Electricity Pricing Challenges in Local Energy Communities Considering Bounded Rationality of Members

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Contents

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- **Introduction to Alexander Project:**

- ALEXANDER, Accelerating Low Voltage Flexibility Participation In A Grid Safer Manner, is a Belgium ETF (Energy Transition Funds) Project initiated in 2021 (to 2025) with various members, including the only Belgium TSO and all Belgian DSOs:

UMONS Université de Mons, KU LEUVEN, ULB, EnergyVille, Universiteit Antwerpen, UHASSELT, vito, elia, fluvius., ORES, Sibelga, resa

- **Project objectives:**

- To **accelerate the transition** towards an adequate, secure and stable Belgian energy system with higher levels of renewable energy sources.
- To design a fundamentally **new approach to understand consumer preferences** in the context of flexibility provision for system purposes, by the use of discrete choice experiments.
- To develop new insights in the heterogeneous and bounded rational behavior of end consumers which allow a better representation and **exploration of the LV flexibility in models for improved security of supply**.
- To identify the **impact on flexibility provision for balancing by commercial parties** in the context of large-scale deployment of LV flexibility.

Introduction to Alexander Project:

- **UMONS contributions to the project:**

WP2 – Consumer barriers

✓ Modeling **collective user behavior** in **energy communities** in forms of:

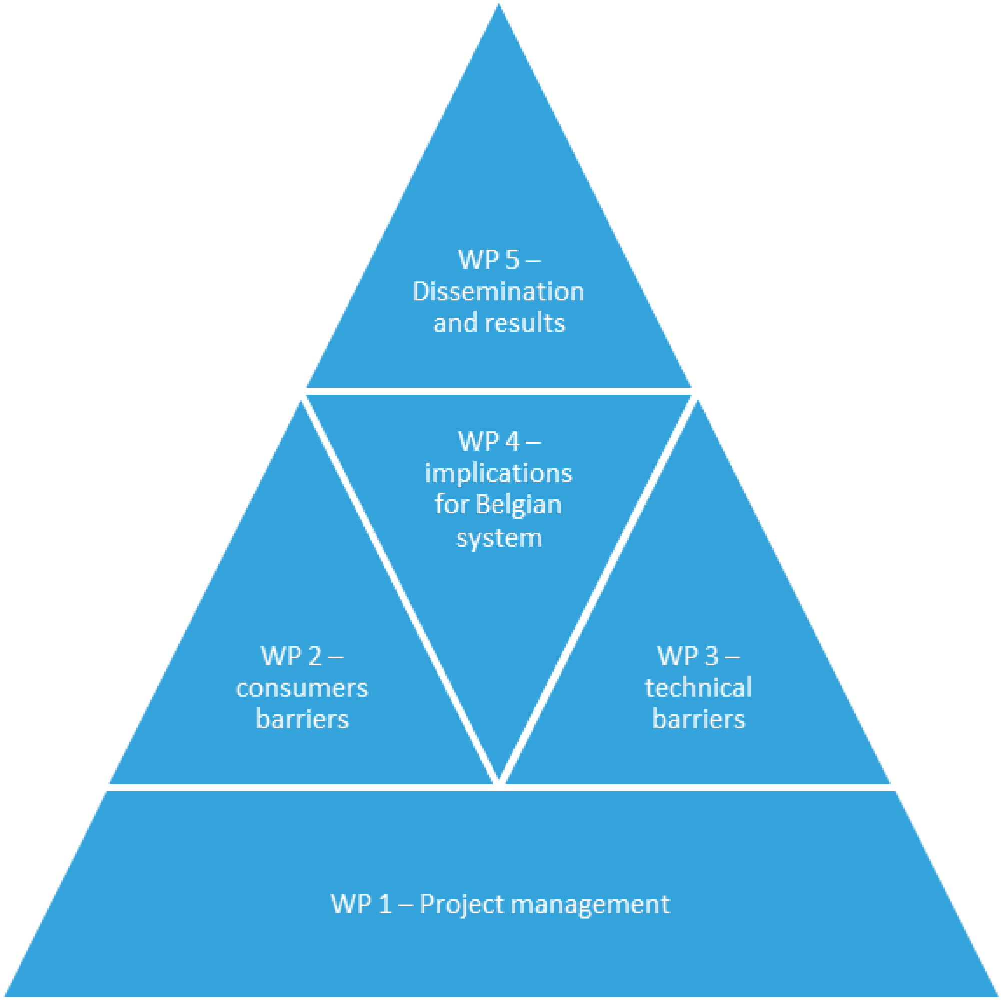
a) heterogeneous preferences including non-economic preference such as locality of supply, green energy provision, etc.
b) bounded rational behavior e.g., users do not optimally response to the price-signals.

