NetOptimization for Large-Scale Integration
of Solar and Wind Power via Storage and Software

NO-GIZMOS
Project Report:

Appendix I: Technical Design & Results

Introduction

This appendix provides the detailed technical specifications, mathematical formulations, and methodological parameters used in the NO-GIZMOS project. It is intended for engineering teams, researchers, and system architects seeking to replicate or build upon the NO-GIZMOS findings.

The document is structured to mirror the main report:

- **Part A: Platform Design** (The Infrastructure)
- **Part B: Operationalization** (The Algorithms per Use Case)
- **Part C: Detailed Results** (Grid & Financial Analysis)

Part A: Platform Design & Architecture

The NO-GIZMOS technical infrastructure was not built from scratch but evolved from the existing **Energy Islands** platform developed by **CGI**. The primary engineering challenge was to transform this monitoring-focused system into a bi-directional control hub capable of executing real-time grid services.

A.1 Architectural Philosophy & Partner Ecosystem

The system follows a "Hub-and-Spoke" architecture where the central platform normalizes data from disparate sources and presents a unified interface to the control algorithms.

Core Components & Responsibilities:

- **The Hub (CGI):** The *Energy Islands* platform. It handles secure data ingestion, identity management, and message routing. It acts as the "Virtual End Node" (VEN) for the grid operator and the central controller for the batteries.
- **The Grid Signal (Enexis):** The DSO acts as the "Virtual Top Node" (VTN), publishing grid constraints and forecasts.
- **The Asset Layer (iwell):** Provides the physical battery hardware (Cube 10 kWh) and a RESTful API for telemetry and setpoint injection.
- **The Intelligence (TU/e):** The control algorithms (Python-based) run as external agents, consuming data via the SensorThings API and sending schedules back to the platform.
- **Analytics (Hanze UAS):** Performs post-event analysis using the aggregated data logs.

A.2 Interface 1: Grid Integration (OpenADR)

To facilitate communication between the DSO (Enexis) and the Aggregator (NO-GIZMOS/CGI), we selected the **OpenADR 2.0b** protocol. This standard was chosen for its flexibility in defining custom events, essential for a research pilot.

Implementation Details:

- **Topology:** Enexis hosts the VTN (Server); CGI hosts the VEN (Client).
- **Communication Model:** "Pull" model. The VEN polls the VTN (interval: 30-60s) to check for new events.

- **Security:** Mutual TLS (mTLS) with client/server certificates via the OpenADR CA chain.

The Data Payload (The "Event"): Unlike standard demand response (which often sends simple "shed load" signals), NO-GIZMOS required rich data exchange. Enexis transmits a daily `EiEvent` containing 24-hour profiles for the local transformer.

- `x-predictedLoad`: The forecasted baseline load (kW).
- `x-maxImportPercentage` / `x-maxExportPercentage`: Dynamic capacity limits relative to the transformer rating.

Snippet: XML Payload Structure

```
<ei:eventSignal>
    <ei:signalName>x-predictedLoad</ei:signalName>
    <ei:signalType>x-loadControlCapacity</ei:signalType>
    <ei:intervals>
        <ei:interval>
            <xcal:dtstart>2025-10-13T08:30:00Z</xcal:dtstart>
            <xcal:duration>PT15M</xcal:duration>
            <ei:signalPayload>
                <ei:payloadFloat>19.4</ei:payloadFloat> <!-- kW Forecast --
>
            </ei:signalPayload>
        </ei:interval>
    </ei:intervals>
</ei:eventSignal>
```

A.3 Interface 2: Asset Control (iwell API)

Direct control of the residential batteries is managed via **iwell's proprietary API**. This REST interface allows the platform to act as a "remote operator."

Telemetry Points (Read):

- `StateOfChargePercentage` (%): Critical for managing battery health and availability.
- `GridPowerW` (W): Net exchange at the meter connection (import/export).
- `BatteryPowerW` (W): Real-time charging/discharging rate.

Control Points (Write):

- `PowerSetpointSchedule`: The platform pushes a JSON array containing a series of setpoints (start time, end time, power in kW).

- **Latency:** The control loop operates on a 15-minute basis, but setpoints are pushed day-ahead or intra-day depending on the Use Case.

A.4 Interface 3: Data Fabric (OGC SensorThings)

To decouple the specific device protocols from the optimization logic, the platform exposes all data via the **OGC SensorThings API**. This standard was selected because it natively handles the complex relationships between "Things" (Houses), "Datastreams" (Power), and "Observations" (Values).

Dual Functionality:

1. **Sensing (Read):** The TU/e algorithms query the `Observations` endpoint to fetch normalized history for creating forecasts.
2. **Tasking (Write):** Uniquely, NO-GIZMOS utilizes the `Tasking` capability of SensorThings. The algorithm posts a `Task` (the calculated schedule) to the platform, which then translates this generic task into the specific API calls required by the iwell batteries.

A.5 Design Decisions: Rejected Alternatives

To assist future architects, we document why two prominent industry standards were **not** selected for this pilot.

1. GOPACS & Shapeshifter (Rejected)

- *Context:* The Dutch standard for congestion management markets.
- *Reasoning:* GOPACS is designed for a mature market with strict settlement rules (energy blocks in MWh, requiring bid prices). NO-GIZMOS operated at the LV/neighborhood level where flexibility needs to be fluid and experimental. The overhead of formal market settlement would have stifled the research into physical grid behaviour.

2. S2 Protocol (Rejected)

- *Context:* A standard for Home Energy Management Systems (HEMS) to optimize behind-the-meter assets.
- *Reasoning:* S2 is optimized for a single building (e.g., balancing a Heat Pump with a specific EV charger). NO-GIZMOS required *collective* optimization of a grid segment (Multiple Buildings -> One Transformer).

Furthermore, at the time of development, no robust open-source S2 implementation existed for the specific battery hardware, meaning the development cost outweighed the benefit for this specific scope.

Part B: Operationalization (The Algorithms)

This section details the algorithmic logic used for each use case, progressing from simple rule-based heuristics (UC1 & 2) to complex multi-objective optimization (UC3-6).

Our in-depth explanations of our key Use Cases 1-3 also include formulaic logic written in LaTeX, according to the following conventions.

Table 1. Notation for the optimization problem formulation.

Notation	Interpretation	Dimension	Unit
Sets			
$\mathcal{T}$	Collection of time steps	$\{0, \dots, T\}$	-
B	Collection of batteries	$\{0, \dots, B\}$	-
Parameters			
$\hat{p}_t^{\text{trafo}}$	Predict Transformer power	$\mathbb{R}^T$	kW
ω	Weighting factor	$\mathbb{R}_+$	-
γ	Capacity limitation price	$\mathbb{R}_+$	€/kWh
p_t^{-trafo}, p_t^{+trafo}	Transformer lower (export) and upper (import) bounds	$\mathbb{R}_+^T, \mathbb{R}_-^T$	kW
SoC_i^0	Initial state of charge of battery i	$\{0-1\}^B$	-
SoC_i^{min}	Min. state of charge of battery i	$\{0-1\}^B$	-

SoC_i^{max}	Max. state of charge of battery i	$\{0-1\}^B$	-
$\eta_i^{ch}, \eta_i^{dis}$	Charge and discharge efficiency of battery i	$\{0-1\}^B$	-
Δ_t	Length of a time step	$\mathbb{R}$	hour
E_i	Energy capacity of battery i	$\mathbb{R}_+$	kWh
$\bar{p}_i$	Power rating of battery i	$\mathbb{R}_+$	kW
Control Variables			
$p_{i,t}^{ch}, p_{i,t}^{dis}$	Charge/discharge of battery i at time t	$\mathbb{R}_+^T$	kW
Dependent Variables			
p_t^{trafo}	Net active power flow via transformer w/ batteries	$\mathbb{R}_+^T$	kW
$SoC_{i,t}$	State of charge of battery i	$\{0-1\}^{B\times T}$	-
$\bar{\epsilon}, \underline{\epsilon}$	Import and export congestion slackness	$\mathbb{R}_+^T$	kW

B.1 Use Case 1: Maximizing Household Self-Consumption

1. Purpose This phase served as the project baseline. The batteries operated in "island mode," ignoring the neighborhood and the grid, focusing purely on keeping solar energy within the home. This strategy is often referred to as a "greedy algorithm" because it single-mindedly pursues the optimal outcome for the individual without consideration for the wider system.

2. Technical Objective Maximize the instantaneous consumption of self-generated solar power at the individual household level.

3. Algorithmic Formulation (Rule-Based) Unlike later use cases, UC1 did not use predictive optimization. It utilized a reactive logic loop:

- **Monitor:** Real-time net load at the household meter.
- **Logic:**
  - IF [Solar Generation > Household Consumption]: Charge battery with surplus.
  - IF [Household Consumption > Solar Generation]: Discharge battery to meet demand.
- **Constraint:** Never export battery energy to the grid; never charge battery from the grid.

4. Key Mechanism The system acts as a simple buffer. It proves that while effective for the individual (self-consumption rose from ~30% to ~60%), it contributes little to grid stability because the buffer is often full by the time the evening peak stress occurs.

B.2 Use Case 2: Neighborhood-Level Coordination

1. Purpose This use case marked the first step towards collective action. The goal was to treat the group of households as a single "virtual" entity. Instead of each battery reacting only to its own home, the algorithm aggregated data to create a community-level profile.

2. Technical Objective Maximize the collective self-consumption of the entire community, effectively "sharing" surplus PV from one roof to a neighbor's battery.

3. Algorithmic Formulation (Heuristic) This utilized a rule-based algorithm with an iterative learning component:

- **Aggregation:** Sum the load and PV generation profiles of all participants.
- **Dispatch Logic:**
  - Identify the "Community Net Position" (Surplus or Deficit).
  - **Surplus:** Instruct batteries with available capacity (low SoC) to charge, even if their specific house has no surplus.
  - **Deficit:** Instruct batteries with stored energy to discharge to lower the community import.
- **Learning:** The algorithm included a feedback loop to refine its accuracy based on the previous day's performance (iterative daily learning).

