energy consumption	*347,061*	*MWh*
Total energy demand	*1274,174*	*MWh*
Total PV generation	*617,599*	*MWh*
Collective KPIs		
Collective Self-consumption	*56,20*	*%*
Collective Self-sufficiency	*27,24*	*%*
NAEB	*-681,419*	*MWh*

D. Expected energy exchange following networks interconnection.

Following the evaluation of the residential and industrial networks, the potential for energy collaboration is assessed through the energy share of PV surpluses. This involved temporally aligning surplus generation from one sector with the demand of the other, considering Equations (13) and (14), introduced in Section 3.2.3.

The identified intervals of potential power exchange suggest that residential contributions are prominent during the winter months, while industrial contributions are greater in the summer, as illustrated in Figure 17.

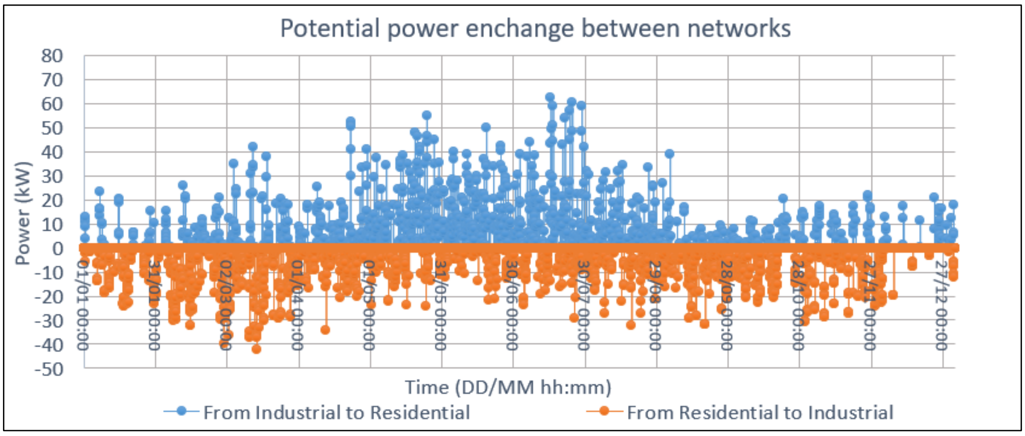

Figure 17 - Expected networks' power exchange.

Table 12 summarizes the expected total energy exchanged through the year and respective percentage from PV surpluses. The reduction in PV surplus feed-in is primarily seen on the residential side, due to the alignment between residential PV surpluses during winter and the industrial sector's operational hours, which in this season typically lack sufficient PV generation to cover the aggregated businesses demand, illustrated in Appendix 3.

Table 12 - Expected total energy exchanged and reduction in grid exports after network interconnection.

Expected energy exchange between regions				
Results	Units	Residential → Industrial	Industrial → Residential	Total energy exchanged
Energy exchanged	kWh	5304,45	3120,76	8425,20
Grid exports saved	%	12,43	1,41	3,19

Influence of Residential Scale on energy exchange Dynamics

Figure 18 illustrates the impact from the number of residential units in the amount of energy exchanged between the two regions, where a scaling factor was applied to the original neighborhood model, varying both levels of residential demand and PV generation.

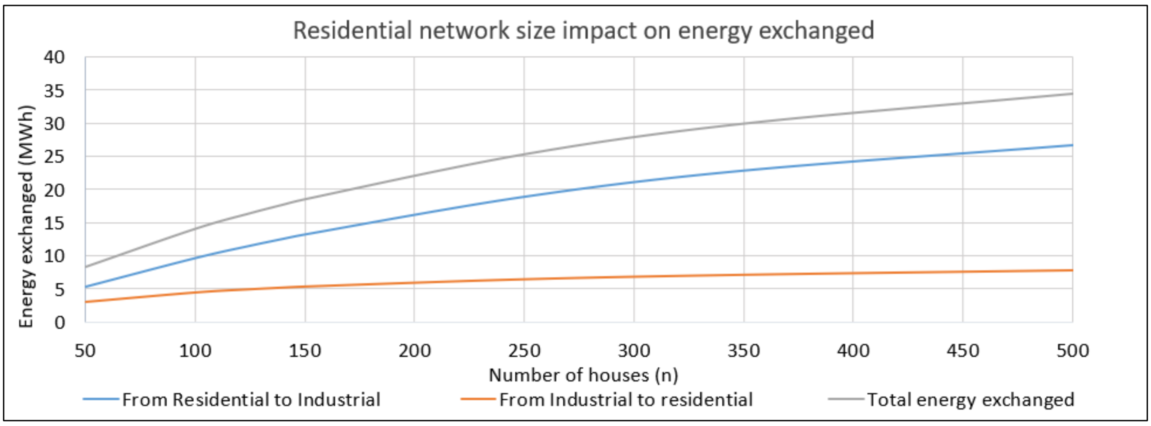

Figure 18 - Impact of residential network's size on the energy exchanged.

Results suggest that increasing the number of households leads to a corresponding rise in energy exchanged, primarily driven by the residential contributions. Therefore, highlighting the important role residential network in the energy exchange, particularly during winter months.

Figure 19 shows the impact from this variation on the collective KPIs, combining both industrial and residential networks.

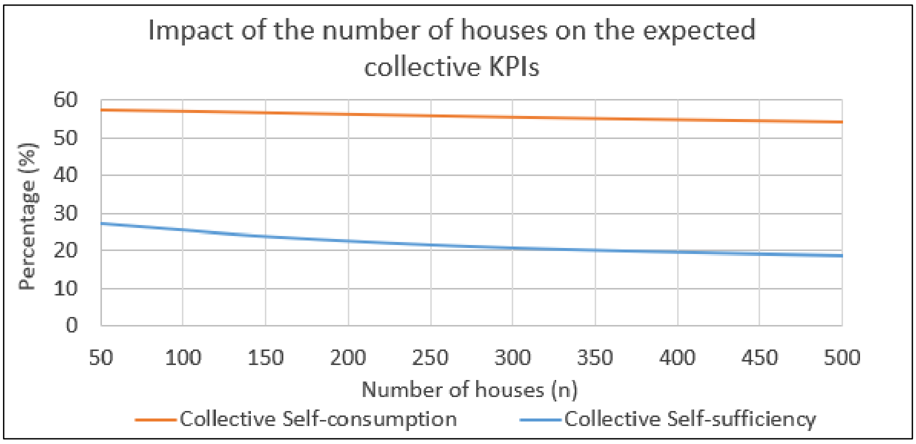

Figure 19 - Impact of residential network's size on the expected collective KPIs.

Although the amount of exchanged energy tends to increase with the number of households, this increase does not scale proportionally with the growth in PV generation and residential load demand. Therefore, the collective self-consumption and self-sufficiency exhibit a declining trend, indicating a relative inefficiency in energy utilization within the system as household numbers rise.

Research stage 2 – Interconnected networks model.

This section presents the results obtained in RS2 after interconnecting the networks and enabling the sectors' energy exchange.

Table 13 shows the total energy exchanged and consequent energy savings per region following the networks interconnection.

Table 13 - Total energy exchanged and energy savings per region.

Result	Unit	Residential side	Industrial side	Total
Annual grid imports saved	MWh	3,031	5,296	8,327

Results in Table 13 show align with those expected, indicated in Table 12, showing consistent energy exchange patterns, although minor variations arise from the random EV charging behavior, therefore varying the total contributions for its charge, and transmission losses in the interconnection cable and transformers.

Figure 20 analyzes the hourly distribution of the total energy exchanged between the networks following their interconnection.

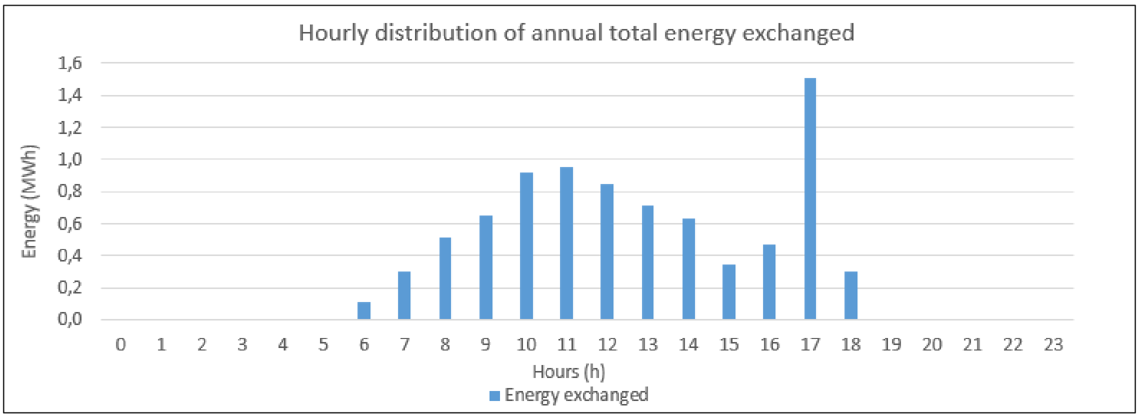

Figure 20 - Hourly distribution of annual total energy exchanged after networks interconnection.

Results shows the highest grid import savings at 17:00 in 1,51 MWh corresponding to 18,13% of the total energy exchanged. Seen in Figure 16 as a period of rising demand, pointed to probable congestion period in the utility grid, suggesting that energy exchange could effectively reduce the energy consumption during critical hours.

Further insight is provided in Figures 21 and 22, which illustrate the hourly distribution of the total summer (April to September) and winter (October to March) energy savings.

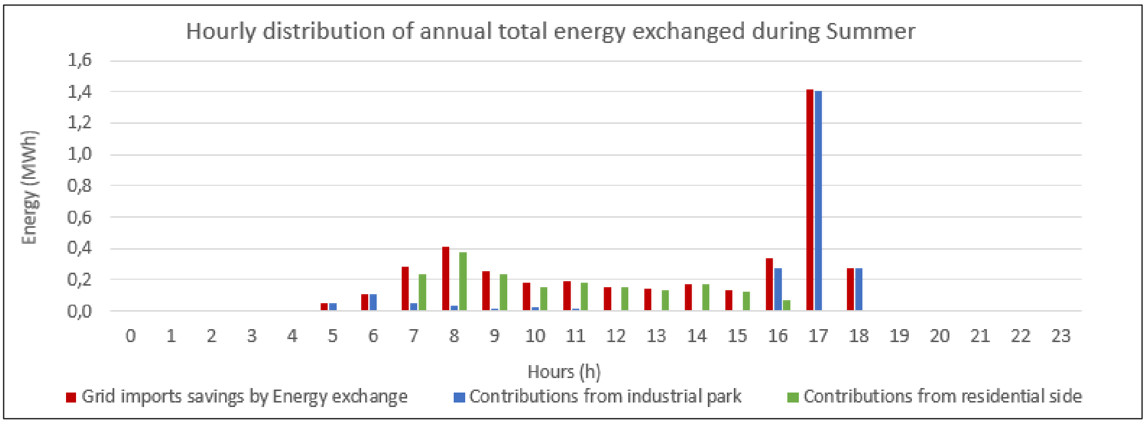

Figure 21 - Hourly distribution of total networks' contributions and consequent total energy savings during the summer.

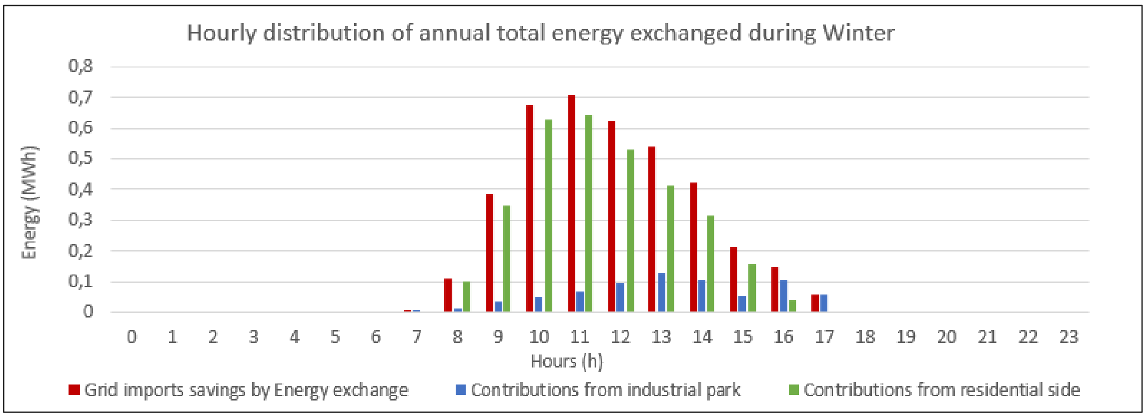

Figure 22 - Hourly distribution of total networks' contributions and consequent total energy savings during the winter.

A comparison of networks seasonal contributions reveals distinct patterns in energy exchange. During summer, the industrial park, equipped with a larger PV capacity, can produce substantial surpluses, usually until 18:00 seen Appendix 3, allowing to support the residential network mainly at 17:00 during its rising demand and EVs charge.

In winter, the residential network emerges as primary source for energy sharing. Despite reduced PV generation, there are days when it can still exceed the residential demand. Enabling surpluses to be shared to the industrial park, especially during 10:00 and 11:00, after residential morning peak demand decrease and during industrial peak demand.

Table 14 shows the main results and collective KPIs, after enabling the energy exchange. It compares the results expressed as the percentual increase for absolute values, and absolute difference for self-consumption and self-sufficiency.

Table 14 – Main results and collective KPIs after allowing energy exchange.

Results	Units	R. Stage 1	R. Stage 2	1->2 (%)
Total Grid usage	MWh	945,780	935,089	-1,13
Total PV excess exported to grid	MWh	264,361	256,026	-3,15
Local energy consumption	MWh	347,061	355,441	2,41
Total energy demand	MWh	1274,174	1271,710	-0,19
Total PV generation	MWh	617,599	617,599	0,00
Impact on collective KPIs after MV-LV interconnection				
Collective self-consumption	%	56,20	57,55	1,36
Collective self-sufficiency	%	27,24	27,95	0,71
NAEB	MWh	-681,419	-679,063	0,35

The obtained KPIs show modest improvements due to small contributions from the energy exchange when compared with the system's scale, increasing 1,36 % for self-consumption, 0,71 % for self-sufficiency. Although, results show a reduction of 0,35% for NAEB the reason is pointed to the EVs demand variation, primarily due the nature of the energy exchange equally offsetting exports and imports from the networks before their collaboration.