Topic of the presentation

WP4 – Implications for Belgian system

✓ Exploring the potential of **energy communities** in providing **flexibility services**:

a) price-based strategies within local markets.
b) market-based strategies within national and local markets.



More info on project website:
https://alexander-project.vito.be

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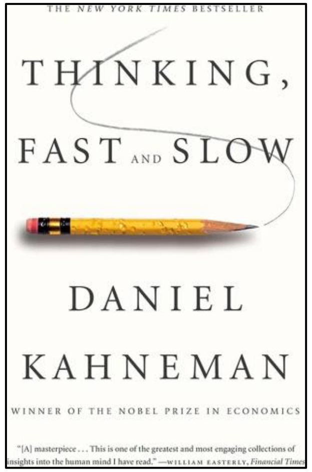
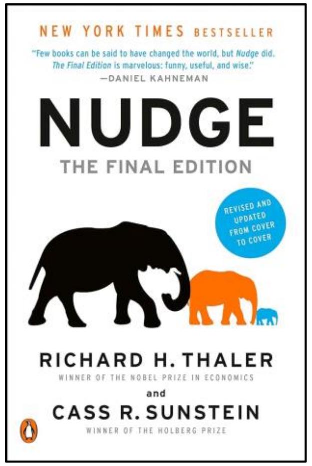
Definitions

- **What is rational behavior (in economics)?**
- According to rational choice theory, people consciously evaluate costs and gains in their decision-making process.

- **What is bounded rational behavior?**

- People face cognitive limitations in making optimal decisions, leading to decisions that may not be truly optimal but rather fall within the range of near-optimal choices.





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Definitions

- **Some paradigms of bounded rationality:**

- *Prospect theory:* Individual often overestimates the likelihood of rare events, especially when those events are associated with significant gains or losses. Therefore, individual strongly prefers to prevent potential losses rather than achieve potential gains, and thus shows **more willingness to take risks to prevent loss** than risks to achieve a profit.

- *Simplified choice strategies:* Individuals in many cases **do not perform assessment but intuitive judgment** based on simplified choice strategies (as result of choice overload phenomenon).

- *Limited observability:* (generally in two-player or bi-level framework) individual has **incomplete information about the other individual's strategies**, leading to a situation where they might make decisions aimed at avoiding potential losses.

- Other paradigms: *status-que biases*, *anchoring*, etc.

Pricing Challenges in Energy Communities

- Despite the importance of non-economic motivations such as environmental and altruistic values, recent studies indicate that financial benefits remain the primary motivation for end-users to join and participate in local energy communities in EU countries.

- To incentivize end-users, community managers (aggregators) offer competitive electricity prices compared to retail market prices.

- This opens a number of questions in the current electricity markets; we refer a few of them below:

i. *How to determine these competitive prices based on retail prices such that community members and aggregator benefit from the new pricing scheme?*

ii. *How grid costs should be paid by the end-users in the framework of energy community?*

iii. *And finally, what would be the responses of the members to the defined competitive prices?*