4. Key Mechanism "Virtual Energy Sharing": By decoupling the battery's action from the homeowner's instantaneous need, the system mimicked a physical community microgrid without changing the physical cabling.

B.3 Use Case 3: Following Grid Operator Signals

1. Purpose Here, control was handed over to the DSO. Enexis provided a bandwidth (upper and lower limit) for the transformer load. The algorithm's sole task was to schedule batteries to keep the actual load within this bandwidth, prioritizing grid stability over household needs.

2. Technical Objective Minimize transformer power peaks and excursions outside the DSO bandwidth.

3. Algorithmic Formulation (Optimization) The problem is formulated as a multi-period mixed-integer quadratic program (MIQP).

$$
\begin{aligned}
\underset{p_{i,t}^{ch}, p_{i,t}^{dis}, \delta_{i,t}}{\text{minimize}} & \sum_t \left(p_t^{\text{trafo}}\right)^2 + \omega \sum_t \sum_i \left[\left(p_{i,t}^{ch}\right)^2 + \left(p_{i,t}^{\text{dis}}\right)^2\right] \\
\text{s.t. } & p_t^{\text{trafo}} = \sum_i \left(p_{i,t}^{ch} - p_{i,t}^{\text{dis}}\right) + \hat{p}_t^{\text{net}}, \forall t \\
& 0 \le p_{i,t}^{ch} \le \delta_{t,i} \bar{p}_i, \forall i, \forall t \\
& 0 \le p_{i,t}^{\text{dis}} \le \left(1 - \delta_{t,i}\right) \bar{p}_i, \forall i, \forall t \\
& SoC_{i,0} = SoC_{i,T} = SoC_i^0, \forall i \\
& SoC_i^{\min} \le SoC_{i,t} \le SoC_i^{\max}, \forall i, \forall t \\
& SoC_{i,t} = SoC_{i,t-1} \\
& + \left(\eta_i^{ch} p_{i,t}^{ch} - p_{i,t}^{\text{dis}} / \eta_i^{\text{dis}}\right) \Delta_t / E_i, \forall i, \forall t \\
& \underline{p}_t^{\text{trafo}} \le p_t^{\text{trafo}} \le \bar{p}_t^{\text{trafo}}, \forall t
\end{aligned}
$$

- **Primary Term:** Minimizes the squared net power flow at the transformer (flattening the curve).
- **Secondary Term:** Penalizes unnecessary battery cycling (charging one while discharging another).
- **Constraints:**

  Maintain net grid load within DSO bandwidth limits (i.e., p_t^{-trafo} and p_t^{+trafo}):

  $$p_t^{trafo} = \sum_t \left(p_{i,t}^{ch} - p_{i,t}^{dis}\right) + p^{t_{net}}$$
  $$p_t^{-trafo} \le p_t^{trafo} \le p_t^{+trafo}$$

4. Key Mechanism Quadratic Peak Penalization: By squaring the transformer load in the objective function, the algorithm disproportionately penalizes extreme peaks, forcing the batteries to act most aggressively when the grid is most stressed.

B.4 Use Case 4: Balancing Community and Grid Interests

1. Purpose This "Sweet Spot" scenario attempted to minimize community electricity costs while *also* respecting grid constraints. It introduced the concept of a "congestion cost"—a shadow price that signals the value of grid capacity.

2. Technical Objective Minimize (Community Electricity Cost + Virtual Congestion Penalty).

3. Algorithmic Formulation (Multi-Objective) This builds on UC3 but introduces price data and slack variables for congestion.

$$\begin{aligned}
\underset{p_{i,t}^{ch},p_{i,t}^{\text{dize}}}{\text{minimize}} \; & \underbrace{\sum_t \lambda_t (p_t^{\text{com}})\Delta t +}_{\text{community costs}} \quad \underbrace{\gamma \sum_t (\bar{\epsilon} + \underline{\epsilon})\Delta_t}_{\text{congestion management}} \quad + \\
& \underbrace{\omega \sum_t \sum_i \left(p_{i,t}^{ch} + p_{i,t}^{\text{dis}}\right)}_{\text{battery operation costs}} \\
\text{s.t. } & p_t^{\text{trafo}} = \sum_i \left(p_{i,t}^{\text{ch}} - p_{i,t}^{\text{dis}}\right) + \hat{p}_t^{\text{trafo}}, \forall t \\
& p_t^{\text{com}} = \sum_i p_{i,t}^{\text{net}}, \forall t \\
& p_{i,t}^{\text{net}} = p_{i,t}^{\text{load}} - p_{i,t}^{PV} + p_{i,t}^{\text{ch}} - p_{i,t}^{\text{dis}}, \forall i, \forall t \\
& 0 \le p_{i,t}^{\text{ch}} \le \bar{p}_i, \forall i, \forall t \\
& 0 \le p_{i,t}^{\text{dis}} \le \bar{p}_i, \forall i, \forall t \\
& SoC_{i,0} = SoC_{i,T} = SoC_i^0, \forall i \\
& SoC_i^{\min} \le SoC_{i,t} \le SoC_i^{\max}, \forall i, \forall t \\
& SoC_{i,t} = SoC_{i,t-1} \\
& + \left(\eta_i^{ch} p_{i,t}^{ch} - p_{i,t}^{\text{dis}} / \eta_i^{\text{dis}}\right)\Delta_t / E_i, \forall i, \forall t \\
& \underline{p}_t^{\text{trafo}} - \underline{\epsilon} \le p_t^{\text{trafo}}, \forall t \\
& p_t^{\text{trafo}} \le \bar{p}_t^{\text{trafo}} + \bar{\epsilon}, \forall t \\
& \sum_t \sum_i \lambda_t \left(p_{i,t}^{\text{net}}\right) \le \sum_t \sum_i \lambda_t \left(p_{i,t}^{\text{load}} - p_{i,t}^{PV}\right)
\end{aligned}$$

- **Component 1 (Economics):** Minimizes the bill based on Day-Ahead market prices.
- **Component 2 (Grid):** A high "internal price" applied only when the load exceeds the DSO bandwidth (p_t^{-trafo} and p_t^{+trafo}).
- **Constraints:** Includes all UC3 constraints plus community energy balance.

4. Key Mechanism The "Shadow Price": The congestion penalty is not a real cost paid by residents. It is a mathematical lever that makes "harming the grid" virtually expensive for the algorithm. This naturally aligns battery behavior with grid needs during peaks (avoiding the penalty) while leaving them free to arbitrage prices during off-peak hours.

B.5 Use Case 5: Impact on Medium Voltage (MV) Grid

1. Purpose This use-case moved the goalposts from the local street to the regional grid. The batteries were dispatched based on predictions of the Medium Voltage transformer load, testing if small assets could solve large problems.

2. Technical Objective Reduce peak generation and consumption at the MV transformer level.

3. Algorithmic Formulation Use Case 5 targets the reduction of peak generation and consumption at the upper medium-voltage (MV) transformer level. The mathematical formulation is identical to that employed in Use Case 3; however, instead of relying on low-voltage (LV) transformer measurements, this use case utilizes data from medium-voltage transformers.

4. Key Mechanism Savitzky-Golay Filtering: To prevent the batteries from chasing noise, the historical MV load profile is smoothed using a Savitzky-Golay filter. This ensures the batteries target the *structural* peak (the macroscopic trend) rather than transient, short-term fluctuations that do not threaten grid thermal limits.

B.6 Use Case 6: Hybrid Control (Behavioral)

1. Purpose This final test augmented the automated control of UC4 with manual "demand shifting" by residents (e.g., "turn on washing machines now"). It utilized a "flash mob" metaphor to synchronize human action with battery dispatch.

2. Technical Objective Enhance the peak-shaving capacity of UC4 through coordinated load shifting.

3. Algorithmic Formulation

- **Automated Layer:** Runs the UC4 Multi-Objective Optimization.
- **Manual Layer:** A "soft control" input where an engineer examines the weekly forecast on Friday for the highest generation and consumption peaks, creates a initial “heads-up” overview for the residents with the request to put these moments into the calendar. Upon confirmation of the peaks the day ahead, a direct call-to-action is generated and shared with the residents to shift as much consumption to the generation peak or away from the consumption peak.

4. Key Mechanism Human-in-the-Loop: Residents act to create additional flexibility, by soaking up further excess PV while the batteries are charging.

Note on evaluation criteria

In this project, while multiple evaluation criteria were evaluated (as described in our various technical publications), but of primary interest were battery performance and battery grid impacts.

Battery performance was judged based on the following factors:

a) The degree to which the battery could reduce **electricity costs** for the battery owner and/or community, assuming flexible contracts where electricity prices correspond to day-ahead market rates.
b) The degree to which the battery could increase **self-consumption** for the battery owner and/or community, where self-consumption is defined as:

$$Self\ consumption = \frac{PV\ energy\ consumed}{PV\ energy\ generated}$$

c) The number of **battery (dis)charge cycles** required to achieve these results (which is indicative of battery degradation and lifetime).

Battery grid impacts were measured using several indicators, which are indicative of grid congestion (a through c) and power quality (d through h).

a) The degree of peak reduction on the grid in terms of **magnitude**, for both consumption and production periods. This is indicative of the level of grid congestion.
b) The degree of peak reduction on the grid in terms of **duration**, for both consumption and production periods. This is indicative of the level of hours of grid congestion.
c) The amount of **load variance**. Large, abrupt swings in local supply and demand can lead to power quality issues and increased wear and tear on grid assets.
d) The average **variance in power flows** (ΔP) with and without the battery. Greater power variance can lead to voltage issues and increased thermal stress on grid assets.
e) The **smoothing index** is the degree to which the batteries reduce (or perhaps increase) power flow variance.
f) Similarly, the **reduction in standard deviation** is the degree to which extremes (i.e., high peaks/troughs) in the power flow profile are reduced.
g) The amount of electricity supply/demand **shifted** in time by the batteries. This indicator describes how much flexibility the batteries can provide.
h) The **flexibility index** is the degree to which the batteries were able to shift power variance (i.e., it is the electricity shifting capability of the battery from the time of low demand/high generation/lower price to peak hours/no PV generation/higher electricity prices).