The new results for grid imports and exports results show a total grid imports reduction of 1,13%. Although EV behaviour shifts the moment of peak demand, no impact is found on the system's annual peak demand or export values, illustrated in Appendix 5. As during those moments both regions are, simultaneously, importing and exporting energy. Concluding that although the interconnection can decrease grid's dependency, it doesn't reduce the systems' peak interactions with the grid.

Figure 23 illustrates the increase in the monthly collective KPIs from the energy exchange.

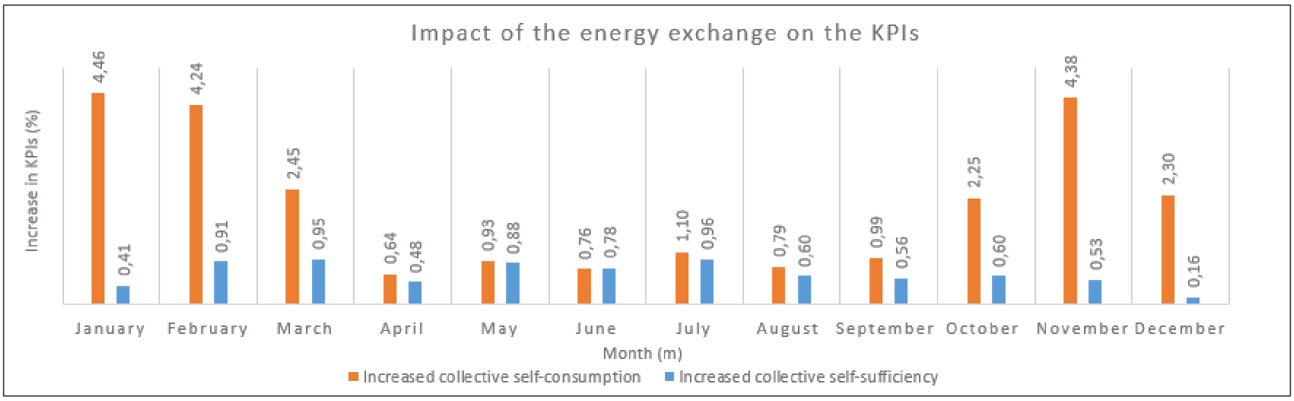

Figure 23 - Monthly KPIs Improvements after enabled energy exchange.

The increase in the monthly KPIs reveal to have the highest self-consumption gains during winter months, due to lower PV generation. Whereas the higher gains for self-sufficiency are found during summer months, due to the higher amount of exchanged energy and lower demands.

Research stage 3 – Interconnected Network with Shared BESS

The third stage of research (RS3) evaluates the impact of integrating a shared BESS into overall system performance, comparing the main results and KPIs with those previously obtained.

To ensure compliance with system infrastructure constraints, the BESS operation was restricted by the power capacity of the packaging company's grid-connection, indicated in Table 5. Therefore, due to the variability introduced by the random EVs charge, resulting in variable maximum power values under different simulations, the shared BESS power was restrained to 120 kW. This constraint was applied to prevent the annual maximum power from exceeding the permissible value, ensuring a safe BESS integration.

Figure 24 shows the peak power measured at the company's grid-connection (line 6), following the integration of the shared BESS.

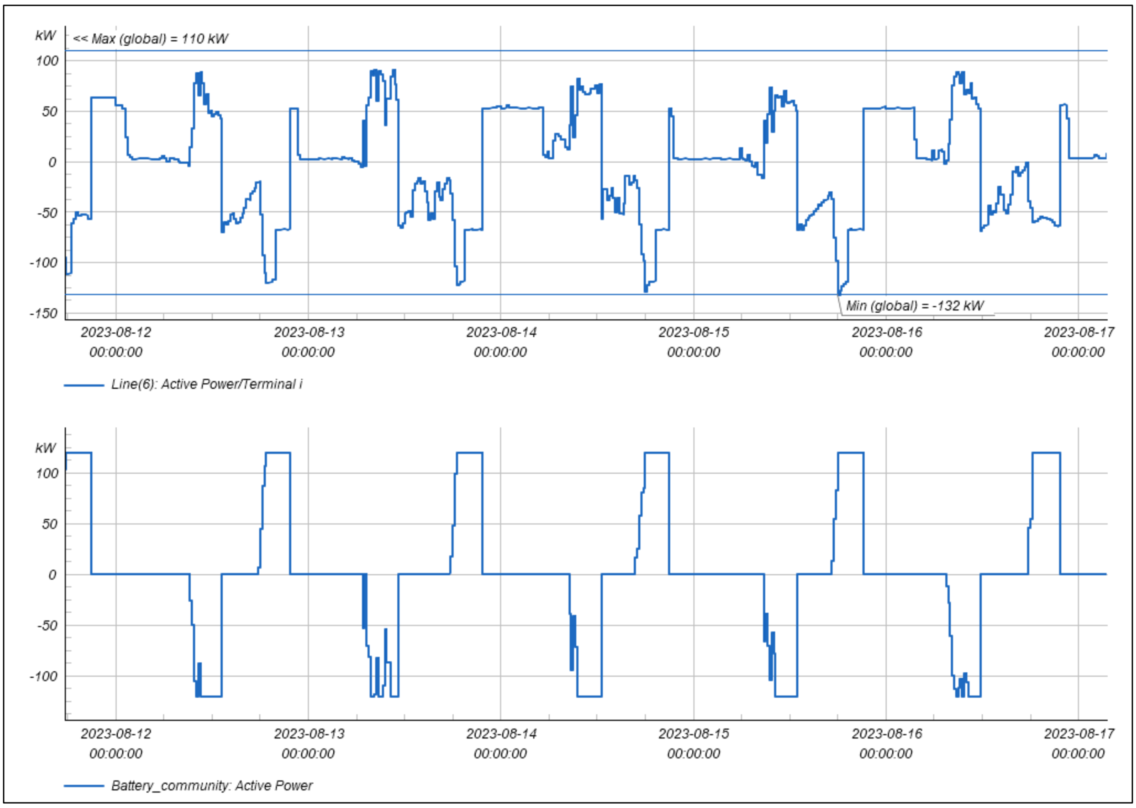

Figure 24 - Maximum active power at the packaging company grid-connection post-shared BESS deployment

The results indicate that peak power events occur during periods when the shared BESS is discharging at full capacity to the network, while simultaneously the company exports PV surpluses. The variability of the EVs charge compromises the safety of the company's grid-connection when the BESS is required to discharge at full capacity when higher values of PV surplus are being exported from the grid.

Table 15 summarizes the overall energy savings after integrating the shared BESS.

Table 15 - Energy savings per region and total contribution from energy exchange and BESS.

Results	Units	Residential side	Industrial side	Total
Energy saved by energy exchange	MWh	2,980	5,026	8,006
Energy saved by shared BESS	MWh	20,416	68,880	89,296
Total Energy saved	MWh	23,396	73,907	97,302

The results highlight a significant contribution from the shared BESS, accounting for 92% of the total energy savings. Of this share, approximately 70,8% occur on the industrial side, due to the priority in fulfilling the industrial demand before sharing with the residential network .

Figure 25 illustrates the hourly distribution of the annual contributions from the shared BESS.

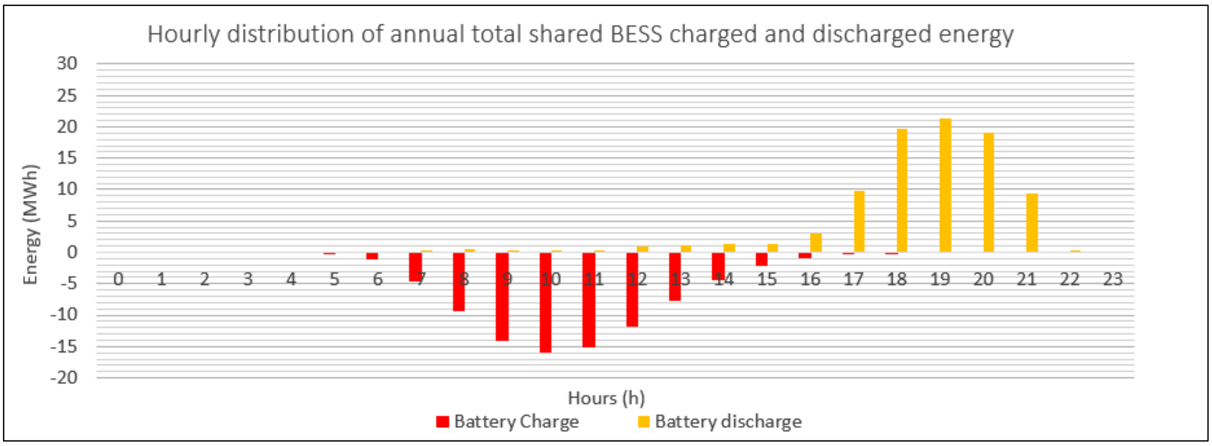

Figure 25 - Hourly distribution of annual contributions from the shared BESS.

The distribution indicates higher shared BESS contributions between 18:00 and 20:00, corresponding the hours of higher increase and peak demand, mainly driven by the EVs charge. Therefore, the total grid imports during these hours are shown in Figure 26 to be reduced by approximately 25%.

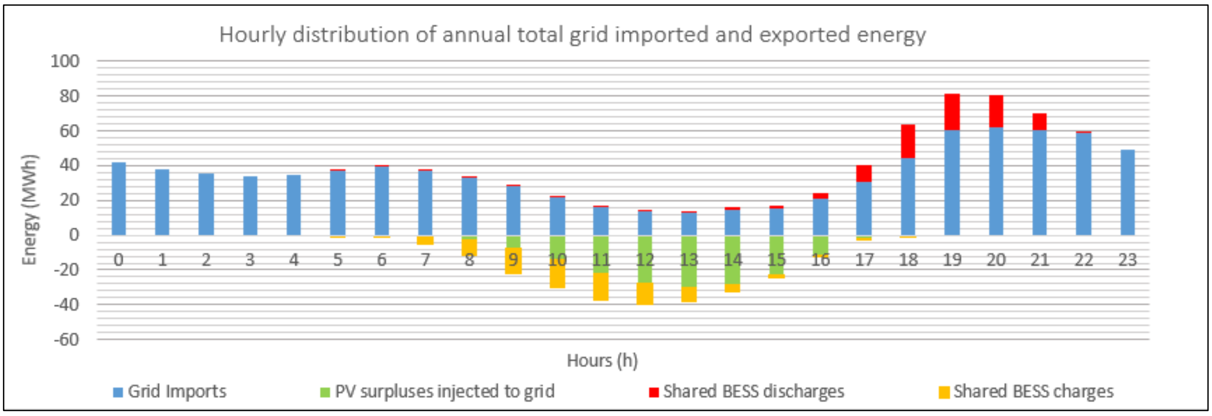

Figure 26 - Hourly distribution of annual total grid interactions post-shared BESS deployment.

The main results and KPI values from the RS3 are shown in Table 16, benchmarked against the baseline results from RS1 and RS2.

Table 16 - Main results and collective KPIs after shared BESS

Results	Units	R. Stage 1	R. Stage 2	R. Stage 3	2->3 (%)	1->3 (%)
Total Grid usage	MWh	945,780	935,089	841,757	-9,98	-11,00
Total PV excess exported to grid	MWh	264,361	256,026	169,011	-33,99	-36,07
Local energy consumption	MWh	347,061	355,441	442,924	24,61	27,62
Total energy demand	MWh	1274,174	1271,710	1267,665	-0,32	-0,51
Total PV generation	MWh	617,599	617,599	617,599	0,00	0,00
Impact on collective KPIs after shared BESS integration						
Collective self-consumption	%	56,20	57,55	71,72	14,17	15,52
Collective self-sufficiency	%	27,24	27,95	34,94	6,99	7,70
NAEB	MWh	-681,419	-679,063	-672,747	0,93	1,27

Compared to the baseline configuration, the new configuration shows a collective performance increase for self-consumption and self-sufficiency in 15,52 % and 7,7 %, respectively. Of these gains, 14,17 % in self-consumption and 6,99 % in self-sufficiency are caused by the shared BESS integration, as shown by the comparison with RS2, where gains from the energy exchange are excluded.

Similarly with findings from RS2, the variation in the NAEB is explained by the EVs random charge, reflecting the nature of BESS operation under the assumed ideal storage conditions, which does affect the NAEB, since stored energy offsets both imports and exports.

Results show a grid imports reduction of 11,00 %, compared with those from RS1, from which 9,98 % result from shared BESS contributions. However, the stage found no measurable impact on annual peak import and export values, shown in Appendix 6.

Figure 27 illustrates the shared BESS impact in the monthly collective KPIs, higher performance gains are seen during summer, whereas the exclusive PV surplus BESS charge limits the BESS contributions during the winter.

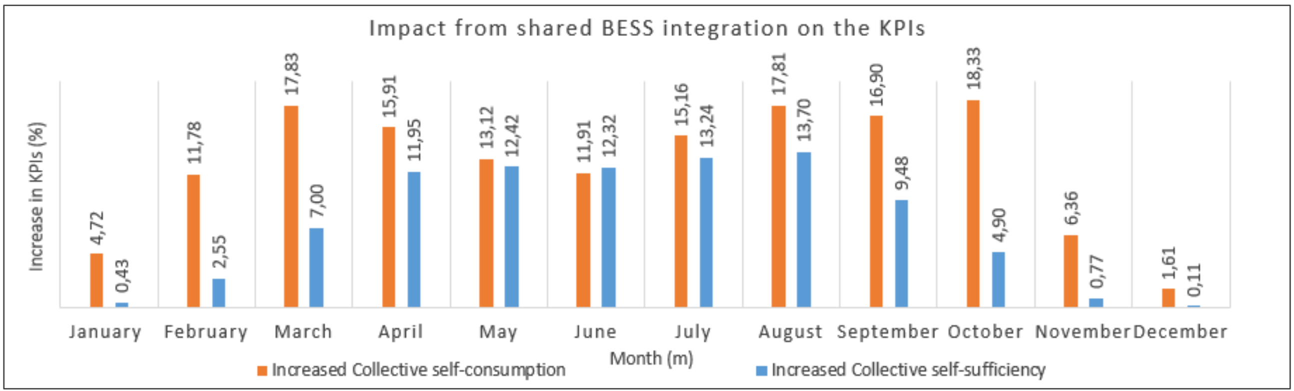

Figure 27 - Monthly KPIs improvements following shared BESS integration.