Use Case

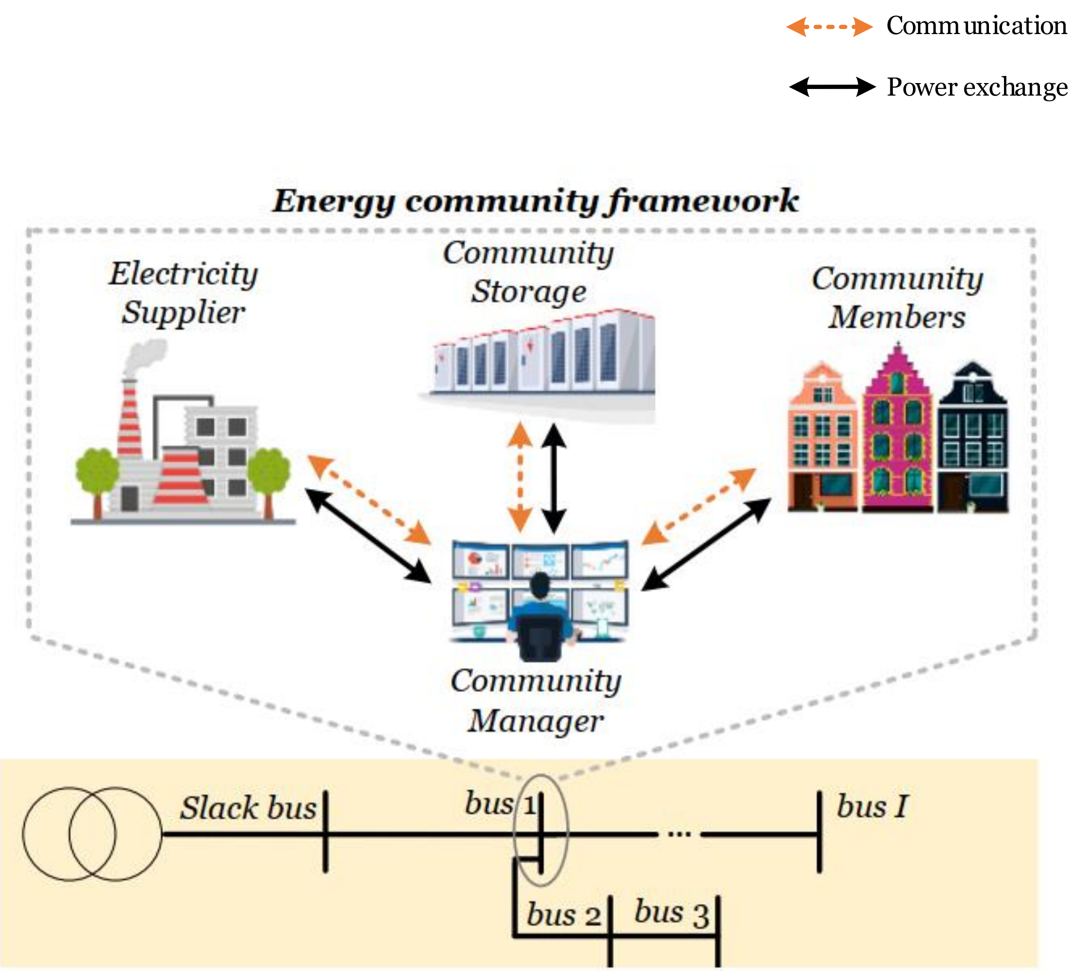
- **The use case comprises of:**

- A centralized energy community with 15 members at a node of 14-bus distribution network (dataset based on Flobecq (a city in Wallonia, Belgium) grid dataset).

- A community manager as a coordinator of the community.

- A community energy storage in service of local energy exchanges controlled by the community manager.

- An energy supplier for external energy exchanges.



-How to Determine Competitive Internal Electricity Prices?

- Community aggregator receives dynamic retail prices and implements an internal pricing mechanism, such that:

External buying price $\geq$ Internal buying price $\geq$ Internal selling price $\geq$ External selling price

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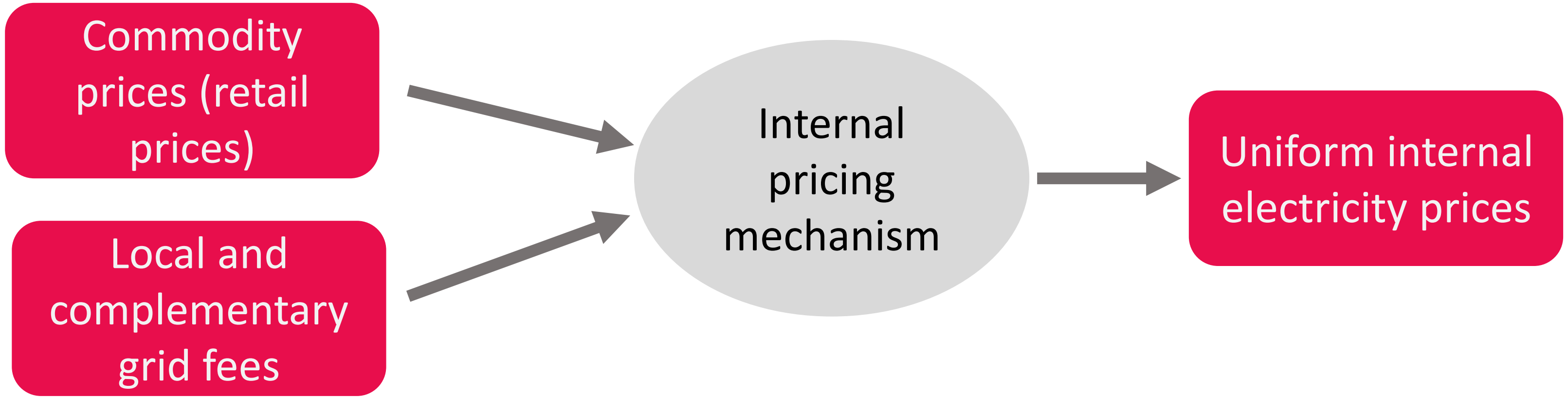
-How Members Pay for the Grid Costs?

- *Conventional scheme:* Users directly pay grid costs for the grid usage.

- *Discount incentivization:* Users pay less electricity for the local exchanges with local grid fees. They pay more for external exchanges with upstream suppliers with complementary grid fees. The scheme proposed by the BRUGEL, energy market regulator in Brussels (only for purchasing power).