Note on Validation: The Battery Fingerprint

Before analyzing the quantitative results in Part C, it is useful to understand how we can visually validate that the algorithms described above were actually controlling the hardware as intended. We utilized "Battery Fingerprint" graphs—scatter plots plotting **Time of Day** (X-axis) against **Battery Power** (Y-axis).

- **Positive Values (Above axis):** Indicate charging.
- **Negative Values (Below axis):** Indicate discharging.

These graphs visualise the control logic in action. For example, a dense cluster of negative dots during the evening peak proves the Peak Shaving logic of UC3 is active.

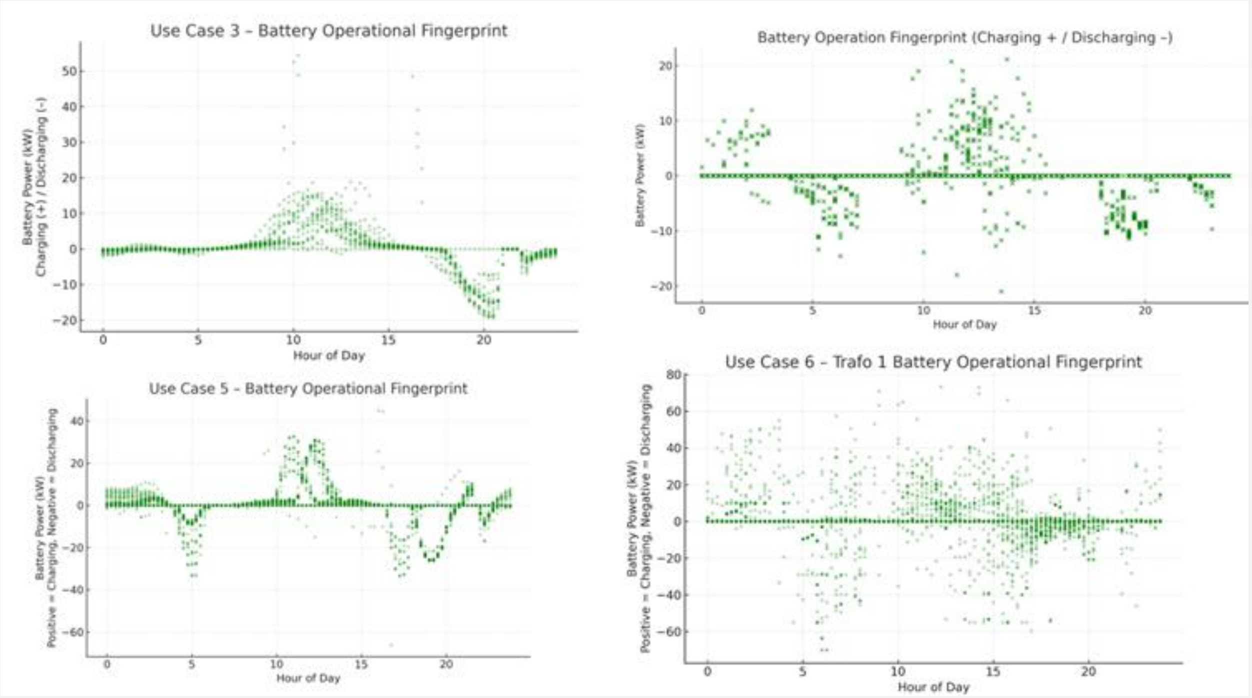


Figure 1 A cumulative scatter plot showing the 'fingerprint' of battery operations. The clear clustering of charging events (top) and discharging events (bottom) at specific times confirms the algorithm is strictly following the optimization schedule rather than

Part C: Detailed Results

This section presents the quantitative impact analysis for the physical use cases. It distinguishes between the technical impact on grid stability and the financial impact on the participating households (assuming dynamic tariffs).

C.1 Grid Impact Analysis

We quantify the technical success of each strategy using metrics such as peak shaving (kW), import/export reduction (%), and the "Smoothing Index" (where a value >1 indicates reduced volatility).

UC1: Household Self-Consumption (Baseline)

- **Grid Logic:** Purely reactive to individual household load; blind to grid state.
- **Outcome:**
    - **Peak Reduction:** Negligible. Simulation showed a collective peak load reduction of only **0.6% (approx. 5kW)**.

- **Generation Peaks:** No measurable reduction (0%) as battery charging coincides with solar availability, not necessarily grid stress.
- **Exports:** Reduced during sunny months, but simply shifts the timing rather than solving the peak injection problem structurally.

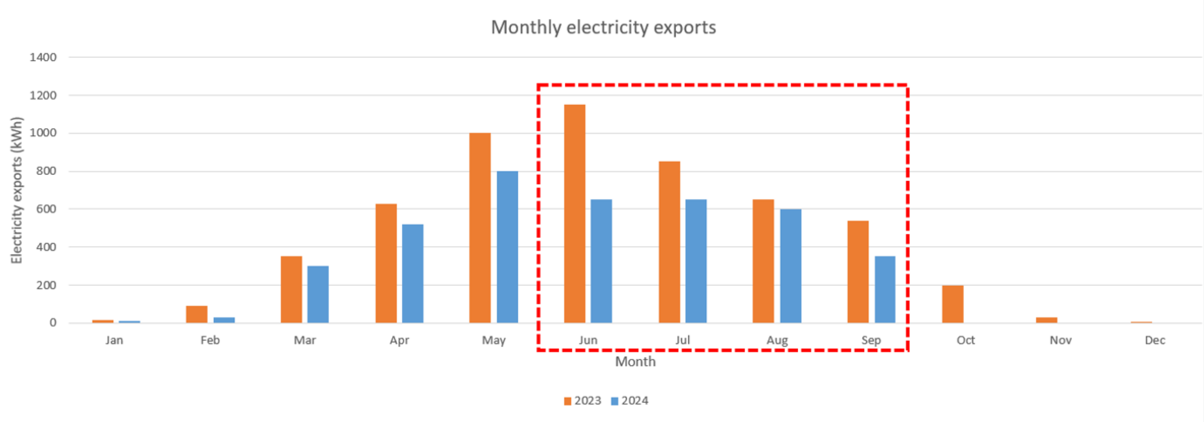


Figure 2 Comparison of average household imports in 2023 (no battery) vs 2024 (battery), showing reduction in volume but not necessarily peak intensity.

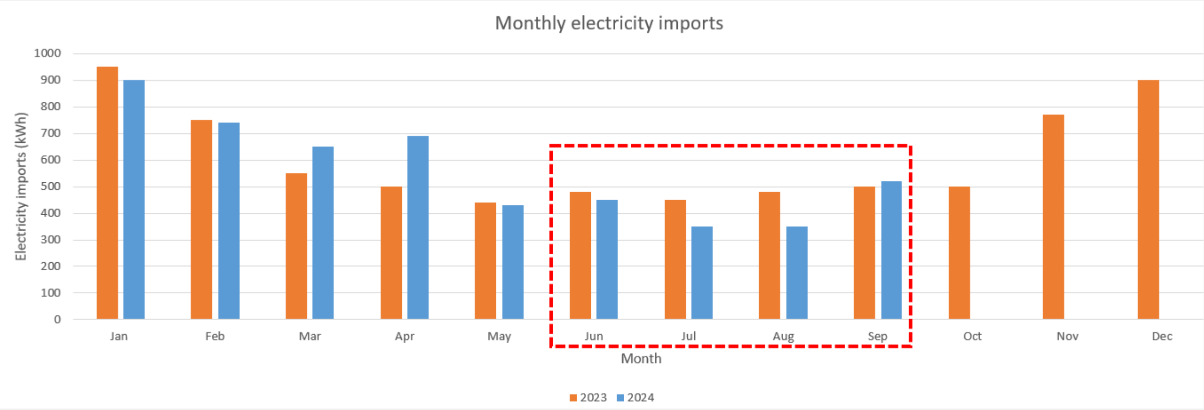


Figure 3 Comparison of average household exports in 2023 (no battery) vs 2024 (battery), showing reduction in volume but not necessarily peak intensity.

UC2: Neighborhood Coordination

- **Grid Logic:** Aggregates load/generation to treat the neighborhood as a single node.
- **Outcome:**
  - **PV Surplus Export:** Reduced by approximately **34%** compared to baseline.

    - **Behavior:** Midday export peaks were significantly flattened as the system prioritized charging any available battery in the cluster, rather than just the one with the generating panels.

UC3: Grid Operator Signals (Winter & Summer Tests)

- **Grid Logic:** Explicit peak shaving based on DSO bandwidths.
- **Outcome:**
    - **Peak Shaving:** Reduced peak load by **4.3%** and peak generation by **4.3%** (Simulation).
    - **Import/Export:** In physical tests, reduced relative import by **6%** and export by **11%**.
    - **Volatility:** Reduced the standard deviation of transformer load by **27%**.
    - **Smoothing Index:** Consistently **> 1.10**, indicating a less volatile grid profile.

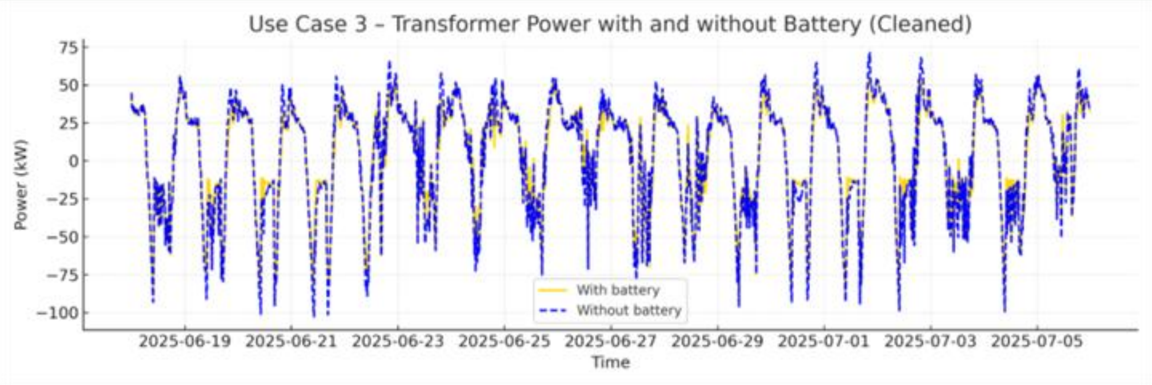


Figure 4 Line graph showing the 'With Battery' profile (Yellow) tracking consistently inside the 'Without Battery' profile (Blue), visually demonstrating peak shaving.