Results show higher self-consumption gains during March and October, due to being winter months with higher solar irradiance. During the summer, self-sufficiency shows its highest improvements, due to the higher BESS utilization following the increased PV generation.

Impact of the BESS size on the KPIs

After the integration of the shared BESS, a sensitivity analysis was conducted to assess the impact of storage capacity on system performance and evaluate the potential benefits of expanded capacity. Figure 28 illustrates the results from the analysis in the increased storage capacity up to double the original capacity.

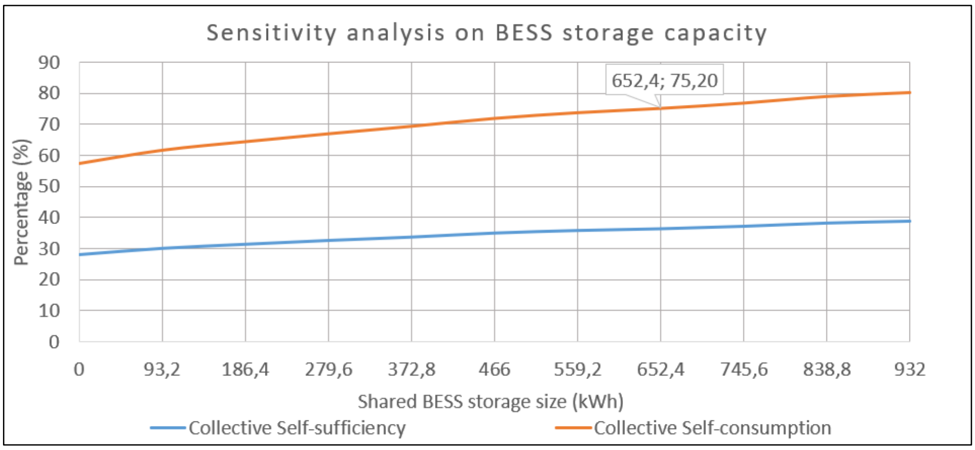

Figure 28 - Impact of Shared BESS size on system's KPI.

The outcomes indicate that achieving 75% self-consumption is possible for a storage capacity over 652,4 kWh.

However, a non-linear relationship is found between the BESS capacity and performance gains, as doubling the storage capacity led only to a self-consumption gain of 8,57% compared with the initial capacity. The limited contributions from the additional storage result from limited PV surpluses during winter, therefore additional capacity would mainly absorb excess summer PV generation, offering minimal contributions during the winter, critical period for energy availability. This limitation is illustrated by the state of charge of the shared BESS, illustrated in Figure 29.

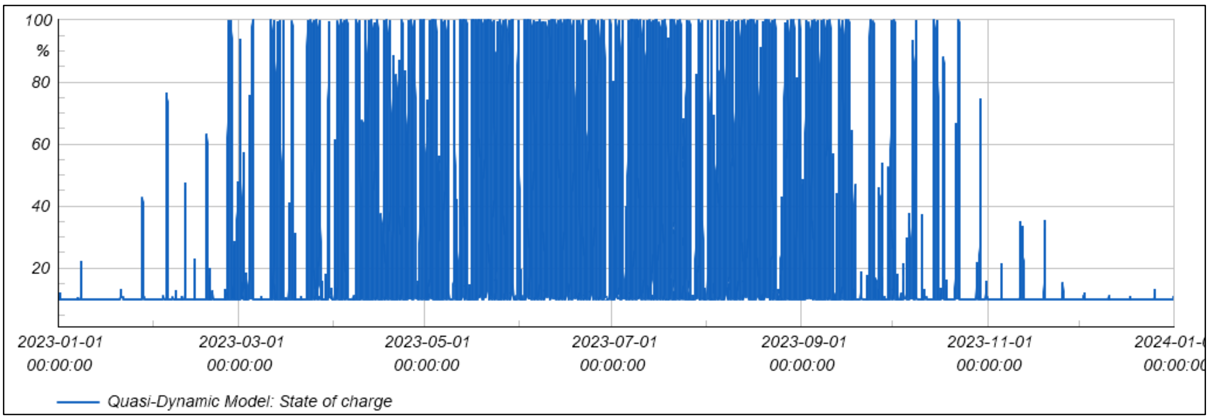

Figure 29 - Shared (466kWh) BESS state of charge throughout the year.

Impact of the BESS location

To assess the impact of the BESS location, and associated power constraint, on system performance two alternative cases were simulated: one with no power constraint and another with reduced power. These variations assess the shared BESS contributions under different grid-connection capacities depending on the place of deployment.

Table 17 - Shared BESS total contribution and contributions per region for different power constraints.

BESS Power constraint	Lower Connection Capacity (71 kW)	Current Grid Connection (120 kW)	No Power Constraint (200 kW)
Contribution from shared BESS (MWh)	83,413	89,296	91,504
BESS usage by residential side (MWh)	8,166	20,416	38,645
BESS usage by Industrial park (MWh)	75,247	68,880	52,860

Results indicate that the annual total contributions of the BESS are marginally affected by power capacity constraints and, consequently, having limited impact on overall KPIs. However, the available power capacity significantly influences sectoral distribution of energy, particularly benefiting the residential sector when no constraints are considered, primarily due to higher power availability to contribute to the increased EVs power demand.

This limitation also reduces BESS's contribution during hours of probable grid congestion, as restricted power limits the BESS's load-shifting capability during high-demand periods.

Figures 30 and 31 illustrate this effect, showing greater savings during peak hours when no power constraint is applied.

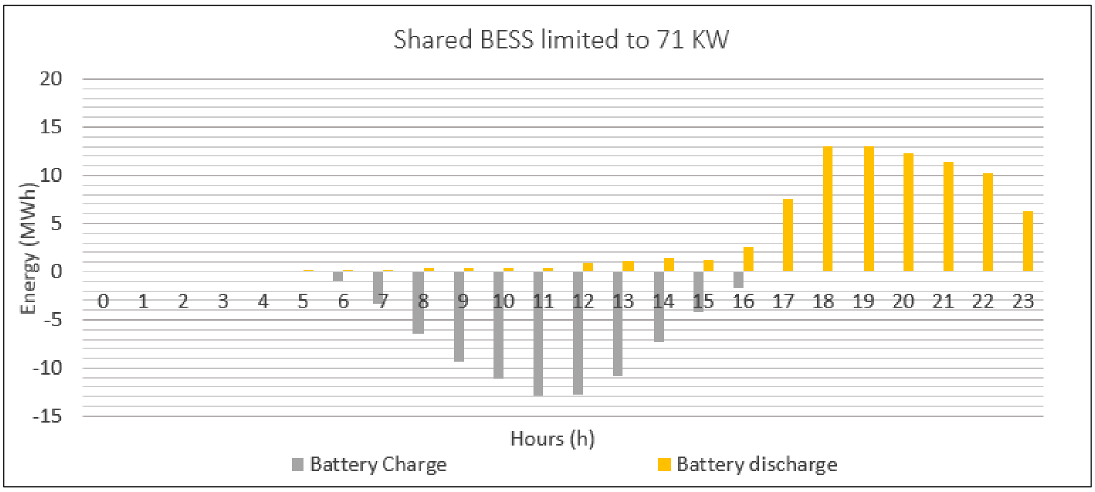

Figure 31 - Hourly distribution of annual shared BESS contributions when limited to 71 KW.

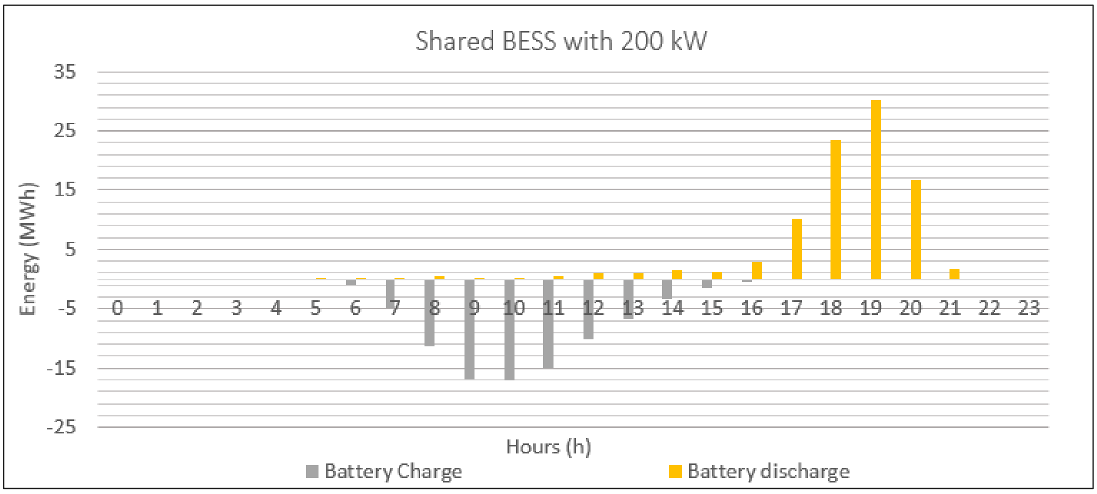

Figure 30 - Hourly distribution of annual shared BESS contributions when applied without power constraints.

Research Stage 4 – Technical assessment for target KPIs fulfilment

This stage evaluates the feasibility and energy assets required to achieve the proposed REFORMERS' KPI goals: (1) achieving at least 75% annual self-consumption and (2) attaining a positive NAEB. The strategy to meet these KPIs involves adjusting the installed capacities for both PV installations and shared BESS.

The influence of increasing PV installed capacity on KPIs was first evaluated, by using a uniform scaling factor applied in 10% steps to all PV installations to find the required installed capacity to achieve the positive NAEB, under the interconnected networks configuration.

Figures 32 shows the variation of the NAEB values while changing the PV installed capacity in the system.

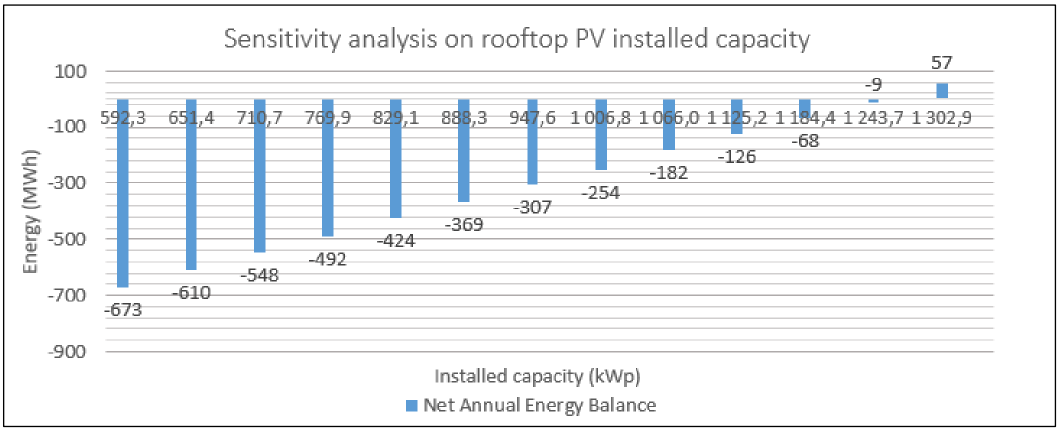

Figure 32 - Impact of PV Installed Capacity on the NAEB

Considering the possible variations in the annual total demand, the simulation results demonstrate that achieving a positive NAEB is theoretically possible for a PV installed capacity of 1,3 MWp.

Figure 33 shows self-sufficiency improvements with the increased PV, while self-consumption significantly declines, primarily caused by the large summer surpluses that cannot be locally consumed or stored.

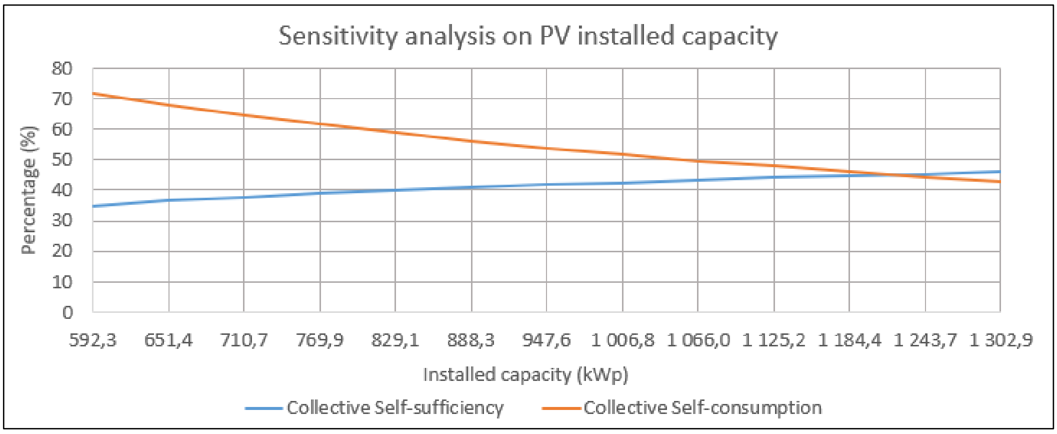

Figure 33 - Impact of PV Installed Capacity on the Collective Self-consumption and Self-sufficiency values.

Among the scenarios analysed, the most technically viable configuration to maximize NAEB was achieved for a total PV installed capacity of 888,13 kWp, considering the PV model indicated in Section 3.3. This setup involved doubling the residential PV installations (78 kWp) and adding 108,94 kWp to each carpentry workshop, yielding a NAEB of -363,1 MWh. To ensure that the additional PV capacity does not exceed the companies' grid connections limits, Appendix 7 presents the corresponding cables' power flow analysis following the PV expansion.

Despite the theoretical feasibility, practical constraints ,mentioned in Section 3.2.3.D, limit the implementation of such capacity. Therefore, the second part of the stage studied the feasibility of achieving 75% self-consumption within the expanded PV model.