- *Our Proposed Scheme:* The manager is responsible for community grid costs and members indirectly pay for local and complementary grid costs through uniform internal electricity prices (only for purchasing power).



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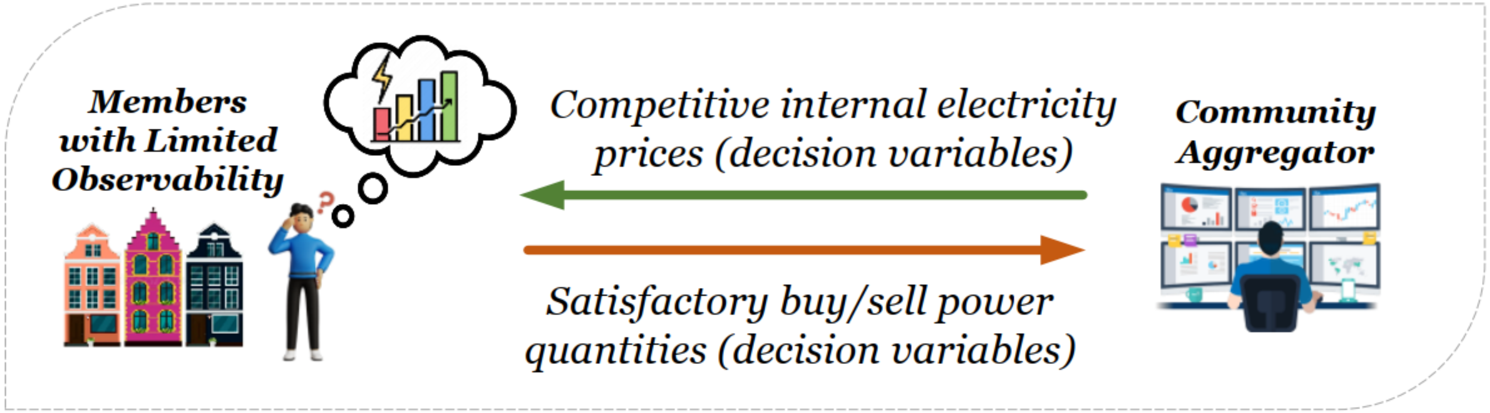
-What About Users Responses to the Internal Prices?

- *Rational Choice Theory:* When internal price signals are sent to users, it is expected they **optimally react** to those signals by their purchasing and selling power requests.

- *A paradigm of bounded rationality*: Users have **limited observability** over the strategies (internal **price signals**) of the community manager. Therefore, their response is not optimal rather "**satisfactory**".

- Why? Internal prices are impacted by the consumption behavior of members i.e., the more they consume, the higher the prices. Incomplete information about the real-time consumption behavior of other members leads to limited observability of price signals by users.



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Decision-Making under Decision Uncertainty

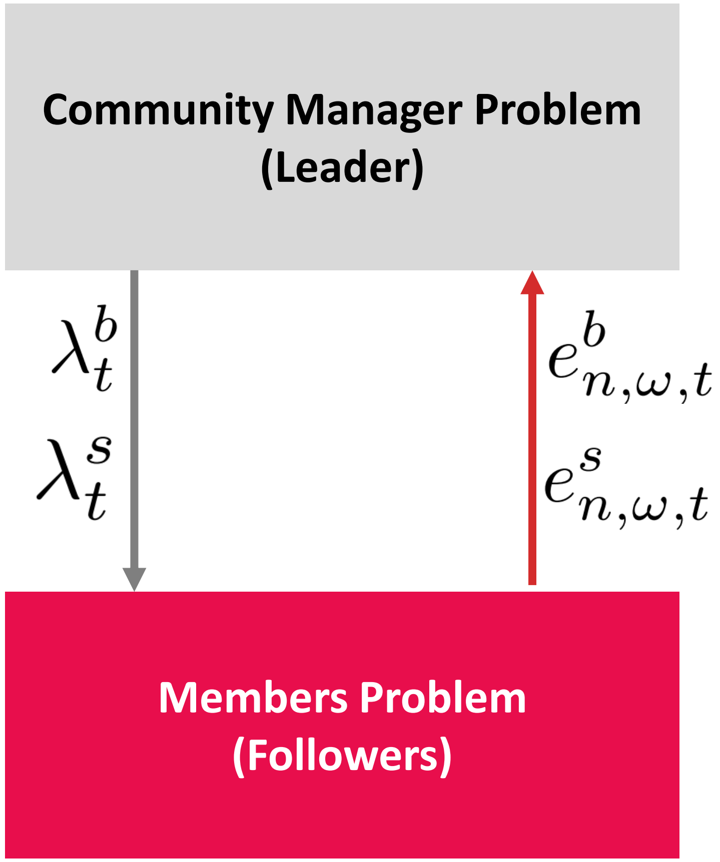
- Limited observability is a **source of uncertainty** in the decision-making process of members.