UC4: Balancing Community & Grid (The "Sweet Spot")

- **Grid Logic:** Respects DSO bandwidth constraints while optimizing for price.
- **Outcome:**
    - **Compliance:** Successfully maintained transformer load within requested bandwidths.
    - **Power Distribution:** Analysis of the load distribution histograms confirms the elimination of extreme load events. The "tail" of the distribution is effectively clipped at the constraint limit.

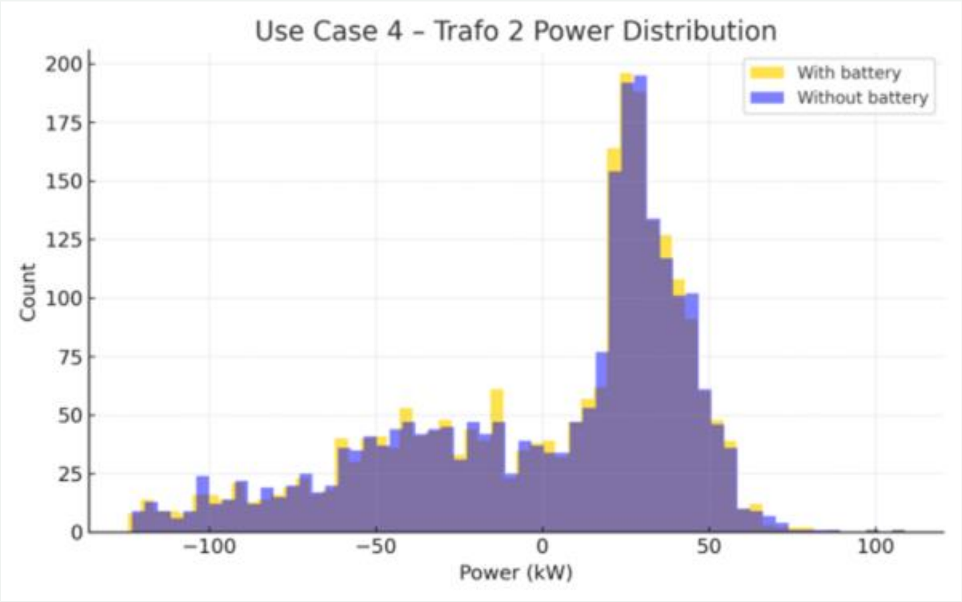


Figure 5 A frequency distribution showing how the battery eliminates the 'tails' (extreme import/export events), effectively compressing the grid usage into a safe zone.

UC5: Medium Voltage (MV) Impact

- **Grid Logic:** Dispatches batteries based on MV-level forecasts.
- **Outcome:**
  - **Peak Reduction:** Achieved an average MV peak reduction of **3.5%**, with a maximum of **6%**.
  - **Data Sensitivity:** The experiment revealed a critical dependency on data latency. Using week-old grid data reduced effectiveness to just **1.4%**, proving that real-time data is essential for MV services.
  - **LV Side-Effect:** While targeting MV peaks, the system simultaneously reduced LV export peaks by **8%** and imports by **4%**.

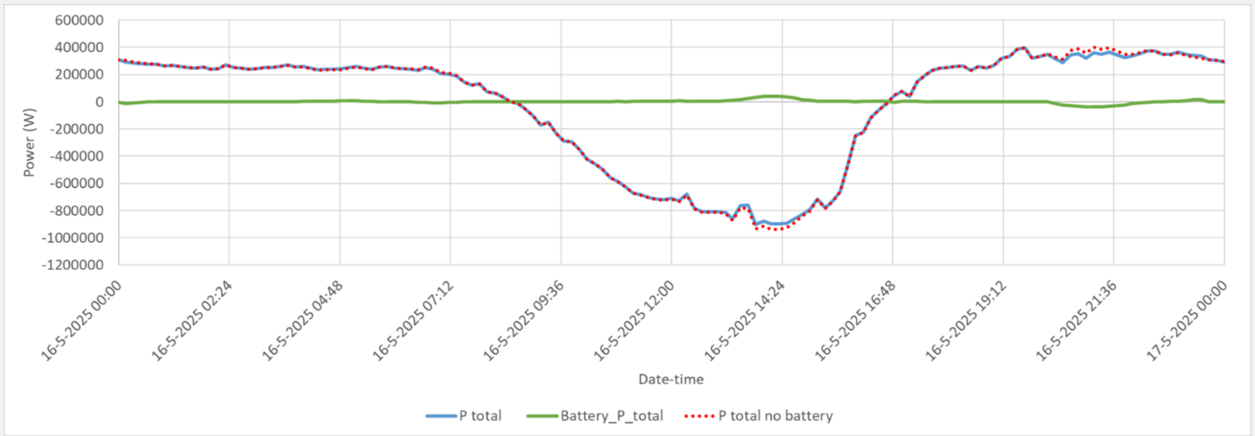


Figure 6 Measured Peak Reduction During Mid-Day and Evenign on the Medium Voltage (MV) Grid vs Simulated Case of No-Action.

UC6: Hybrid Control

- **Grid Logic:** Automated dispatch + Human demand response.
- **Outcome:**
  - **Peak Shaving:** Achieved the highest absolute peak reduction of **10.27 kW** on Transformer 1.
  - **Smoothing Index:** Reached **1.18** (Trafo 1), the highest stability score of all use cases.
  - **Distribution:** Successfully eliminated the "tails" of the power distribution curve, confirming robust protection against extremities.

General outlook

This section provides a consolidated overview of the technical performance of all strategies (Use Cases) tested throughout the project. The tables and visualizations below offer a high-resolution comparison of how each algorithm performed against a "no-battery" baseline. Table 1 focuses on technical grid metrics—showing the "smoothing" effect and the amount of energy successfully shifted in time—while the Power Distribution bar graphs illustrate how coordinated steering effectively eliminates extreme 'tail' events (the most severe peaks and troughs).[1]

[1] Note: Parameters were calculated at the two LV/MV transformers where the batteries were located behind; Parameters were not calculated for use cases 1 and 2 due to a lack of measurement data.

Table 1:Battery influence metric table

Trafo No	Mean |ΔP| with battery (kW)	Mean |ΔP| without battery (kW)	Smoothing index (σ_wo/σ_w)	Flexibility index	Battery energy shift (kWh)	Std with / without battery (kW)	% std reduction with battery
Use case 3- Summer							
Trafo 1	8.30	8.71	1.10	0.18	1431.55	33.14 / 36.38	8.90
Trafo 2	7.60	8.75	1.12	0.14	1463.75	24.65/ 27.62	10.75
Use case 3- Winter (December)							
Trafo 1	63.91	63.05	1.22	0.06	2796.79	13.71/16.80	18.39
Trafo 2	41.82	41.37	1.12	0.05	1560.51	9.98/11.15	10.49
Use case 4							
Trafo 1	14.04	14.09	1.009	0.03	307.48	42.09/ 42.47	0.89
Trafo 2	3.44	3.82	1.03	0.01	125.56	16.40/ 16.88	2.84
Use case 5							
Trafo 1	8.05	8.70	1.06	0.17	4387.72	34.82 / 37.07	6.0
Trafo 2	8.08	8.27	1.05	0.10	2221.49	22.13 / 23.14	4.36
Use case 6							
Trafo 1	10.27	13.88	1.18	0.14	5624.58	21.65/ 25.43	14.87
Trafo 2	6.64	8.08	1.11	0.078	2388.14	15.40 / 13.90	9.74