Figure 34 illustrates the sensitivity analysis conducted on the shared BESS storage capacity to determine its effect on self-consumption and self-sufficiency under the expanded PV scenario.

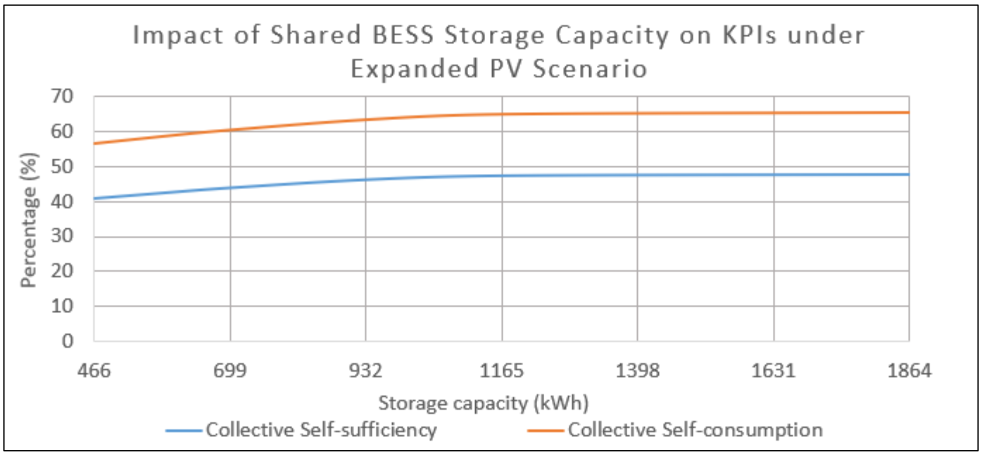

Figure 34 - Impact of Shared BESS Storage Capacity on KPIs under Expanded PV Scenario

Results show that both KPI goals couldn't be simultaneously achieved, even with significantly increased storage. Self-consumption values begin to saturate at approximately 67% when BESS size reaches 1165 kWh, making it the minimum storage size to obtain the best performing scenario. To the expanded PV model is then added a 1165 kWh shared BESS.

Table 18 illustrates the obtained KPIs and results for the expanded assets scenario.

Table 18 - Main results and KPIs achieved under expanded assets.

Results	Units	R. Stage 1	R. Stage 4	1->4 (%)
Total Grid usage	MWh	945,780	672,720	-28,87
Total PV excess exported to grid	MWh	264,361	306,389	15,90
Local energy consumption	MWh	347,061	614,957	77,19
Total energy demand	MWh	1274,174	1274,362	0,01
Total PV generation	MWh	617,599	930,195	50,61
Obtained KPIs under expanded assets				
Collective self-consumption	%	56,20	66,11	9,92
Collective self-sufficiency	%	27,24	48,26	21,02
NAEB	MWh	-681,419	-366,331	46,24

Under this configuration, the KPIs show significant improvements, particularly in self-sufficiency and NAEB due to expanded PV capacity. However, gains in self-consumption decrease compared with those obtained in RS3 (Table 16). This decline is driven by the 50,61% increase in PV generation and increased PV surpluses by 15,90%, compared with the baseline configuration. The results highlight the difficulty of achieving the targeted KPIs under strong seasonal solar intermittency and limited BESS power, which restrict the system's ability to effectively store the additional solar generation, especially during summer.

Although this configuration results in an annual grid imports reduction of 28,87%, the energy exchange with the external grid, shown in Appendix 7, shows no decrease in peak demand, for the same reasons outlined in RS3. The expanded shared BESS manages to reduce the peak export hours found in the previous stages; however, a new export peak is found minutes later, limiting the peak reduction to 3,3%.

Economic considerations

This section provides an evaluation of the economic impact of the proposed LES configurations across the three research stages on community costs reduction, and payback periods on the invested assets, considering the electricity prices from Table 6.

Baseline – Split Networks (Stage 1)

In the initial configuration, where the residential and industrial networks operate independently without any energy exchange or shared BESS integration, only the base community energy costs were calculated. Results are indicated in Table 19.

Table 19 - Baseline grid imports and associated community costs.

Results	Units	Residential side	Industrial side	Total
Energy Imported from grid	MWh	266,268	679,512	945,780
Community costs	€	84140,76	189583,82	273724,58

For the baseline scenario, the total annual electricity imported from the grid resulted in a total of 945,78 MWh, and a consequent annual community costs of 273.724,58 €, from which 70% of the associated costs are from the industrial imports.

Stage 2 – Enabled Energy Exchange

In RS2, the enabled the energy exchange between the two networks resulted in a total grid import saving of 8,327 MWh (0,88%), as indicated in Table 20.

Table 20 - Grid imports and community costs saved after enabled energy exchange.

Results	Unit	Residential side	Industrial side	Total
Imports saved by energy exchange	MWh	3,031	5,296	8,327
Community costs saved	€	957,71	1477,52	2435,23

This stage finds a modest reduction in community costs of 2.435,23€ (0,89%) from the enabled energy exchange. However, it highlights the potential economic benefits from a multisectoral energy collaboration in lowering grid reliance without the need for any additional assets' investment.

Stage 3 – Energy Exchange with BESS Integration

RS3 introduces the shared BESS system, with an associated capital investment for two (233kWh) storage units of 171.334 €.

Table 21 summarizes the energy savings from RS3.

Table 21 - Grid imports and community costs saved by shared BESS.

Results	Units	Residential side	Industrial side	Total
Imports saved by energy exchange	MWh	2,980	5,026	8,006
Imports saved by shared BESS	MWh	20,416	68,880	89,296
Total grid imports saved	MWh	23,396	73,907	97,302
Community costs saved from shared BESS	€	6451,33	19217,61	25668,94
Total community costs saved	€	7393,09	20619,93	28013,02

Results show a total grid imports reduction of 97,302 MWh (-11%) compared with RS1, reducing the community costs in 28.013,02€ (10,23%), from which the shared BESS contributes in 25668,94€ (9,38%), resulting in an investment payback period of 6,7 years.

Results from Table 21 show that while only 22% of the BESS contributions are for the residential side, they result in 25% of the community costs reduction due to higher electricity prices, therefore enhancing the value of the stored energy.

Table 22 shows the energy contributions from the two storage systems integrated into the system, households BESS and shared BESS.

Table 22 - Individual and Shared BESS contributions to grid imports and community costs savings.

Results	Units	Residential side	Industrial side	Total
Grid imports (no storage)	MWh	277,838	679,512	957,350
Imports saved by Individual BESS	MWh	11,570	0,000	11,570
Imports saved by shared BESS	MWh	20,416	68,880	89,296
Community costs (no storage)	€	87796,88	189583,82	277380,70
Community costs saved by individual BESS	€	3656,12	0,00	3656,12
Community costs saved by shared BESS	€	6451,33	19217,61	25668,94

Although the storage capacities difference, when normalizing results to the aggregated households BESS capacity and comparing to the grid imports if no BESS were integrated, Results show higher contributions from the shared BESS, reducing the community costs in 1,81%, while the combined individual BESS reduces 1,32%. Highlighting the collective economic benefits from BESS under centralized control.

Stage 4 – Achieving target KPIs (Expanded PV + BESS)

Although the performance targets were not achieved in RS4, this section evaluates the economic viability and benefits of the scenario under expanded PV and BESS capacity.

It is important to mention that not all energy savings in RS4 result directly from the energy exchange and shared BESS. The increased PV capacity also significantly improves direct self-consumption within each network, particularly among smart houses equipped with individual BESS.

Table 23 presents a detailed breakdown of the contributions to total energy savings compared to RS1, totaling 273,06MWh (28,27%).

Table 23 - Energy savings and community costs reduction under the expanded PV and shared BESS.

Results	Units	Residential side	Industrial side	Total
Grid Imports	MWh	52,864	220,196	273,06
Energy saved by shared BESS	MWh	31,075	170,874	201,950
Energy saved by energy exchange	MWh	3,490	8,330	11,820
Individual BESS contributions	MWh	19,298	0,000	7,728
Expanded PV direct self consumption	MWh	10,571	40,991	51,562
Total contributions from multisectoral collaboration	MWh	34,565	179,205	213,770
Community costs saved by expanded PV	€	3501,58	12358,45	15860,03
Community costs saved by expanded BESS	€	9819,71	47673,98	57493,69

The capital investment for this stage includes 108.110€ for the additional PV 295,88 kWp and 428.335€ to the five BESS units, totaling 536.445€.

Considering different investments for each asset, the annual contributions for the community savings from shared BESS results in a BESS payback period of 7,5 years. While the PV payback time is found for 6,8 years.

If considered a collective investment the total economic savings from both PV and shared BESS would be accounted to the total investment (536.635€), resulting in a total community costs reduction of 73.354€. Therefore, resulting in a payback time of 7,3 years, a very competitive period when compared with the obtained in RS3, and possible earnings following it.

Validation of the Simulation Model and Data

This chapter presents the validation of the simulation model and the input data used during the study, given that the modelled system does not fully represent the existing regional grid. Given the absence of fully measured datasets for all elements involved and infrastructure in the system, a hybrid validation was applied. This combines comparisons with external datasets, expert consultation, and internal consistency checks for the models' outcomes.

Validation of Residential data

The modelling of the residential energy system relied on publicly available datasets and estimation procedures to ensure the accuracy and representativeness of both electricity consumption and PV generation. This section focus on the accuracy of the used data in the model, after the estimation procedure. To validate the accuracy of the modelled profiles, the calculated net imports and exports from the model and the values from DEGO [39] were compared.

The resulting deviations, shown in Table 24, performed consistently with a relative error below 5%, confirming the robustness of the data transformation and profile reconstruction methodology.

Table 24 – Comparison of Estimated and reference grid import/export Values.

	Data From DEGO		Values from the model		Relative Error (%)	
Postcode	Electricity export (KWh)	Electricity usage (kWh)	Electricity export (KWh)	Electricity usage (kWh)	Electricity export	Electricity usage
1851GD	1476	3000	1429,08	3149,65	3,18	4,99
1851GB	890	1982	893,18	1909,69	0,36	3,65
1851EH-EJ	1053	2501	1059,64	2401,04	0,63	4,00
1851EG	1345	2349	1350,01	2401,04	0,37	2,22

This approach and obtained deviations were reviewed in experts' consultation meetings with energy analysts from the NEC and the representative from the municipality of Heiloo, who agreed that the adopted data sources and modelling assumptions provide a credible and realistic basis for simulating residential energy behavior in the district.

Validation of Industrial data and model's internal consistency

The validation of the industrial park model primarily relies on the accuracy of the estimated energy consumption profiles. This section examines how variations in the assumed annual consumption values influence the model's outcomes under the configuration from RS3. For the three companies where consumption measurements were absent, consumption profiles *were derived using the estimation procedure described in Section 3.1.1, which was reviewed by NEC's energy analysts and approved by the representative of the Heiloo municipality.*

To assess the robustness of these estimations, a sensitivity analysis was conducted to each technical KPI by individually varying the annual energy consumption of each company in ± 25-50% relative to the baseline modelled values, illustrated in Figures 35, 36 and 37.

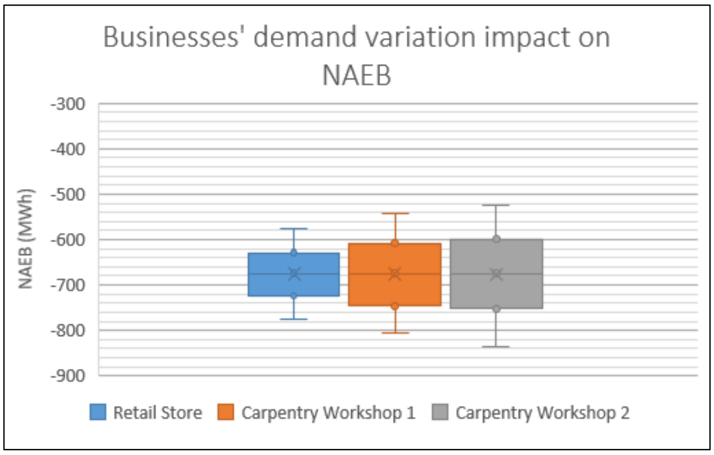

Figure 35 - Businesses' demand variation impact on the NAEB.

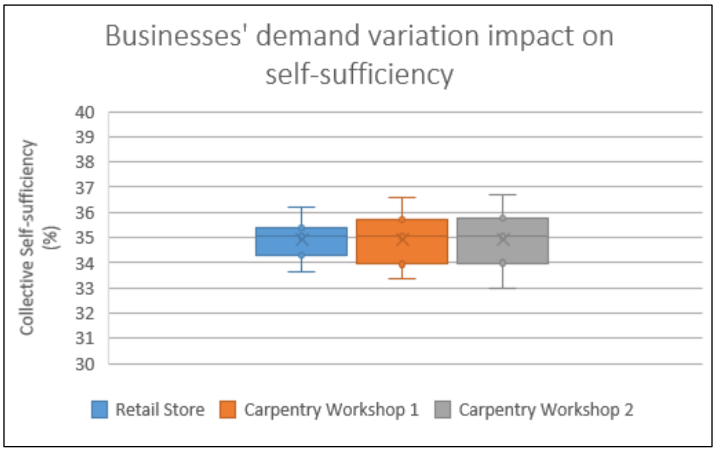

Figure 36 - Businesses' demand variation impact on the collective self-sufficiency.

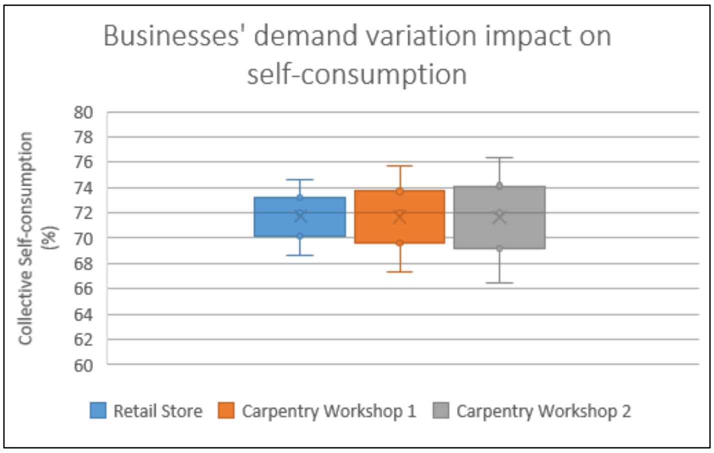

Figure 37 - Businesses' demand variation impact on the collective self-consumption.