- Unlike data uncertainties such as PV generation or load demand uncertainties, limited observability is a sort of **decision uncertainty** because internal electricity prices are upper-level decisions and highly dependent to the actual load consumption of members (decision variable).

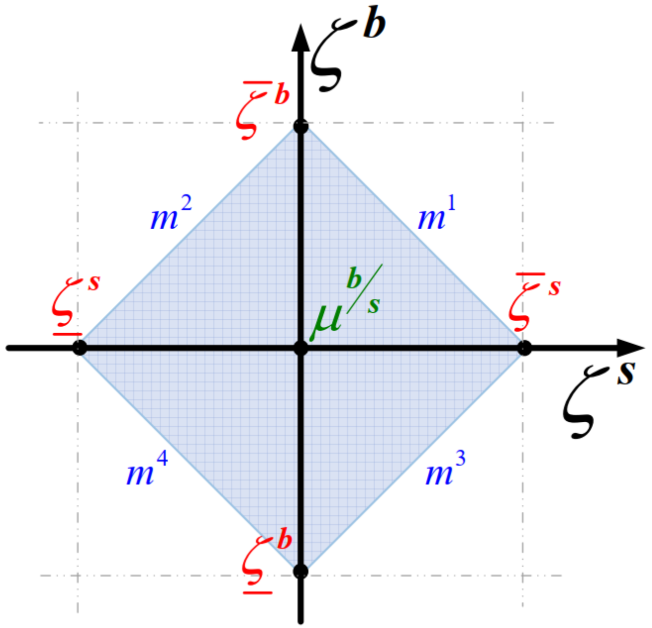
- We propose a strategy for members to hedge against the uncertainties caused by limited observability; the strategy is known to **near-optimality robustness** in operation research literature.

- The proposed method utilizes **robust optimization** toolbox in modeling conservative behavior of users over internal price variations.

-How Does It Look Like?



$$\mathcal{U}(\widetilde{\boldsymbol{\lambda}}) = \{\widetilde{\boldsymbol{\lambda}} = \boldsymbol{\lambda} + \boldsymbol{\zeta} : \boldsymbol{\zeta} \in \mathcal{Z} \subseteq \mathbb{R}^r\}$$



$$\hat{\alpha}_t^j \zeta_{n,\omega,t}^b + \hat{\beta}_t^j \zeta_{n,\omega,t}^s \geq \hat{\Theta}_t^j$$

$$\begin{pmatrix} \hat{\alpha}_t^1 & \hat{\alpha}_t^2 \\ \hat{\alpha}_t^3 & \hat{\alpha}_t^4 \end{pmatrix} = \begin{pmatrix} -1 & -1 \\ 1 & 1 \end{pmatrix}, \begin{pmatrix} \hat{\beta}_t^1 & \hat{\beta}_t^2 \\ \hat{\beta}_t^3 & \hat{\beta}_t^4 \end{pmatrix} = \begin{pmatrix} m_t^1 & m_t^2 \\ -m_t^3 & -m_t^4 \end{pmatrix}$$

$$, \begin{pmatrix} \hat{\Theta}_t^1 & \hat{\Theta}_t^2 \\ \hat{\Theta}_t^3 & \hat{\Theta}_t^4 \end{pmatrix} = \begin{pmatrix} m_t^1 \overline{\zeta}_t^s - \mu_t^b & m_t^2 \underline{\zeta}_t^s - \mu_t^b \\ -m_t^3 \overline{\zeta}_t^s + \mu_t^b & -m_t^4 \underline{\zeta}_t^s + \mu_t^b \end{pmatrix}$$

Solution Method

- Using Algorithm 1, we determine upper and lower boundary values of deviation variables.
- We can then use KKT conditions and strong duality theorem to reformulate the bilevel problem into a single-level problem.
- The final problem is a single-level MIQP problem with second-order cone programming (SOCP) constraints that can be solved using off-the-shelve solvers.