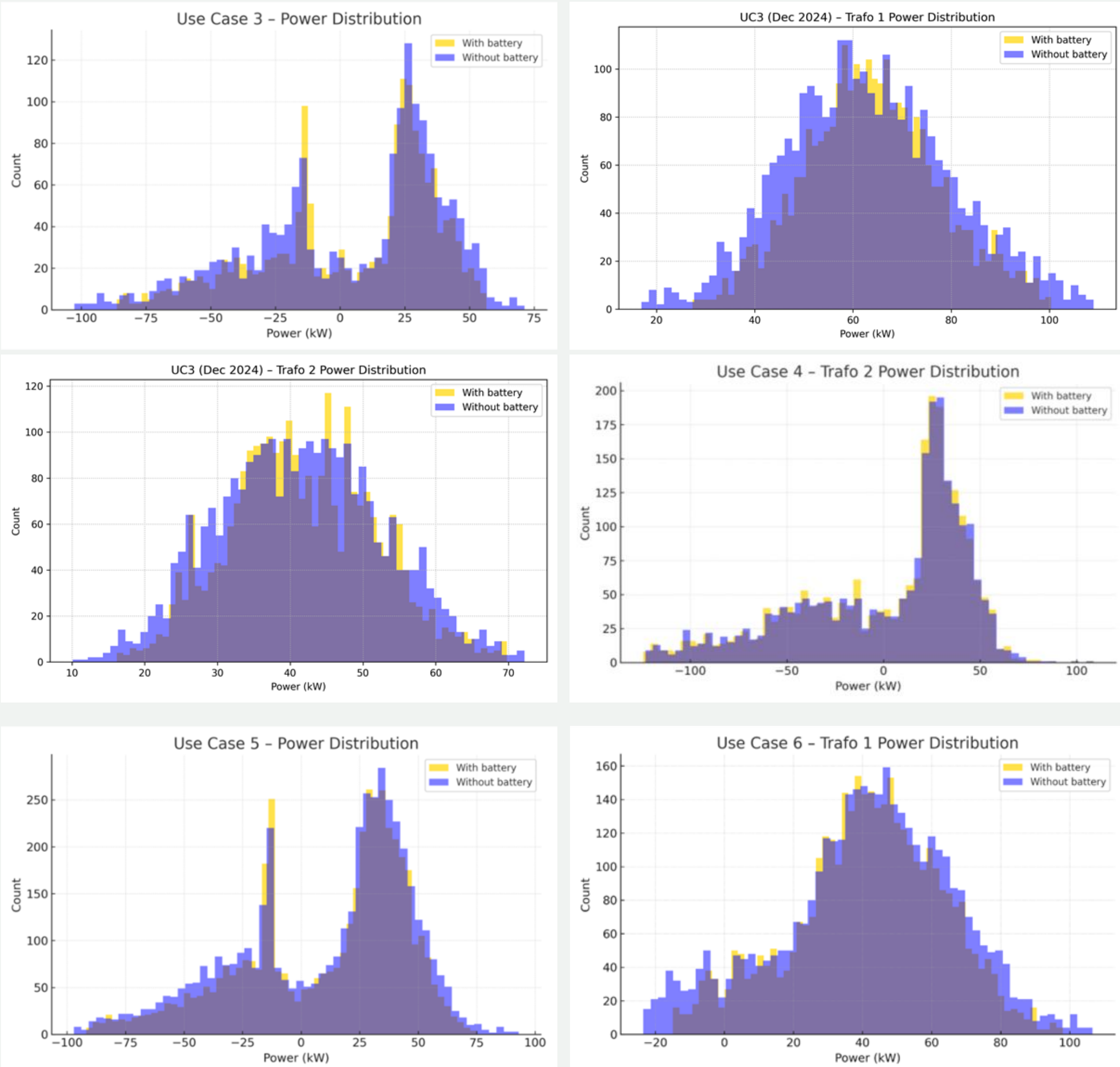


Figure 7 - Transformer load distribution with (yellow bars) and without (blue bard) batteries

The net energy, export, import, cost savings, and compensation depend on the seasons and the algorithm. In winter, the battery is charged from the grid, which introduces some cost. In the summer months, the battery reduces exports substantially, resulting in cost savings. The table below represents the cost and net energy results summary of use cases 3-6.

C.2 Financial Impact Analysis (Residents)

This analysis assumes all residents operate on **Dynamic Tariffs**[2]. Relative costs and savings were calculated based on actual EPEX day-ahead spot-market electricity prices, comparing the situation where the battery was used (i.e., the use cases) with the situation if the battery were not used. The latter was achieved by subtracting the battery (dis)charge profile from the individual household net electricity imports/exports.

UC1: Household Self-Consumption

- **Mechanism:** Avoided purchase of grid electricity.
- **Result:** Positive but modest.
  - **Savings:** Estimated between **€0.18 and €6.13 per week** depending on solar irradiation.
  - **Verdict:** Insufficient to justify hardware investment without subsidy.

UC2: Neighborhood Coordination

- **Mechanism:** Collective arbitrage (charging the "community" battery when cheapest).
- **Result:** Positive.
  - **Cost Reduction:** The community achieved a net cost reduction of **~11%**.
  - **Note:** Savings are aggregate; individual results varied, creating a need for internal settlement.

UC3: Grid Operator Signals

- **Mechanism:** Prioritizing grid stability over price.
- **Result:** Highly seasonal and generally negative.
  - **Winter (Dec):** Net energy costs **increased by ~8%**. Batteries were forced to charge from the grid (incurring losses) to support demand peaks during expensive hours.

---

[2] Under fixed-rate contracts with net-metering, the financial incentive for *any* battery operation is currently negligible or non-existent.

- **Summer (Jun-Jul):** Average savings of **€16.66 per month**. However, this represents a significant **opportunity cost** compared to pure trading strategies (which could yield ~14% higher profits).

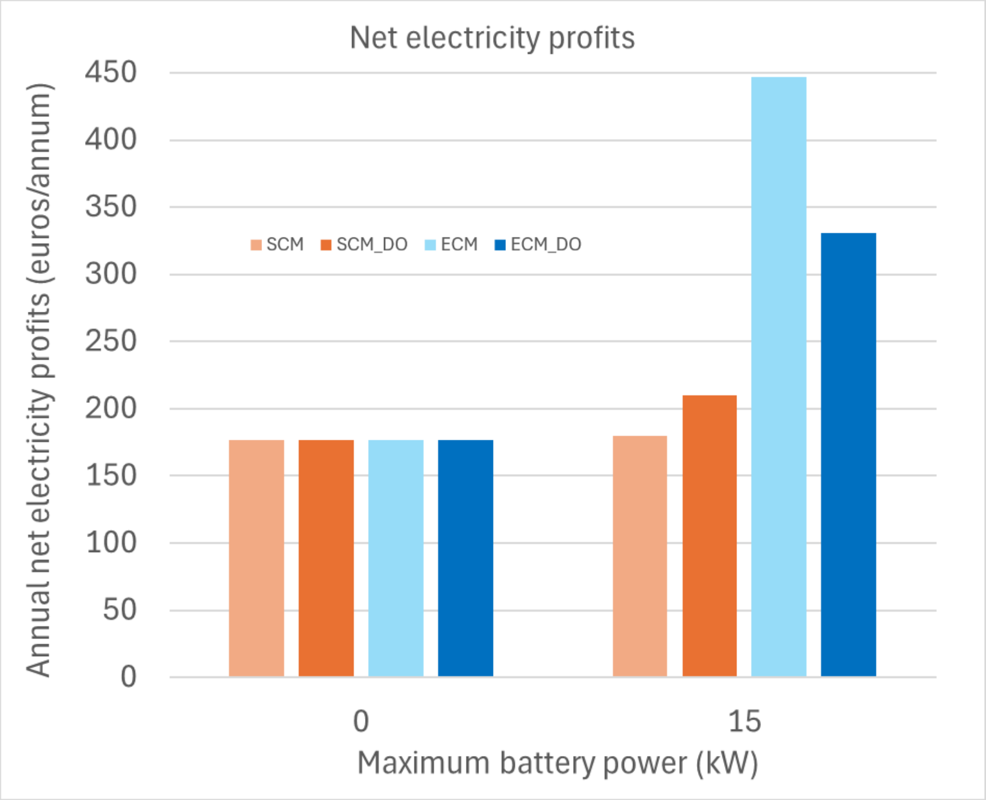


Figure 8 Simulation showing the profit gap between SCM (Self-Consumption) and 'DO' (DSO Override) modes in 2023 (orange) and 2024 (blue), showing the potential for a significant opportunity cost of prioritizing grid stability.

UC4: Balancing Community & Grid

- **Mechanism:** Avoids "Congestion Penalty" (Shadow Price).
- **Result:** The proof of "Win-Win".
  - **Savings:** Average of **€4.30 per month** during the test period.
  - **Significance:** While the absolute amount is low, it proves that providing grid services *does not* require the community to lose money (unlike UC3).

UC5: Medium Voltage Impact

- **Mechanism:** Responding to regional peaks (often correlated with high prices).
- **Result:** Positive.
    - **Savings:** Average of **€30.26 per month**.
    - **Alignment:** Regional grid stress often correlates with high market prices, meaning "helping the grid" and "saving money" aligned naturally in this use case.

UC6: Hybrid Control

- **Mechanism:** Conservative operation to guarantee stability.
- **Result:** Marginal.
    - **Savings:** Only **0.50% - 0.82%**.
    - **Cause:** The system often charged from the grid to ensure reliability for the manual demand response events, incurring round-trip efficiency losses that ate into arbitrage profits.

General outlook

Table 2 below provides a financial and energetic summary of costs and savings across different seasons.

Table 2: Net summary of cost, energy, and savings

Battery	Net Energy(kWh)	Export (kWh)	Grid Import (kWh)	Cost (€)	Compen Sation (€)	Cost Savings (%)	comment
Use case 3-Summer							
With	8575.81	8466.00	17041.81	1434.23	-	9.08	Savings in summer
Without	8247.442	9691.545	17938.986	1577.44			
Use case 3- Winter (December)							
With	72375.49	0.0	72375.49	8259.63	-	0.44	**€10** savings
Without	71474.31	0.0	71474.31	8269.16			
Use case 4							
With	10960.531	11092.09	22052.63	1313.63	-	2.85	Saved energy cost

Without	11107.499	11189.41	22296.91	1352.19			
Use case 5							
With	12307.55	17911.40	46782.487	3954.35	-	5.73	Savings in summer
Without	12239.53	19367.367	48141.981	4194.75			
Use case 6							
With	70498.38	308.67	70807.05	5233.41	-	0.67	Less savings as winter approaches
Without	69757.74	953.57	70711.31	5268.79			

C.3 The Incentive Gap

The data reveals a structural hitch in the business case for community-based congestion management.

1. **Technical Validity:** The results unequivocally prove that household batteries *can* solve grid problems. UC3 and UC6 delivered smoothing indices >1.1 and eliminated extreme load events. The grid operator benefits significantly from this "virtual reinforcement."

2. **Financial Friction:** The most effective grid strategies (UC3 & UC6) yielded the lowest financial returns for residents—or even net losses (UC3 Winter). Conversely, the strategies that made the most money for residents (UC1 & UC2) offered the least support to the grid.

3. **The Conclusion:** The "Shadow Price" used in UC4 proved that a mathematical penalty works to align these interests. For this to become a sustainable business model, this shadow price must become a **real financial incentive**. Without a "Congestion Service Payment" from the DSO to the Energy Cooperative, the natural incentive for households is to pursue "greedy" strategies that may destabilize the grid.