In the figures, the boxplots represent the middle 50% of the obtained values, while the whiskers extend to the maximum of ±50% of the annual demand. The cross symbols ("x") indicate the median, and the dots correspond to the individual simulated data points included in the analysis.

Results from Figure 35 showed the highest sensitivity in the NAEB, with a maximum deviation of -28,7 % under a 50% reduction in Carpentry Workshop 2's annual demand. While in Figures 36 and 37, collective self-sufficiency and self-consumption exhibit limited sensitivity to demand variations.

The largest deviation was observed for Carpentry Workshop 2, where 50% reduction in demand resulted in a maximum decrease of 5,5 % in self-consumption, while a 50% increase in demand led to the maximum self-sufficiency deviation of 2,1 % decrease from its baseline value. This effect is explained by the company's higher energy consumption. A 50% adjustment in its demand corresponded to approximately 156 MWh, which is almost equivalent to the entire consumption of Carpentry Workshop 1, or almost twice the demand of the Packaging Company. This scenario effectively simulates the removal or addition of a mid-sized company within the system. Nevertheless, even under such extreme conditions, the model's overall behaviour remained consistent, confirming its reliability of the results within the defined scope and objectives of this study.

5. Discussion

The findings demonstrate that while connecting residential and industrial loads and adding a shared BESS significantly improve the system KPIs compared to the baseline results (RS1), although the systems' capacities fall short of meeting the ambitious KPI targets. This dual outcome showed considerable progress but incomplete target achievement, while both validate some literature insights and reveals new points to consider for future LES.

Performance impact after enabling the networks collaboration

The research addresses the first research objective by comparing the results from RS2 to RS1. Results showed increased consumption of the locally produced energy in 8,3 MWh (2,41%). Consequently, increasing the collective self-sufficiency and self-consumption in respectively 0,71 % and 1,36 %, while no impact was found on the NAEB.

Although the improvements are modest, 18,13% of the annual energy savings were found at 17:00, hour of likely higher grid stress, due to the contributions from the industrial park supporting the increasing residential demand and EVs charge, primarily during the summer.

The stage also partially addresses the fourth research objective by showing a community costs reduction of 0,89% resulting from the 0,88% grid imports reduction.

In comparison with revised literature, the obtained outcomes align with conclusions from [6] and [8], which reported increased performance in mixed-use communities. However, they show to diverge in the magnitude of the gains, while the improvements found remain more modest. The likely reasons are the different systems configurations and geographical context the case studies. Therefore, the seasonal solar intermittency found in Heiloo, combined with the larger system demand resulted in lower performance gains.

When studying the impact of the number of households, similarities were found between the Figure 18 and the findings from [8] illustrated in Figure 2, where the aggregation of additional households led to a decrease in the additional of amount of energy savings. Consequently, resulting in a decrease of the self-consumption and self-sufficiency values. These findings support the conclusions from [6], as the increased aggregation did not translate into improved performance, highlighting the type of participants and the shape of the load profiles aggregated as more critical factors.

These findings affirm the role of multisectoral exchange in enhancing LES's performance, particularly when supported by complementary demand patterns, such as the residential and industrial sectors.

Performance impact from shared BESS

The RS3 starts by showing practical constrains for the implementation of building-integrated shared BESS, as the demanded power from the shared BESS and additional company's export of PV surplus energy required limiting the BESS maximum rated power to preserve the safety of the company's grid-connection, highlighting practical limitations for this approach.

Results show an annual imports reduction in 25% during highest consumption hours, and early PV exports in 25-50%, highlighting the benefits to the system and utility grid from the BESS integration.

Addressing the second research objective results demonstrated significant improvements in the KPIs, where the shared BESS integration led to a collective self-sufficiency and self-consumption increase in 6,99% and 14,17%, respectively. However, no impacts were found on the NAEB. Similarly with the networks' energy exchange, this effect results from the nature of an ideal BESS that reduces equally the annual grid energy imports and exports.

Despite the overall performance gains, the shared BESS showed no measurable peak power reduction for both import and export values. Analysis revealed that this effect is caused by the applied BESS control strategy, which restricts charging from PV surplus energy and lacks an efficient EMS, leaving its potential peak-shaving capacity to fall short. Under a charge-scheduling control, the BESS could shift the BESS charge hours of higher PV surpluses, ensure the reduction of the peak export power and effectively support the utility grid congestion during periods of critical feed-in.

Results from the analysis on the impacts of the BESS storage capacity show that although the performance increases, the gains per kWh installed decrease, resulting in an increased payback time. However, it was found that by adding an additional 233 kWh unit, the performance goal of 75% self-consumption could be achieved.

The constraints from the location of the BESS show to impact its capacity to discharge during hours of higher grid congestion and contribute to the residential sector. Although not significantly impacting its annual contributions, and consequently the KPIs. This constrain results in a higher shared BESS payback time, due to reduced economic savings from the limited contributions to the residential users, further aggravated under dynamic pricing, by the limited capacity to discharge during hours of higher grid congestion usually associated with higher electricity prices.

The economic analysis for RS3 showed a shared BESS contribution to the community costs of 9,38%, highlighting the increased value of the stored energy when shared with the residential sector, due to the higher electricity prices. Additionally, when comparing the normalized economic contributions from the shared BESS and aggregated household BESS, the shared BESS shows a higher contribution in 0,49%. Highlighting the economic benefits from the shared BESS and multisectoral collaboration, fully answering to the fourth research objective.

When compared to the literature, the outcomes show alignment with the conclusions but divergence on the results. Although the obtained KPIs increase fall short from those found by Albouys-Perrois [13]. When comparing annual total energy contributions and systems' sizes from the shared BESS, although the annual contributions show to diverge in approximately 2 MWh (2,5%), the integration of industrial loads reduces self-sufficiency gains. Similarly, the difference in the reduced energy exports explains the reduced self-consumption gains, due to the large PV capacity installed in the industrial park.

Although the 9,38% community costs savings found didn't met the 16,8% found by Qiao [12], when comparing the results with the required investment, the integration of the shared BESS points to be a more economically efficient solution. These economic benefits are highlighted when comparing the cost savings from the households BESS and the shared BESS, although diverging from the findings from [26], supports the conclusion that centralized coordination enhances system-level savings.

The findings from [25], are supported by the obtained results, as the EVs have large influence on the BESS usage, highlighting the importance of the coordination between EVs and BESS. Additional benefits could be achieved, mainly during summer, if the EV truck was partially charged during the day, reducing the PV surpluses and grid imports during the night.

Overall, the integration of a shared BESS in a multisectoral environment significantly improved the system's collective performance. While the results fall short of those reported in the literature, they demonstrate large potential, while being more economically interesting, when considered the system's configuration and the existing solar intermittency, limiting the use of the BESS, illustrated in Figure 29. Finally, the integration of the shared BESS in MV consumers with higher grid-connection capacities, such as the retail store, combined with virtual energy exchange, could overcome the project's BESS power constraints and enable more equitable energy sharing, by removing the need for physical flow-based prioritization applied in this study.

Achieving REFORMERS' energy goals in the multisectoral network

The final research stage assessed whether the REFORMERS project's energy goals could meet under the different configurations.

Simulations quickly revealed that the required PV installed capacity to meet a positive NAEB isn't technically feasible, demonstrating that the third research objective couldn't be answered under viable system configurations. Due to strong seasonal solar intermittency, achieving a positive NAEB depends on high summer PV generation to offset the grid imports during the winter, rather than consistent reduction in grid reliance throughout the year. This effect is reflected by the significant drop in self-consumption, shown in Figure 33, before increasing the expanded shared BESS.

Under the maximum allowable PV capacity, the system achieved a 46% increase in the NAEB to -366,331 MWh, falling short of the positive NAEB targeted. Under the expanded PV configuration, the analysis on the BESS size showed that the self-sufficiency values saturate at approximately 67% beyond a storage capacity of 1,165 MWh, due to the BESS's power constraint, limiting the BESS charge from the increased PV surpluses.

Under expanded PV and BESS capacities, while the annual peak demand remained unchanged, peak export power showed to increase, due to the increased PV generation. While in RS3, the peak export occurred at 12:45 on May 28, in RS4 this peak shifts to 13:30. As illustrated in Appendix 8, at 12:45, the battery reduces what would have been the peak export by 18,3%. However, because it was not fully discharged the previous day, the shortened charging window prevents it from covering the full generation peak, reaching full charge prematurely. This leads to a new export peak 45 minutes later, limiting the annual peak reduction to 3,3%.

This peak-shaving limitation highlights the need for an improved BESS EMS, to allow the full BESS peak-shaving capacity. Under a scheduled charge, the BESS could ensure 18,3% reduction of the annual peak export , approximating the reduction to the values found by [27] and [14] of 26% and 20%, respectively.

This staged confirmed that, due to strong seasonal solar intermittency and exclusive reliance on PV generation, achieving both 75% self-consumption and a positive NAEB is unfeasible. Although multisectoral energy exchange improves system performance, even under the maximum feasible PV deployment and expanded BESS the LES fall short of meeting the REFORMERS' targets. Reaching these goals would then require long-duration storage or complementary renewable sources.

Based on the outcomes of RS3 and RS4, the proposed LES configuration comprises the proposed 466 kWh shared BESS, alongside the deployment of a shared storage unit at the retail store. This addition would allow the system to meet the 75% self-consumption performance goal and overcome the 120 kW output constrain. Due to the company's higher grid-connection capacity, the additional storage unit could operate under the unrestricted power conditions allowing full utilization of its benefits. While further PV expansion is expected to improve overall system efficiency, it is essential, particularly from a DSO feasibility standpoint, that annual peak export power remain below those observed in RS1, to avoid worsening grid challenges caused by PV surplus grid exports. With the implementation of an optimized BESS EMS, this configuration could effectively reduce the annual peak import and export values found, while fostering a more balanced and high-performance energy system.

Limitations of the model and suggestions for improvements

Although the model was developed with the highest possible accuracy based on the available data, certain limitations persist within the model. The first limitation was set by the PowerFactory Academic licence used. The licence limits all models to a maximum of 50 nodes, requiring an adjusted layouts and the considered number of houses per street, which would affect the energy losses in the system.

The EV template model employed idealized assumptions, underestimating actual annual EV demand. Its random charging behaviour introduced variability across simulations, and *including the EV truck charge during the weekend further distorting its annual profile. This modelling limitation affected the energy balance in each run, which combined with the estimated losses for the local renewable energy, found using Equation (9), resulted in deviations between the grid imports reduction and energy savings.*

Additional modelling limitations were identified in the representation of the BESS, as the assumption of ideal operating conditions introduced uncertainty into the results, due to the increased annual contributions.

The estimation of residential PV generation also introduced inaccuracies. The PV profiles were modelled for ideal conditions introduced in Section 3.1.2, producing higher outputs than would occur under real households' installations, potentially inflating the residential sector's contribution to the annual energy exchange. In addition, because the residential PV profile differs from the measured industrial generation profile, peaks appeared in the power exchanged between the networks. Further analysis showed that these peaks resulted from days with low generation in one profile coinciding with high generation in the other.

Improvements in the model include the integration of measured industrial and residential demand and PV generation data, inclusion of BESS and EV efficiencies, and developing an enhanced EV model capable of scheduling charging periods, particularly considering the operational days from the EV truck, due to its larger storage capacity.

6. Conclusions

Derived from the research question, although not fully achieving the research objectives, the results from the research work showed performance benefits from the energy collaboration and shared BESS integration.

The collaboration between multisectoral MV-LV networks presented improvements in energy performance through energy exchange, primarily driven by the complementary demand profiles, and the inclusion of an MV prosumer as its large PV generation supported the industrial demand, thereby enhancing multisectoral energy exchange and enabling more effective shared BESS integration.

The energy exchange showed a 2,41% increase in the consumption of locally produced energy, increasing the collective self-consumption and self-sufficiency, respectively, in 1,36% and 0,71%, consequently decreasing the community costs in 0,89%. The energy exchange dynamics showed that residential PV surpluses support the industrial demand during daytime operational hours, whereas the industrial park contributed to residential demand primarily during the summer evening peaks during the EVs charge. These results highlight the benefits from multisectoral energy exchange to the system's performance. Therefore, for LES aiming for defined performance benchmarks, integrating multisectoral load profiles shows to improves operational effectiveness and reduce the required investment in energy assets to meet the defined energy goals.

The integration of the shared BESS led to significant performance improvements, increasing the collective self-consumption and self-sufficiency by 14,17 % and 6,99 %, respectively, and reducing the collective electricity costs by 9,38%. Additionally, the annual grid exports reduced in 25–50% during early PV surplus hours, while annual grid imports decreased in 25% during peak demand hours. The economic analysis indicates greater value of stored *energy by the BESS when shared with the residential network, therefore reducing the BESS payback period. However, the study highlights practical constrains for the implementation of building-integrated shared BESS, required limiting the BESS maximum rated power to comply with limits imposed by the company's grid-connection. The study suggests that a shared BESS integration in a MV grid-connected member could overcome these limitations and enhance its overall contributions to the LES, particularly under a larger-scale shared BESS.*

The study highlights the challenges to large LES in achieving ambitious energy goals relying exclusively on PV and BESS in regions with pronounced solar intermittency. The system configuration required to achieve the targeted KPIs was found to be technically unfeasible, primarily due to the extensive PV capacity needed to attain a positive NAEB. Additionally, the impact of increased storage capacity on self-consumption was constrained by the BESS's limited power, being unattainable to meet the 75% self-consumption under the expanded PV. This scenario also reinforces limitations found in RS3, from the BESS's limited capacity to reduce the annual peak import and export values under the applied BESS model.

The findings suggest that the collaboration between residential and industrial sectors offers a strategic pathway to enhance overall system performance, while reducing the investment required to meet defined performance goals. The study envisions a future for LES, where industrial areas collaborate with residential zones to optimize shared resources. Such integration not only improves energy efficiency and cost-effectiveness but also provides a practical solution for integrating BESS, addressing spatial limitations by situating BESS in industrial zones within urban energy ecosystems.