Algorithm 1: Delimitation of the internal prices perturbation ranges

Solve problem (1)-(2) for a full year $\rightarrow F^*, \Omega^{U*}, \Omega^{L*}$;
Compute, $\forall n \in \mathcal{N}$, the hourly cumulative distribution function (CDF) of consumption deviations from the target consumption, $x_{n,t} - \hat{x}_{n,t}$;
Initialize iteration index $i = 1$;
Initialize convergence criterion value $c = \inf$;
while $c > tol$ & $i \leq iter_{max}$ **do**
  for *each day of the year,* $d \in \mathcal{D}$ **do**
    for *each time period of the day,* $t \in \mathcal{T}$ **do**
      for *each member of the REC,* $n \in \mathcal{N}$ **do**
        Draw a random deviation sample from the CDF $\rightarrow \Delta x_n^t$;
        $\tilde{x}_n^t \leftarrow x_n^{t*} - \Delta x_n^t$;
        $\tilde{e}_{n,t}^b, \tilde{e}_{n,t}^s \leftarrow$ (2a);
      end
    end
    Compute the optimal real-time internal prices:
    $\tilde{\lambda}_t^s, \tilde{\lambda}_t^b \leftarrow \arg\min_{\tilde{\Omega}^U}(|\tilde{F}(\tilde{\Omega}^L) - F^*|)$ s.t. (1a)-(1y);
  end
  Compute the hourly PDF of deviations in internal electricity prices and define the perturbation range boundaries as 99^{th} and 1^{st} percentiles:
  $\zeta^{b/s} \leftarrow \tilde{\lambda}^{b/s} - \lambda^{b/s*}$;
  $\overline{\zeta}^{b/s}, \underline{\zeta}^{b/s} \leftarrow P_{99}(\zeta^{b/s}), P_1(\zeta^{b/s})$;
  if $i > 1$ **then**
    Update the convergence criterion value:
    $c \leftarrow \max(|\overline{\zeta}^i - \overline{\zeta}^{(i-1)}|, |\underline{\zeta}^i - \underline{\zeta}^{(i-1)}|)$;
  end
end

Case Studies

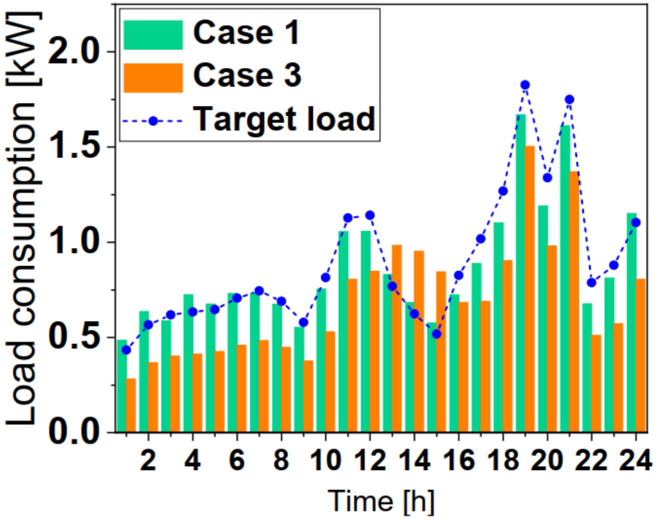
- Case 1: Deterministic bilevel problem + neglecting limited observability toward internal prices.
- Case 2: Stochastic bilevel problem + neglecting limited observability toward internal prices.
- Case 3: Deterministic bilevel problem + proposed method for mitigating limited observability toward internal prices.
- Case 4: Stochastic bilevel problem + proposed method for mitigating limited observability toward internal prices.

Results

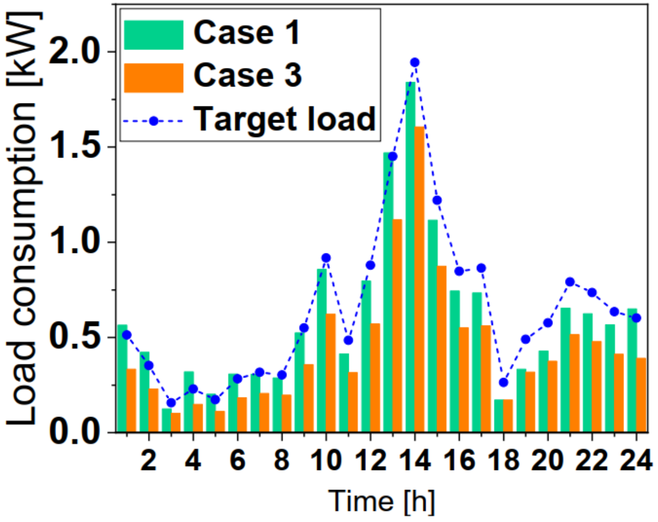
- **Consumption behavior of users under limited observability:**

✓ Lower consumption for both prosumers and consumers during most hours of the day.