Part D: Simulation Results

Several simulations were made to quantify the trade-offs between battery owners (i.e., individual households which are primarily concerned with battery performance) and the grid operator (i.e., DSO, which is primarily concerned with battery grid impacts). Table 1 lists the Key Performance Indicators (KPIs) which were evaluated. Simulations were made for present and future circumstances (described below). All simulations were done on a 15-minute basis for a period of one year using the Battery Energy Storage Evaluation Method (BESEM) model developed by van Someren, et al.[3]

Table 3 - Summary of KPIs

KPI name	Unit	Definition
		KPIs for battery performance
Self-consumption energy	kWh	The difference between household PV generation and electricity exports
Net electricity profits	€	The net profits earned by during a given period, considering hourly pricing on day-ahead hourly electricity markets. It was possible for net electricity profits to be negative, which was interpreted as net costs. Taxes and other fees are excluded.
Battery cycles	n/a	The number of full battery (dis)charge cycles incurred during a given period.
DO override cycles	cycles	The number of full battery cycles incurred by DSO override control (DO) during a given period.
		KPIs for battery grid impacts
Peak grid load	kW	The maximum net electricity load on a given section of the grid.
Peak grid generation	kW	The maximum net electricity generation on a given section of the grid.
Hours of load congestion	hr	The number of hours when power flows from net electricity loads exceeded a given threshold during a given period.
Hours of generation congestion	hr	The number of hours when power flows from net electricity generation exceeded a given threshold during a given period.

The future scenarios are based on 'Netbeheer Nederland Scenario's Editie 2025', which describe four future trajectories forecasted to 2030, 2035, 2040 and 2050. The future trajectories include:

1. Koervaste middenweg (KM): A business-as-usual scenario which assumes the Dutch government policy remains similar to present.

[3] Please see: A Method for Battery Energy Storage Evaluation: Evaluation of battery energy storage system designs accounting for battery interactions with the electricity grid

2. Eigen vermogen (EV): A scenario which assumes that electricity plays an increasingly dominant role in the economy.
3. Gezamenlijke balans (GB): A scenario which emphasizes the continued use of natural gas and increased integration of biogas in the economy.
4. Horizon aanvoer: A scenario which emphasizes the role of hydrogen in the future economy.

For each trajectory and year (i.e., a total of 16 scenarios), different model inputs were derived from the projections in the Netbeheer Nederland report and are listed in the table below. Electricity price forecasts for each scenario were taken from energytransitionmodel.com.

A 2025 scenario was used as a reference in all cases, which roughly corresponds to the results from the practical use cases 1 (wihtout DO) and 5 (with DO). All scenarios used the same 2023 weather profile as a basis for renewable generation.

Table 4 – Scenario input parameters

Input / Scenario	25 KM	30 EV	30 GB	30 HA	30 KM	35 EV	35 GB	35 HA	35 KM	40 EV	40 GB	40 HA	40 KM	50 EV	50 GB	50 HA	50 KM
Price profile	25 KM	30 EV	30 GB	30 HA	30 KM	35 EV	35 GB	35 HA	35 KM	40 EV	40 GB	40 HA	40 KM	50 EV	50 GB	50 HA	50 KM
Load scaling	-	1.25	1.16	1.18	1.21	1.79	1.49	1.57	1.66	2.25	1.85	1.94	2.09	2.4	2.21	2.23	2.43
Small PV scaling	-	1.92	1.35	1.23	1.54	2.65	1.65	1.46	2	3.27	1.96	1.65	235	4.5	2.5	2	3.08
MV scaling	-	1.25	1.16	1.18	1.21	1.79	1.49	1.57	1.66	2.25	1.85	1.94	2.09	2.4	2.21	2.23	2.43
Large wind (MW)	0.050	0.057	0.057	0.057	0.057	0.0857	0.057	0.057	0.0643	0.1	0.064	0.064	0.0786	0.121	0.0714	0.0714	0.0929
Large PV (MW)	0.192	0.432	0.336	0.265	0.336	0.672	0.456	0.36	0.456	0.912	0.6	0.432	0.6	1.392	0.888	0.6	0.888
Grid battery (MWh)	-	0.576	0.464	0.243	0.371	1.177	0.917	0.5	0.889	1.71	1.56	0.832	1.45	2.85	2.38	1.195	2.33
House battery (kWh)	10	16	13	10	10.3	32.7	25.4	13.9	24.704	47.4	43.3	23.1	40.4	79.3	66.1	33.2	64.8
House battery (kW)	10	15	13	10	10.3	15	15	15	15	15	15	15	15	30	30	15	30
Grid scaling?	1	1	1	1	1	2	1	1	2	3	2	2	3	3	3	3	3

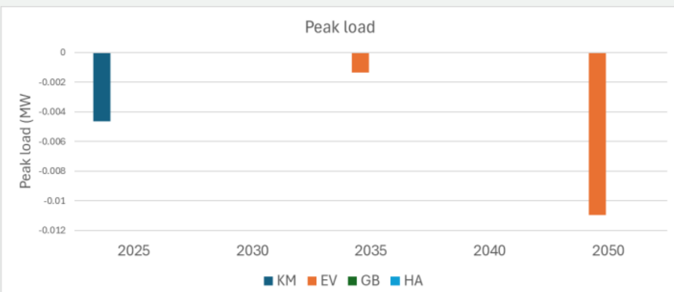
In the model, all scaling factors were applied to standard profiles for household consumption, wind and PV generation, MV grid profile. The MV profile was then modified, assuming that a number of MWh equal to the grid battery's capacity could be shifted each day (i.e., peak reduction was applied to the MV grid profile). Price profiles per scenario were obtained from https://energytransitionmodel.com. Grid scaling was applied in 3 steps, assuming that capacities of all cables and transformers would increase by roughly the factor given. Grid scaling was implemented to avoid running into calculation problems in the model (although the threshold for grid congestion remained consistent at 700 kW to allow comparisons between scenarios).

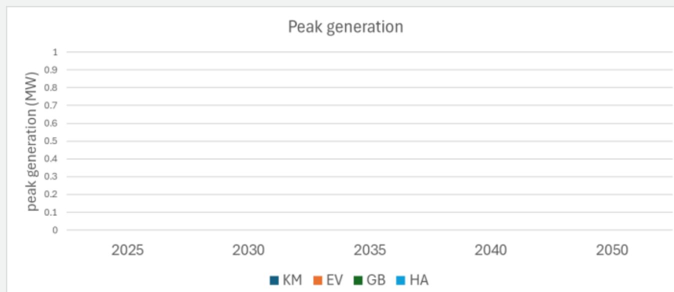
D.1 Battery impacts on the grid

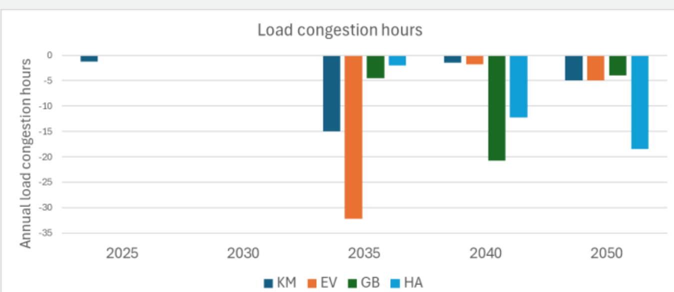
The following graphs depict the relative grid impacts of the (9) household batteries considering different control strategies and future scenarios. If a value is '0', it indicates that the batteries had no impact. Positive results indicate an increase in the given KPI, and negative values indicate a decrease. Please note that the scale of grid impacts (i.e., y-axis values) can vary per result.

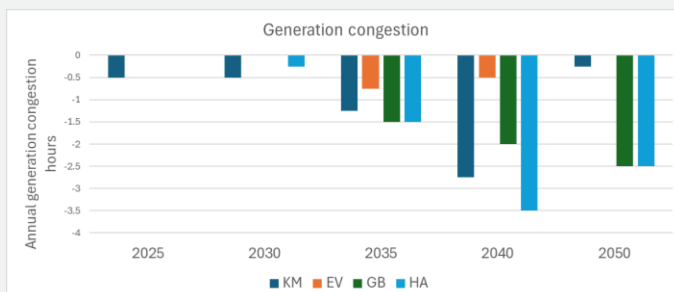
What do these results indicate? The more controllable assets that are available (e.g., household batteries, but may include others), the more potential to manage congestion and minimize its negative impacts. Importantly, scenarios which lead to more electricity consumption also assume more installed battery capacity and quicker grid reinforcement. So, paradoxically, promoting more electrification could reduce congestion problems in the long run (assuming appropriate policies and regulations are adopted).