From the outcomes of this research, three main model extensions are proposed that could enhance the multisectoral energy collaboration and the contributions from shared BESS, serving as a foundation for future research and advanced system configurations.

<u>Adding EMS with dynamic prices:</u> The findings suggest that incorporating dynamic pricing into the model, allowing the BESS to charge from the external grid during low-price periods and discharge during high pricing, could significantly enhance the economic value and utilization of the BESS. Improving the overall system performance and BESS contributions particularly during the winter when PV surpluses are minimal.

<u>Adding wind generation:</u> The solar intermittency was found to be a major limitation in achieving target KPIs. Countries such as the Netherlands experience limited sunshine hours during the winter, limiting the PV generation. Integrating wind generation, could complement the system's renewable generation, resulting in increased performance gains.

<u>Integration of distributed BESS into the centralized EMS:</u> Results suggest that the integration of the individual household BESS, and distributed BESS in the industrial members into a centralized EMS. This addition would allow the system to overcome the power limitations found and search for compensation strategies for the individual BESS owners from the shared energy, and performance contributions to the wider community.

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Appendix 1 – Technical specifications and data used in the model.

Table A1. 1 - Technical Data Used for EVs Modelling

Electric vehicle (EV)			
Vehicle		Residential EV	Electric truck
Model		Tesla Model Y	Mercedes eActros
Charging Power	kW	11,5	50
Hours to start charging	h	16-18	18-20
Storage capacity	kWh	80	621

Table A1. 2 - Technical Data Used for BESS Modelling

Storage units technical specifications			
Storage type		Shared Battery	Household Battery
Model		CELL POWER CESS 233-100	AlphaESS SMILE-G3-BAT-9.3S
Rated Power	kW	100	5
Storage Capacity	kWh	233	9,3
Depth of Discharge	%	90	90
Battery Price	€	85667	N/A

Table A1. 3 - Technical Details from Transformers Applied in the Model

Transformer	Rated Power (MVA)	Frequency (Hz)	MV rated voltage (kV)	LV rated voltage (kV)	Configuration	Short-circuit voltage (%)	Copper Losses (kW)
Industrial transformer	0,630	50	10	0,4	Dyn	6	6,6
Residential transformer	0,400	50	10	0,4	Dyn5	6	5

Table A1. 4 -Technical Details from Cables Applied in the Model

Cable	Section type	Rated voltage (kV)	Rated current (kA)	Resistance (Ω/km)	Reactance (Ω/km)	Frequency (Hz)
MV cables	1x240rm	10	0,415	0,1289	0,1037	50
LV residential	3x150sm	1	0,300	0,2071	0,0691	50
LV industrial	3x240sm	1	0,400	0,1266	0,0691	50

Appendix 2 – Residential and Industrial simulation models.

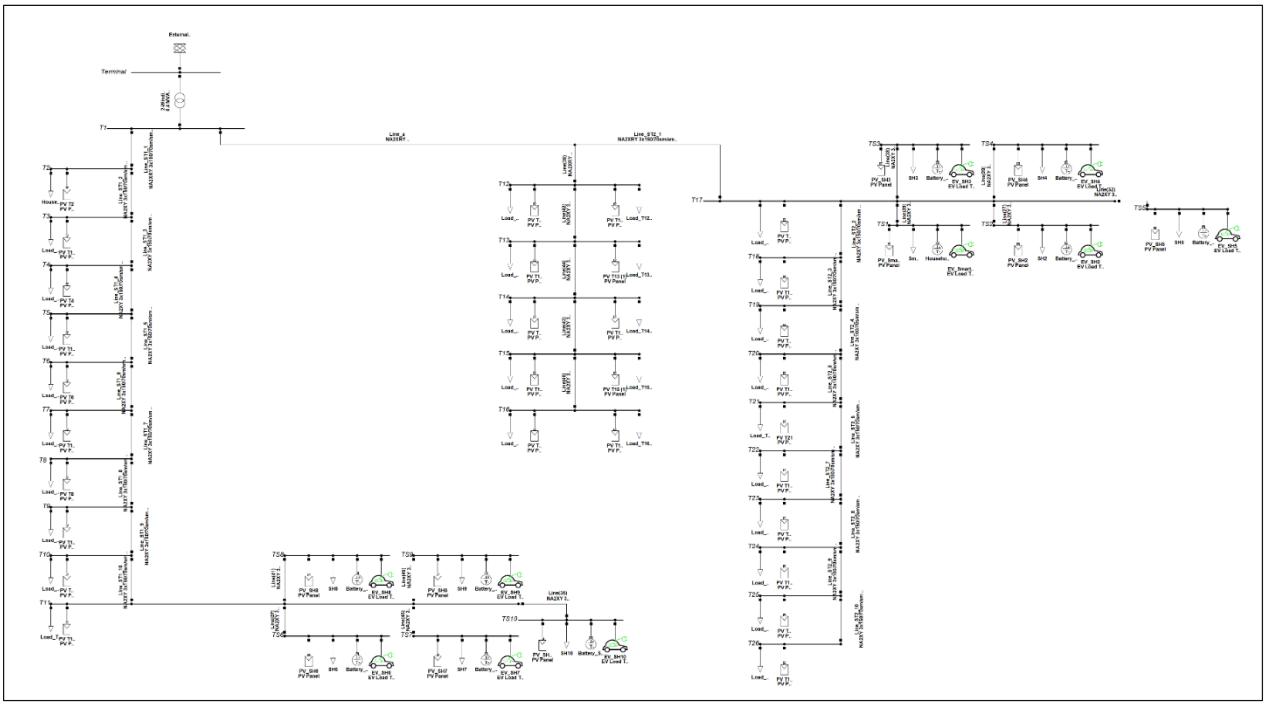

Figure A2. 1 - Single-line diagram of residential network model

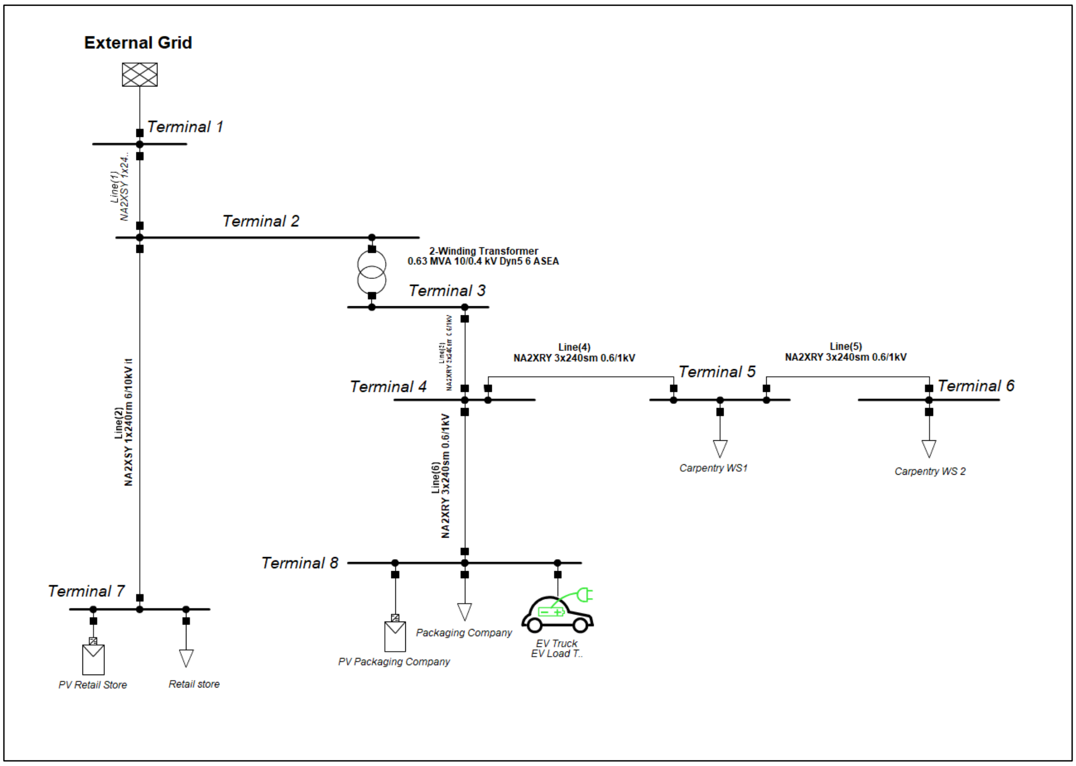

Figure A2. 2 - Single-line diagram of industrial park network model

Appendix 3 - Aggregated industrial Loads and PV generation.

Aggregated industrial Loads and PV generation during Winter reflecting the need for PV generation and peak contributions from Residential network

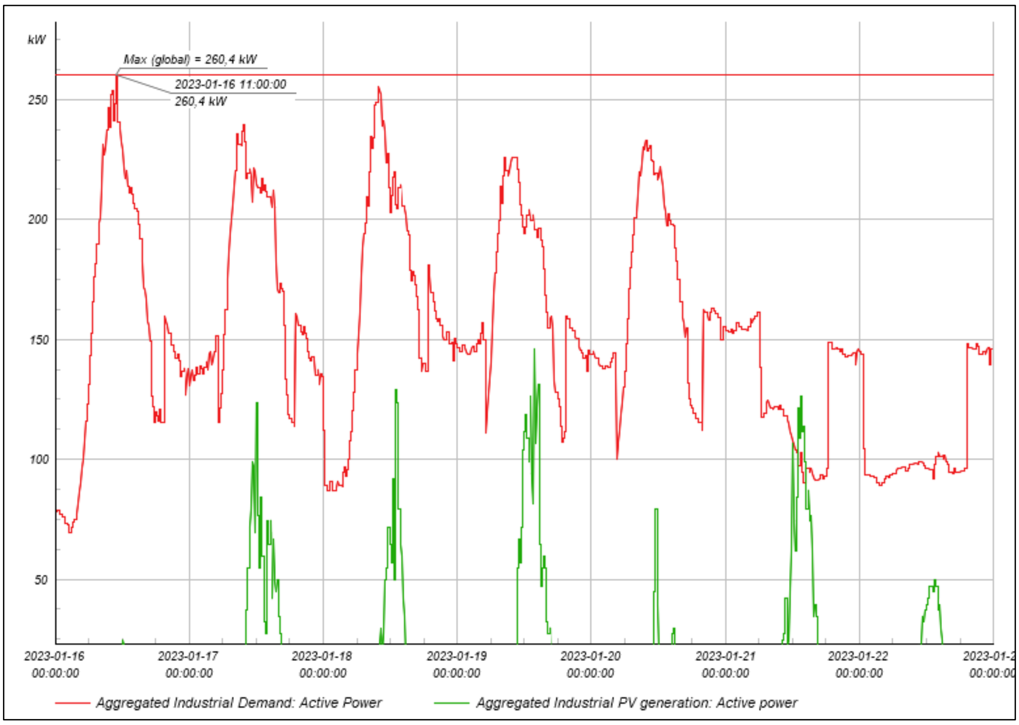

Figure A3. 1 - Aggregated Industrial Loads and PV Generation During Winter

Aggregated industrial Loads and PV generation during Summer showing available PV generation to support the residential evening loads

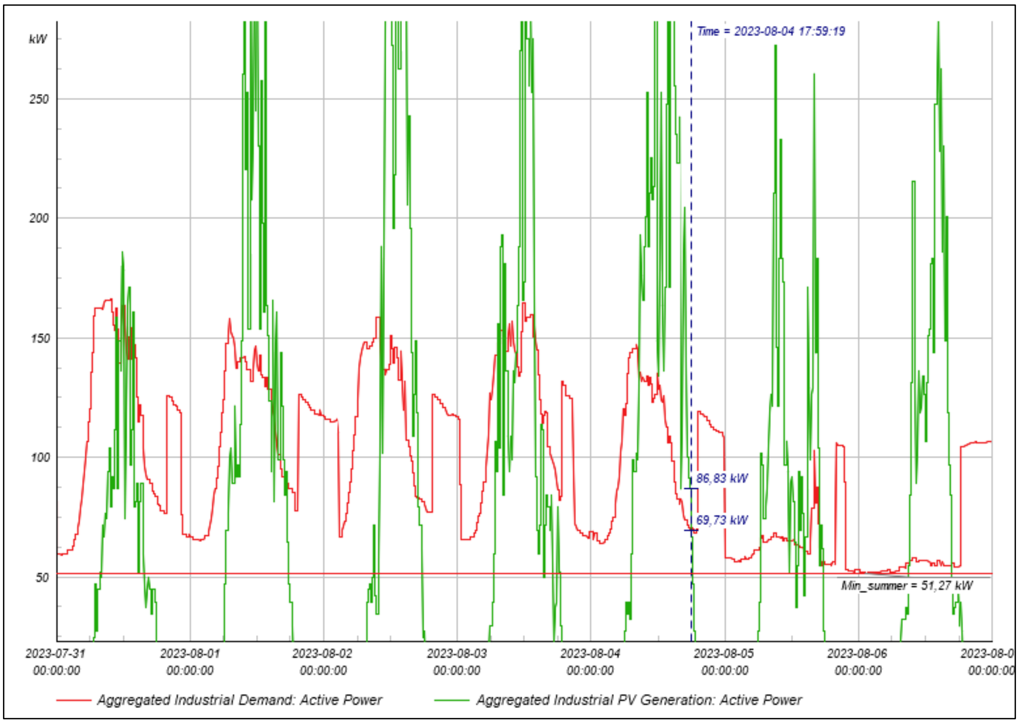

Figure A3. 2 - Aggregated Industrial Loads and PV Generation During Summer

Appendix 4 – Energy exchange with external grid before networks' collaboration.