✓ Increased self-consumption of PV prosumers.



prosumer

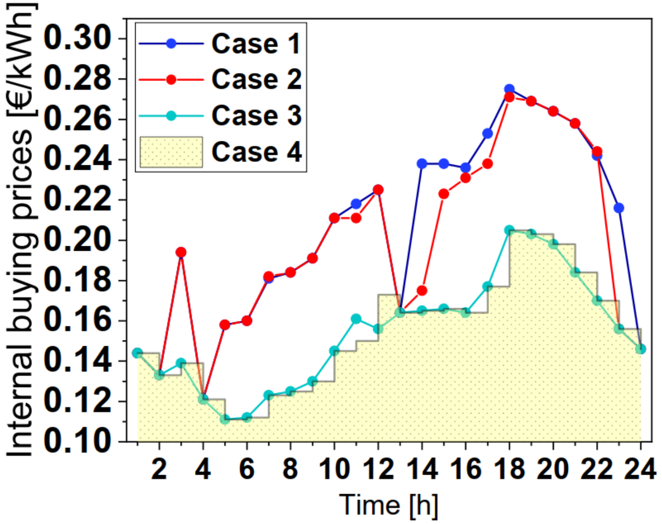


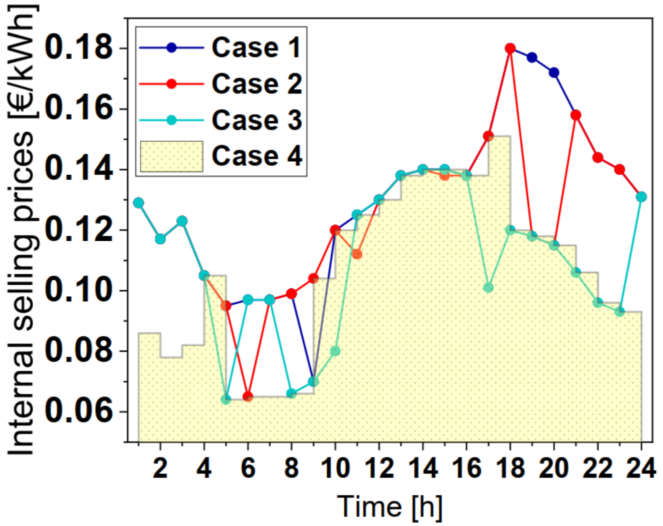
consumer

- **Internal electricity prices under limited observability:**

✓ Reduction in buying electricity prices.

✓ Despite reduction in selling power the selling prices were still competitive.





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Results

- **Social welfare of energy community:**

✓ Less load consumption (and more PV self-consumption) led to improved social welfare for users.

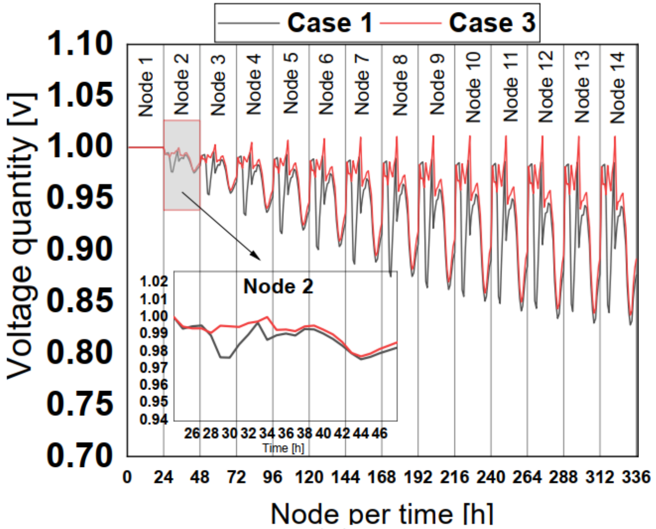
✓ A decrease in revenues of manager due to less selling/buying by the users.

- **Impact on network constraints:**

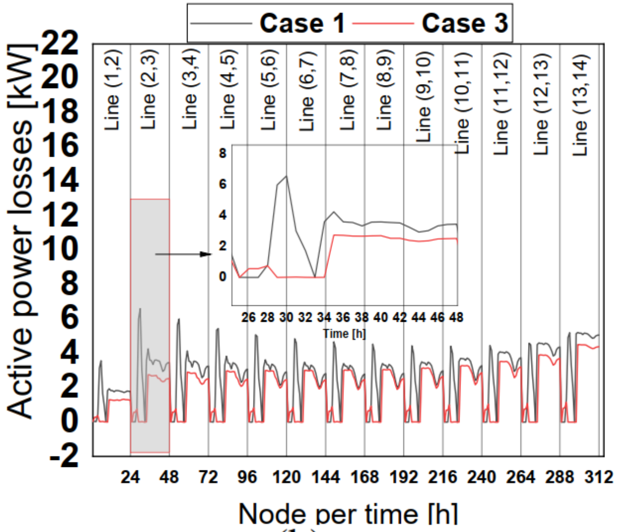
✓ Positive impacts on voltage (less voltage drops) and (less) active power losses.

Table I: Social welfare of the EC in different approaches.