SCM Control

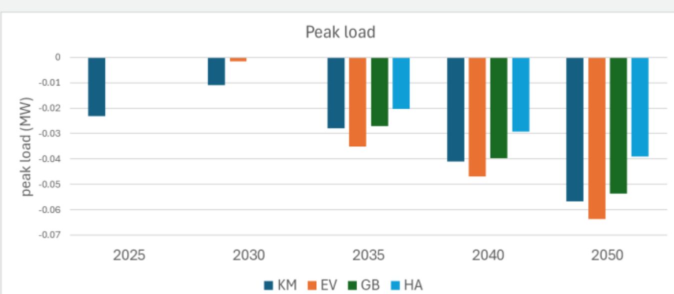


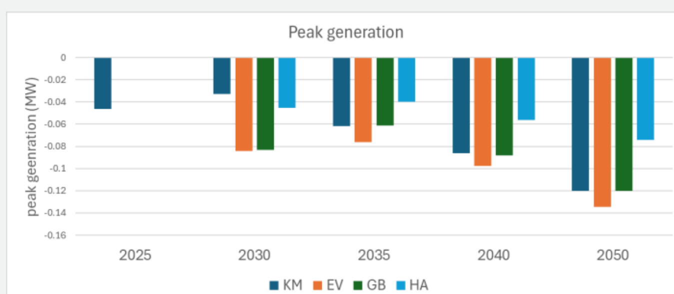


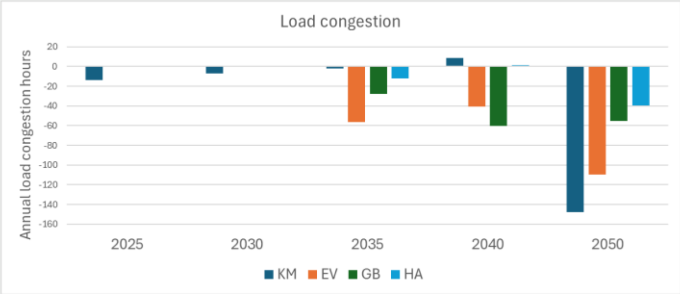


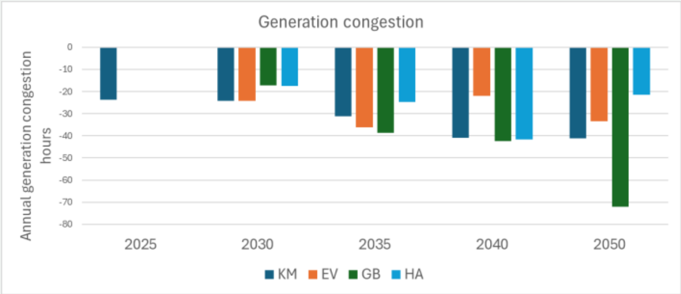


SCM_DO Control

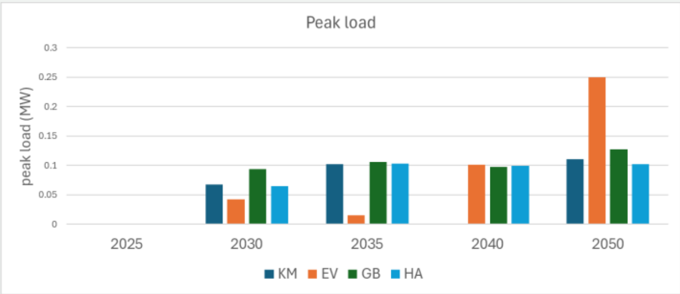


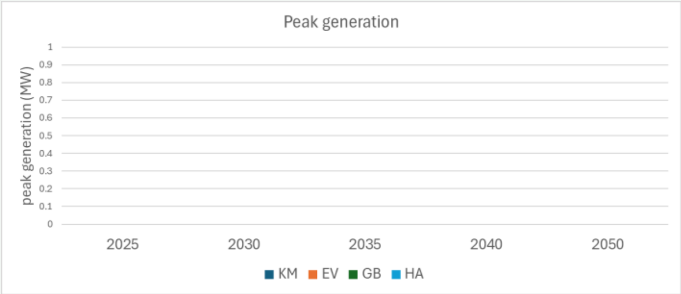


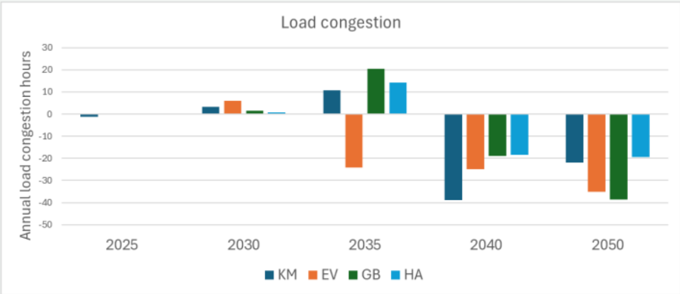


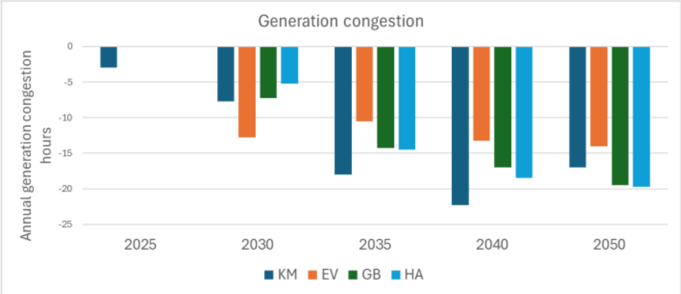


ECM Control

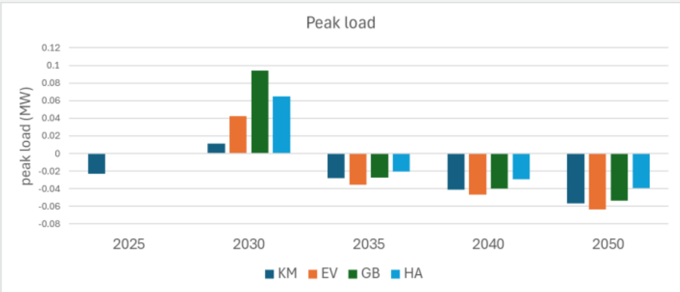


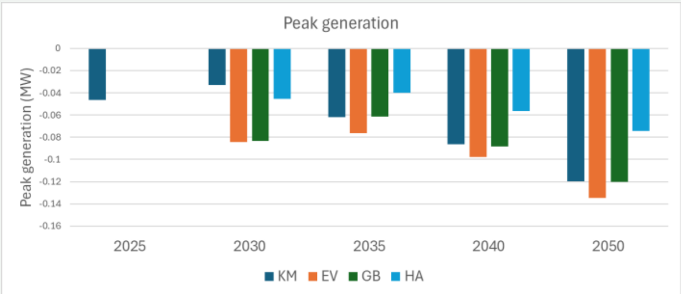


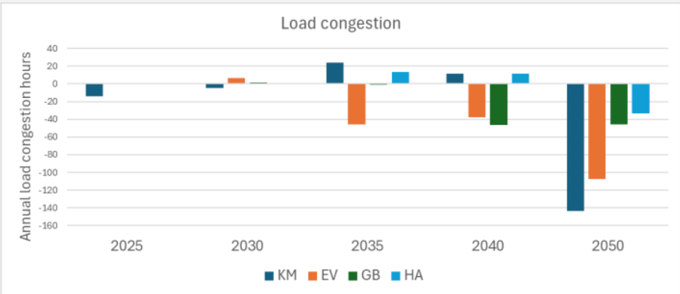


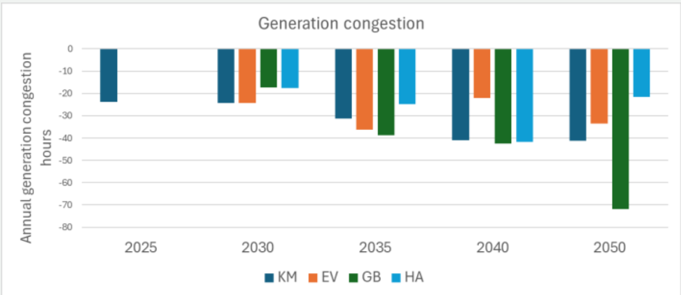


ECM_DO Control







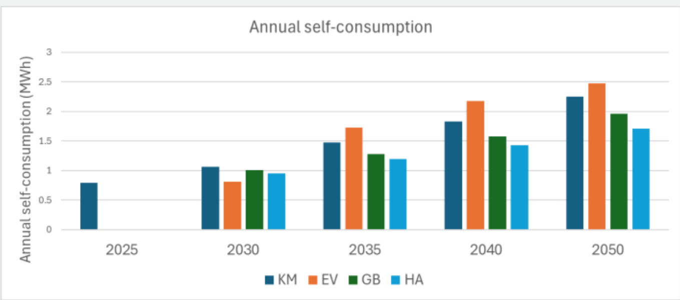


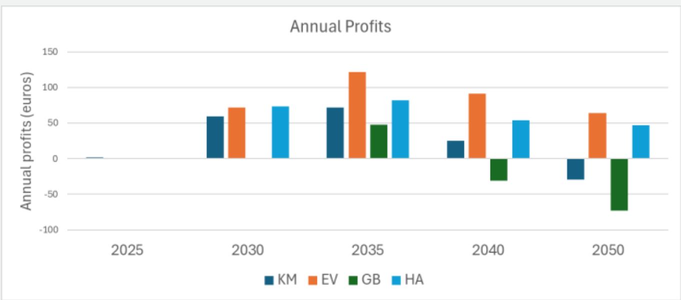
D.2 Battery performance

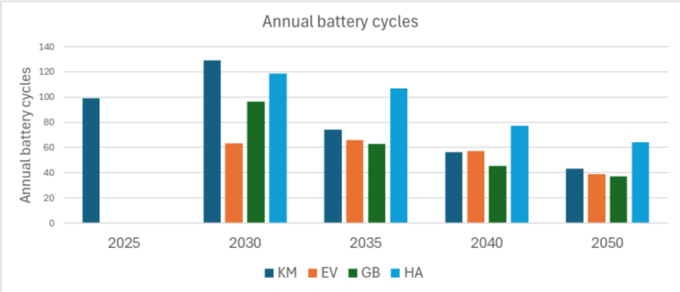
The following graphs depict the relative performance for an individual household battery considering different control strategies and future scenarios. If a value is ‘0’, it indicates that this parameter was irrelevant for the given battery control strategy. Positive results indicate an increase in the given KPI, and negative values indicate a decrease. Please note that the scale of battery performance KPIs (i.e., y-axis values) can vary per result.

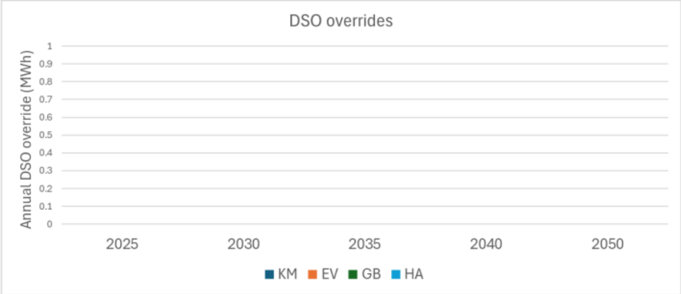
What do these results indicate? A battery becomes more beneficial the more that electrification is pursued/incentivized.