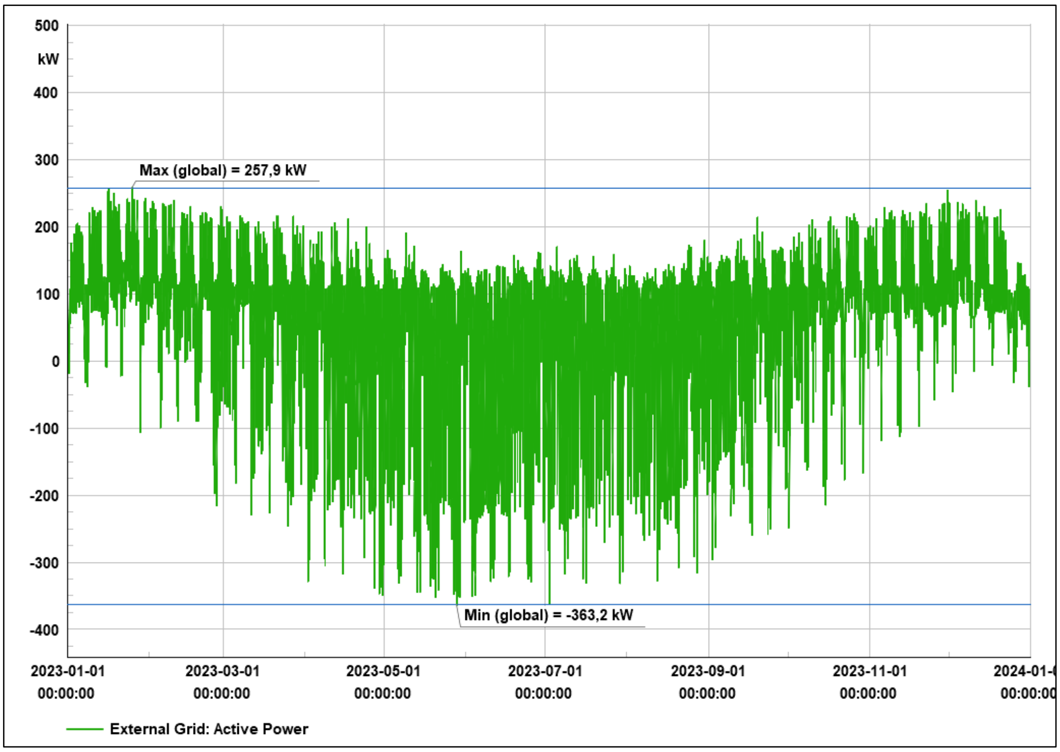

Figure A4. 1 - Industrial Network's Energy Exchange with External Grid.

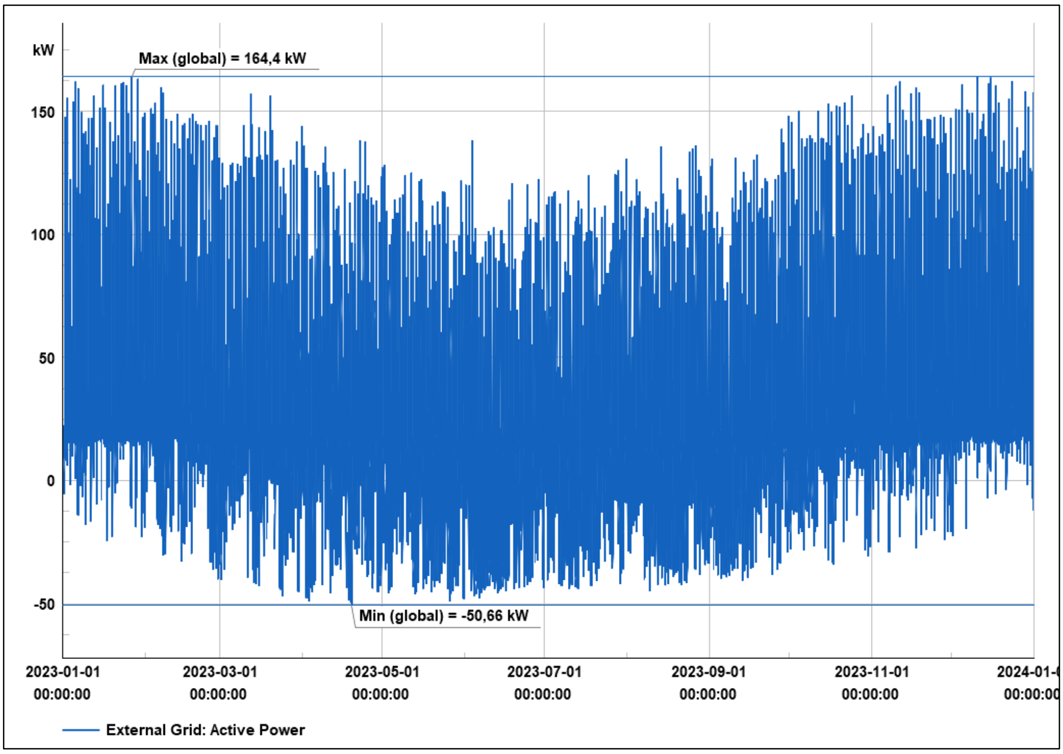

Figure A4. 2 – Residential Network's Energy Exchange with External Grid.

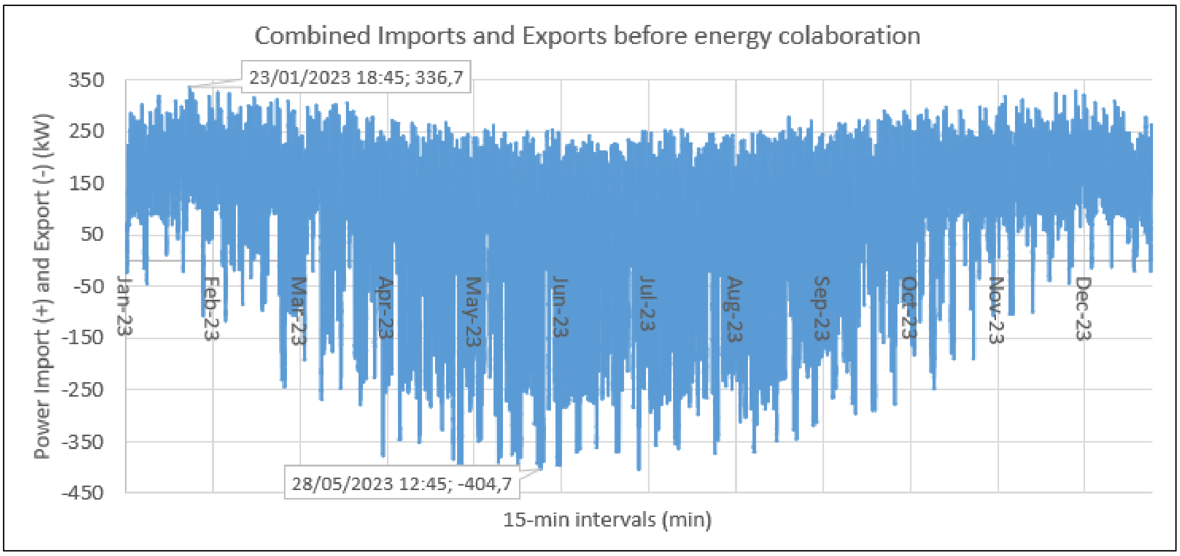

Figure A4. 3 - Combined Networks Energy Exchange with External.

Appendix 5 - Energy exchange with external grid after networks interconnection.

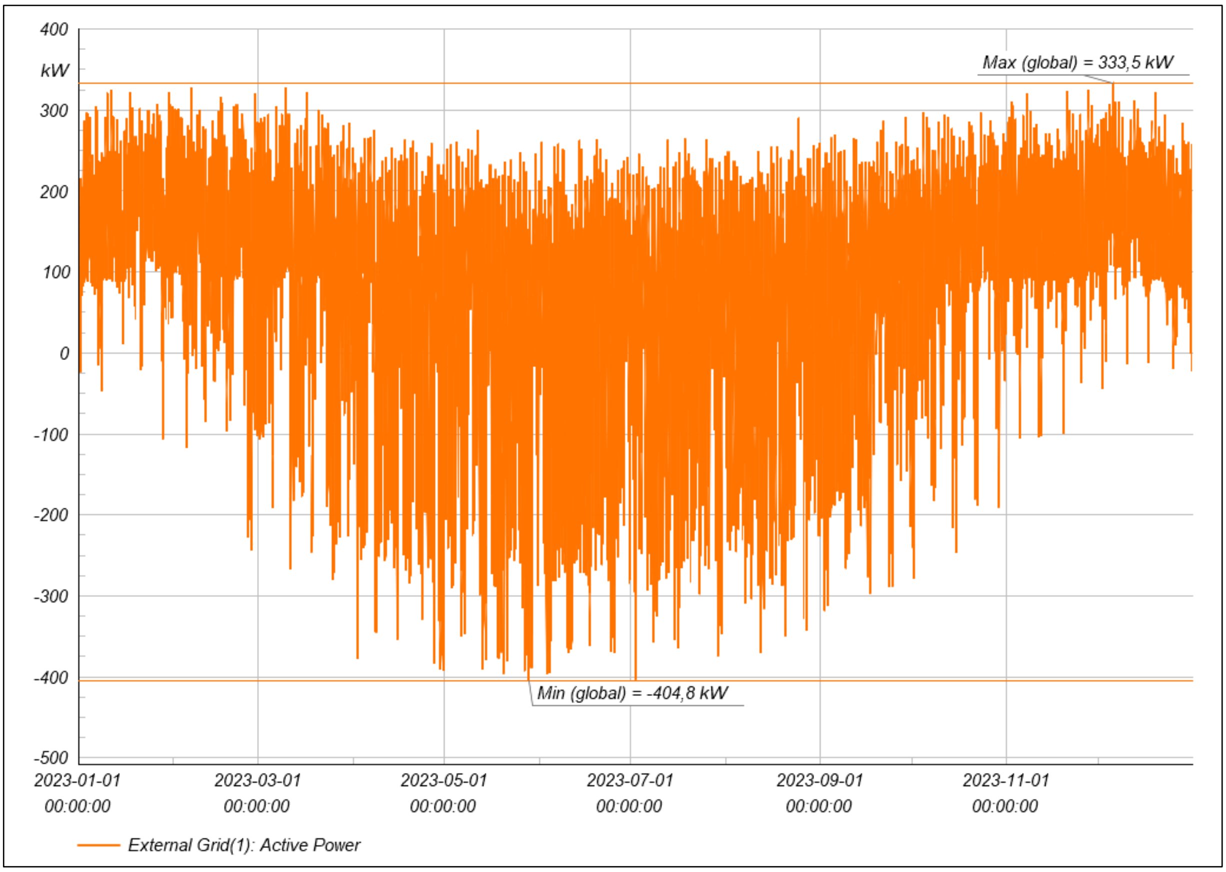

Figure A5. 1 - Energy Exchange with External Grid After Networks Interconnection.

Appendix 6 – Energy exchange with external grid after shared BESS integration.