User ID	Case 1 (€)	Case 2 (€)	Case 3 (€)	Case 4 (€)
P1	-0.37	-0.40	-0.37	-0.31
C2	-3.28	-3.09	-2.93	-2.93
P3	-3.32	-3.31	-3.13	-3.01
C4	-4.24	-4.11	-3.94	-3.94
P5	-2.45	-2.46	-2.39	-2.29
C6	-1.99	-1.92	-1.78	-1.78
P7	-1.60	-1.61	-1.46	-1.34
C8	-2.52	-2.46	-2.31	-2.33
P9	-3.38	-3.41	-3.10	-3.03
C10	-7.38	-7.17	-6.16	-6.16
P11	-4.50	-4.37	-3.78	-3.62
C12	-15.27	-14.91	-12.22	-12.23
P13	-12.49	-12.08	-10.23	-10.22
C14	-2.24	-2.07	-1.96	-1.96
P15	-2.71	-2.72	-2.60	-2.48
CM	-4.49	-6.11	-17.10	-17.70



(a)



(b)

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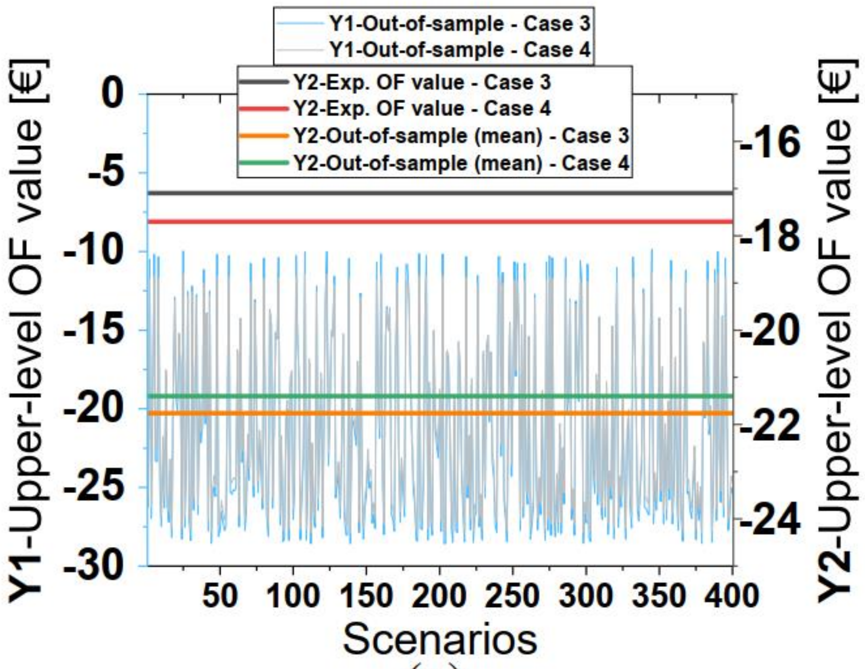
Results

- **Out-of-sample analysis on PV scenarios:**

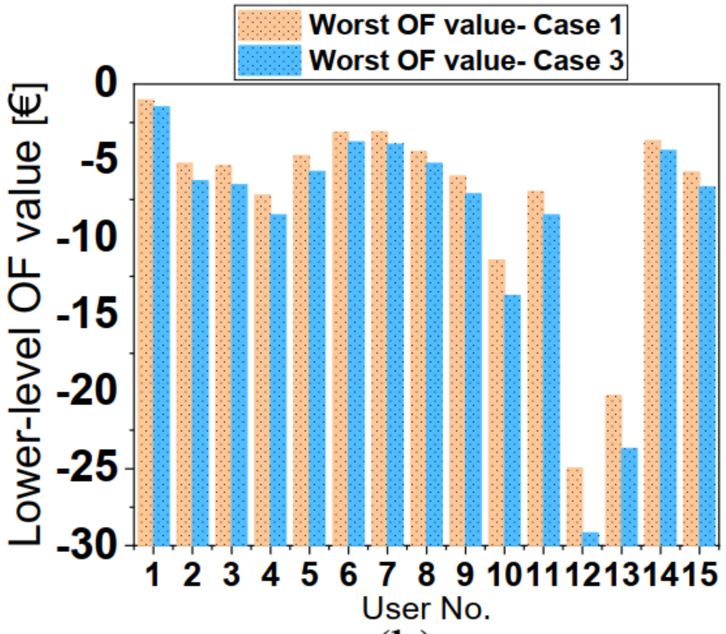
✓ When employing the stochastic method (Case 4), which considers scenarios close to real-world conditions, the objective function of manager shows improvement compared to the Case 3 approach.



(a)

- **Worst case analysis of internal prices :**

✓ Users are more robust against the deviations of internal prices based on the proposed model.



(b)

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Thank You!

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