SCM Control

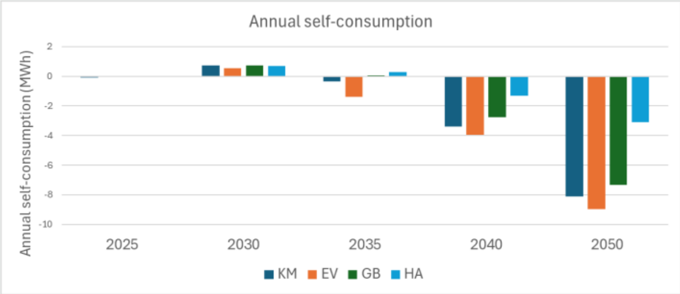


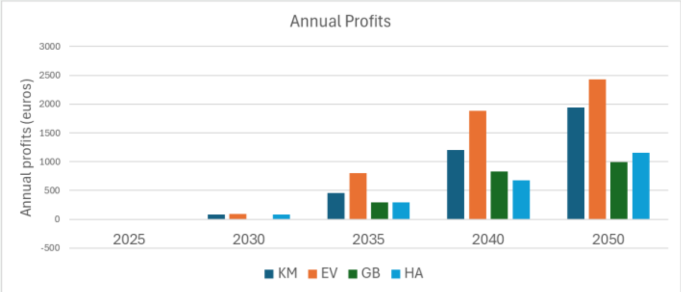


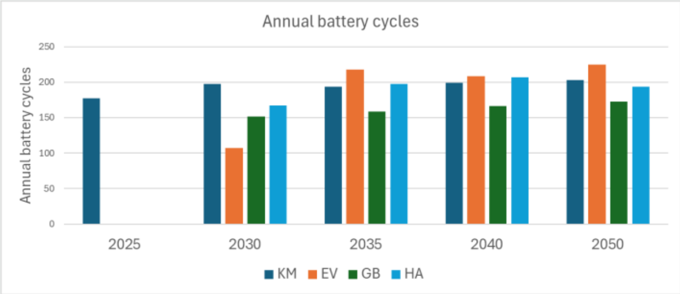


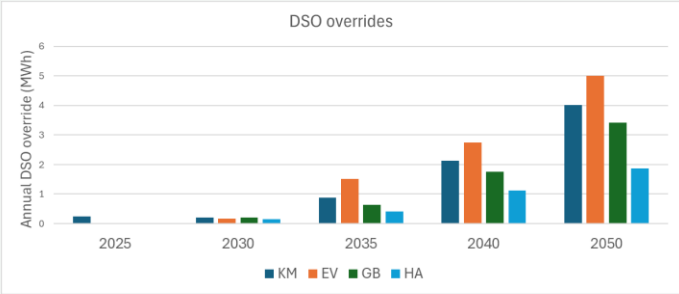


SCM_DO Control

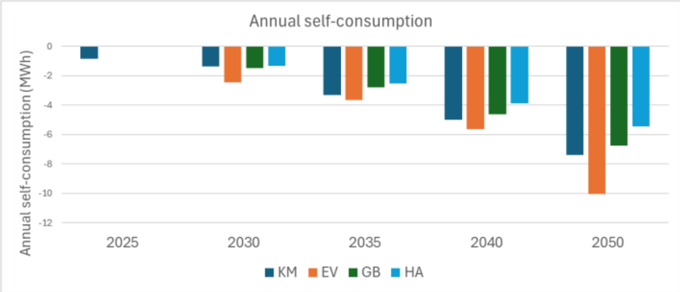


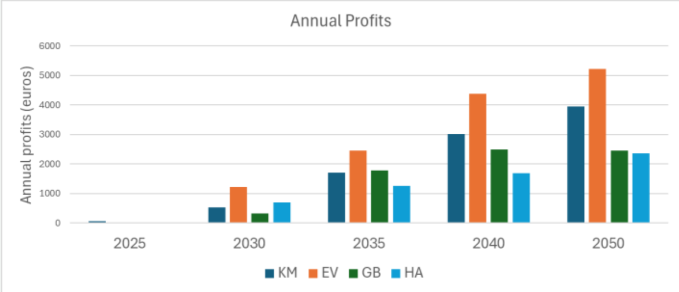


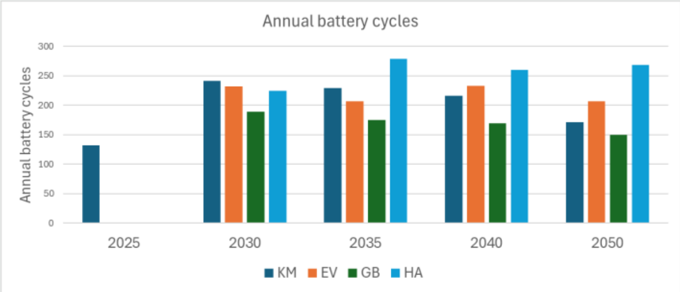


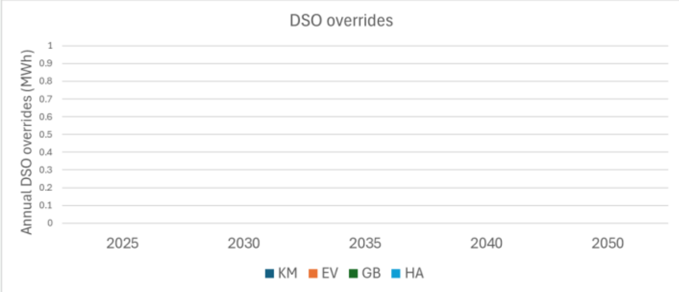


ECM Control

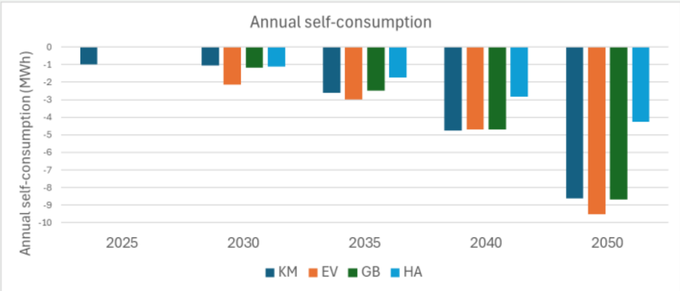


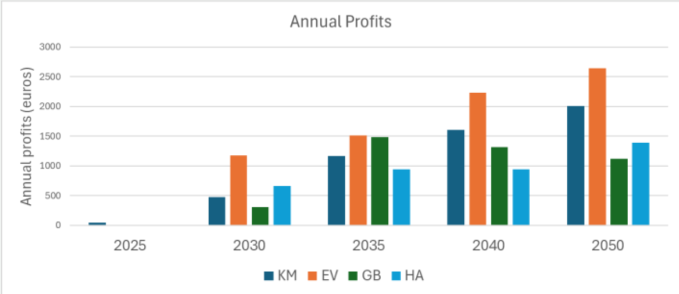


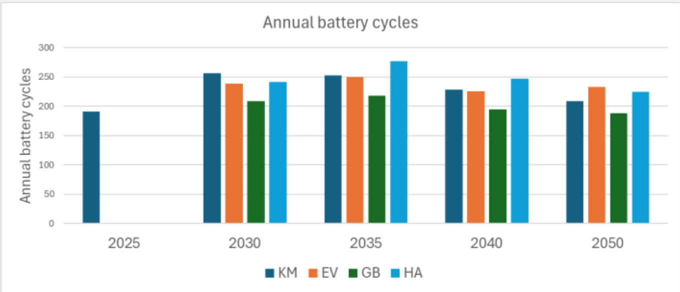


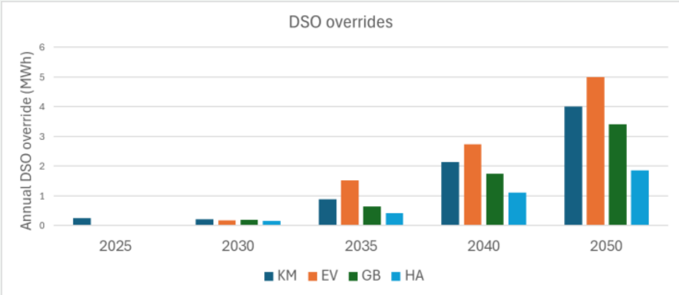


ECM_DO Control









Part E: Sources to go deeper

- Zhan S, Zhang H, Kok JK, Paterakis NG. Model-free Approaches for Real-time Distribution System Operation: A Comparison of Feedback Optimization and Reinforcement Learning. In IEEE PowerTech 2025. Institute of Electrical and Electronics Engineers. 2025
- Zhan S, N. G. Paterakis, W. v. d. Akker, A. van der Molen, J. Morren and H. Slootweg, "Distributed Online Feedback Optimization for Real-Time Distribution System Voltage Regulation," IEEE Transactions on Power Systems, vol. 40, no. 6, pp. 5325-5336, Nov. 2025, doi: 10.1109/TPWRS.2025.3585607.
- Jin L, Zhan S, Zhang Haoyang, Paterakis NG. Multi-Objective Congestion Management in Low-Voltage Grids: Coordinating End-Users and System Operators for Real-World Implementation. In IEEE Innovative Grid Strategies Institute of Electrical and Electronics Engineers. 2025.
- Jin L, S. Zhan, S. Cudjoe and N. G. Paterakis, "Empowering Low-Voltage Grids: Real-World Implementation of Home Batteries for Effective Congestion Management," 2025 IEEE Kiel PowerTech, Kiel, Germany, 2025, pp. 1-6, doi: 10.1109/PowerTech59965.2025.11180463.
- Jin L, L. Bliek, and N. G. Paterakis, “Learning Active Constraints for Bilevel Optimization: Evaluating Classification Metrics on Real-World Distribution System Data”, IEEE Transactions on Smart Grid, 2025, doi: 10.1109/TSG.2025.3632419.
- Cudjoe S, Van der Laan M, Kok K. Integrated PV-Battery Design Mapping Strategies and Control in Decentralised Energy Communities for Enhanced Grid Congestion Relief. In CIRED 2025.
- Van Someren C, Visser M, Slootweg H. How battery energy storage impacts grid congestion – An evaluation of the trade-offs between different battery control strategies. In Journal of Energy Storage 134. 2025.