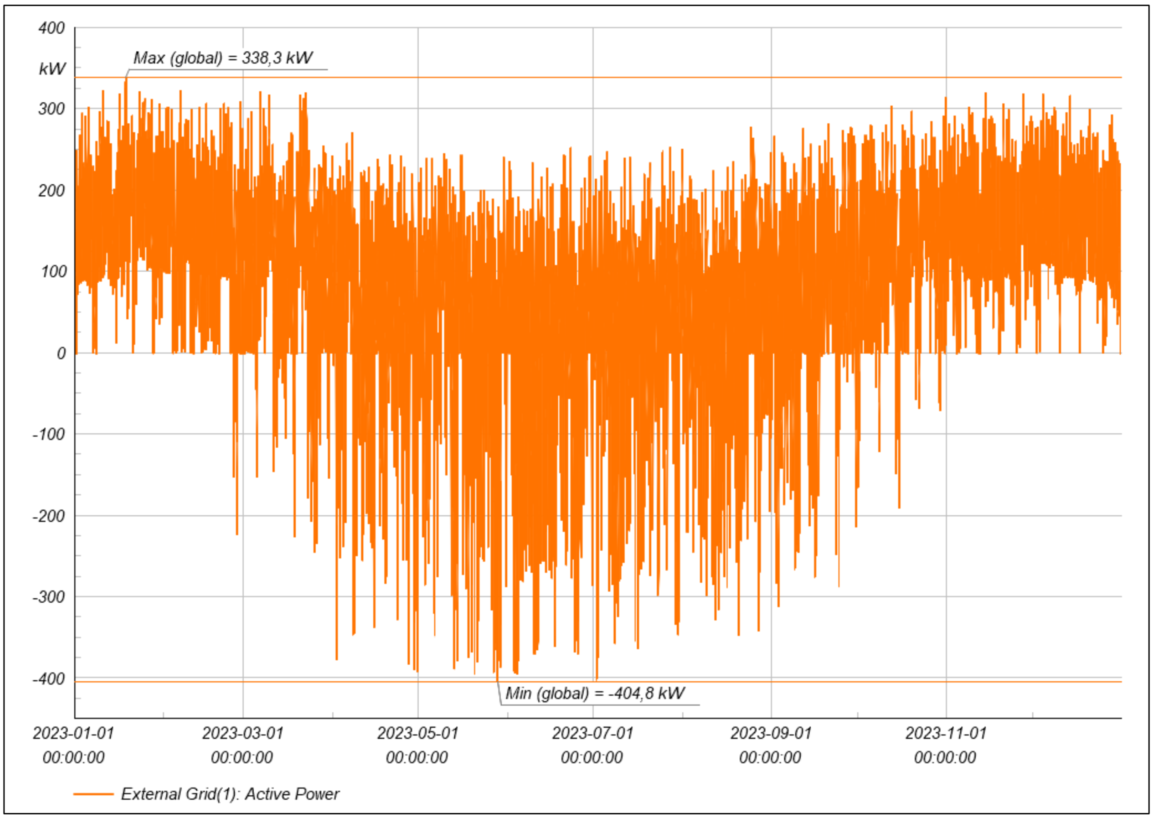

Figure A6. 1- Energy Exchange with External Grid After Shared BESS Integration

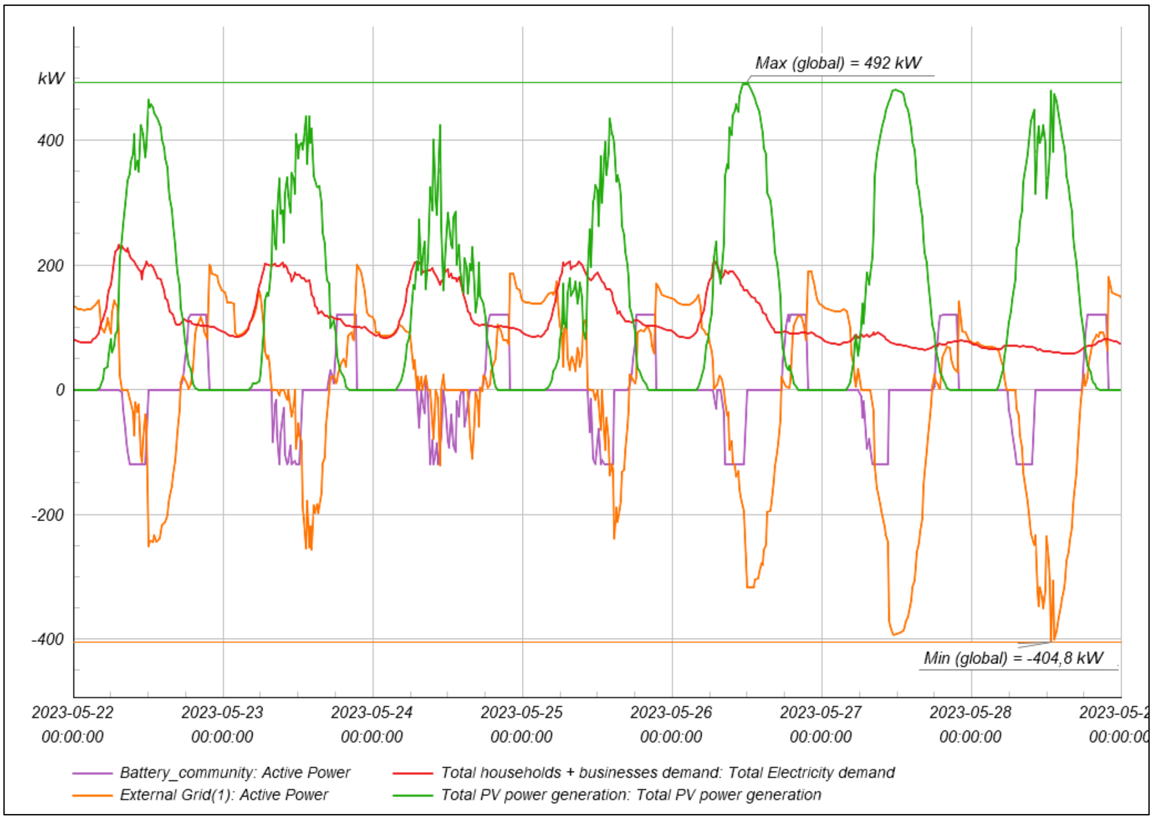

Figure A6. 2 - Energy Exchange with External Grid During Week of Peak Export.

Appendix 7 – Grid connection cables' power flow for companies integrating new PV.

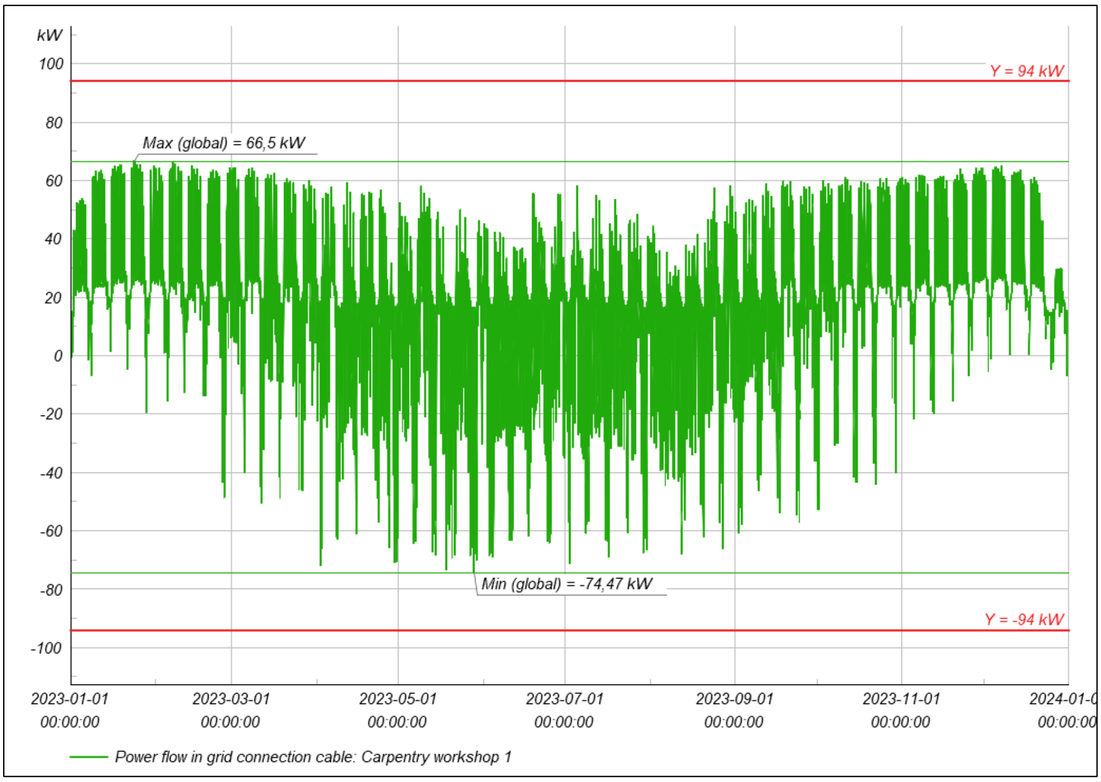

Figure A7. 1- Energy exchange with grid on carpentry workshop 1 after PV integration.

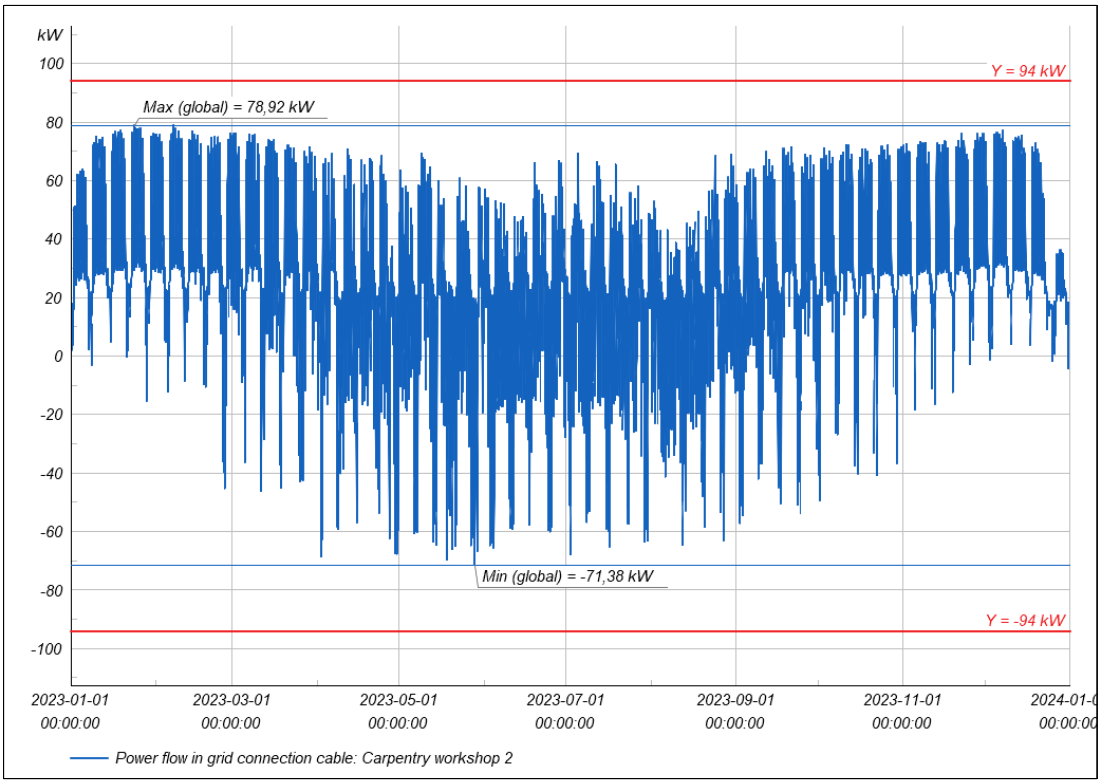

Figure A7. 2- Energy exchange with grid on carpentry workshop 2 after PV integration.

Appendix 8 – Energy exchange with external grid under expanded assets.

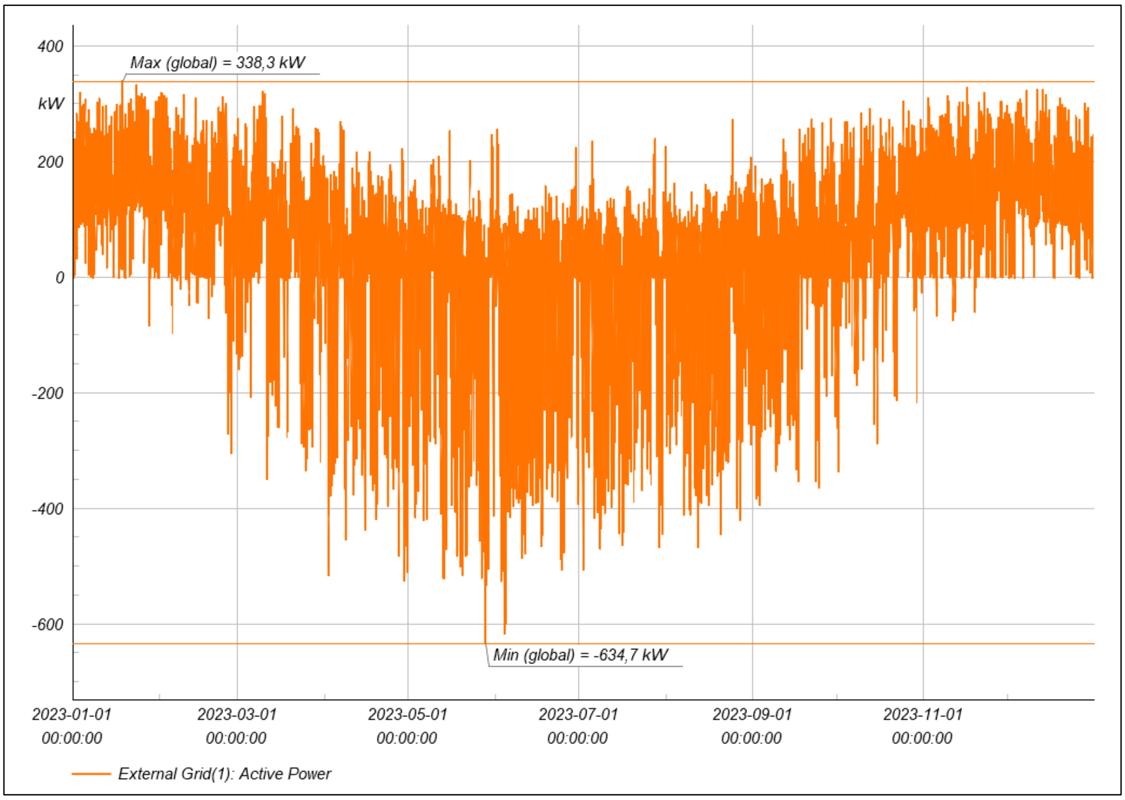

Figure A8. 1 - Annual Energy Exchange With Grid Under Expanded PV and Shared BESS.

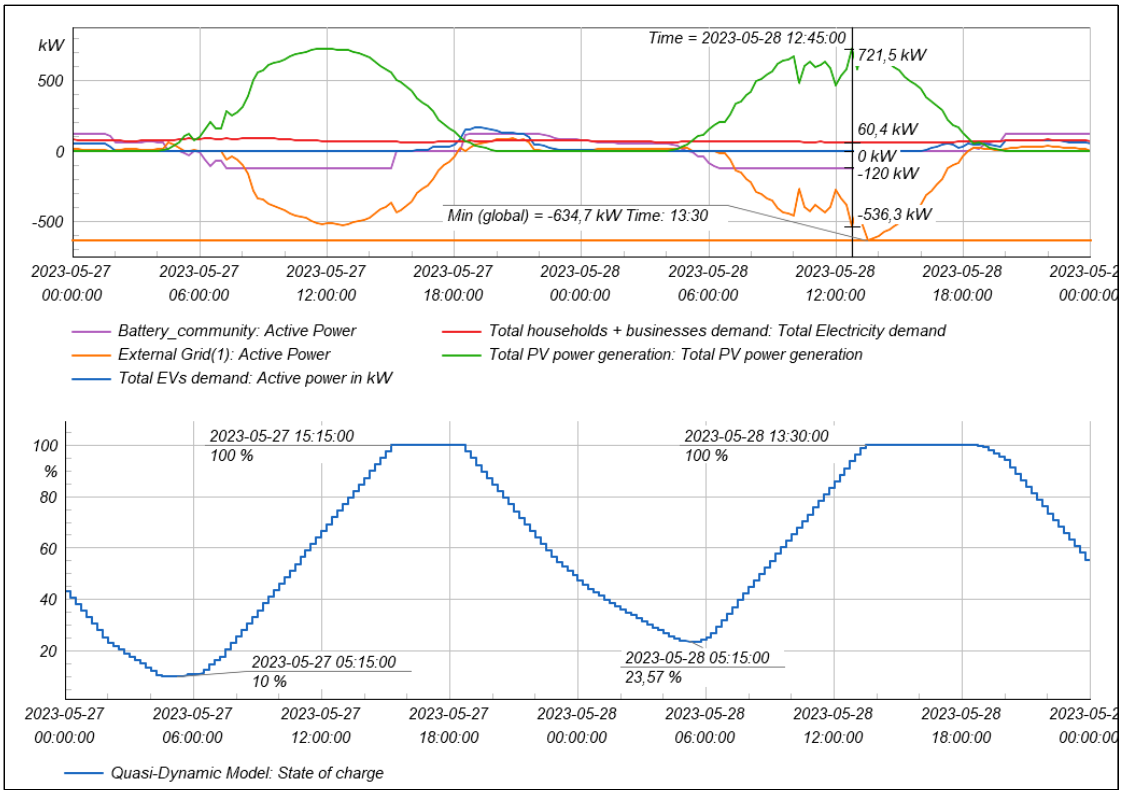

Figure A8. 2 - Energy Exchange During Annual Maximum Export Weekend Under Expanded PV and Shared BESS.