System-friendly operation of smart energy communities

A hybrid agent-based modeling and bilevel optimization approach

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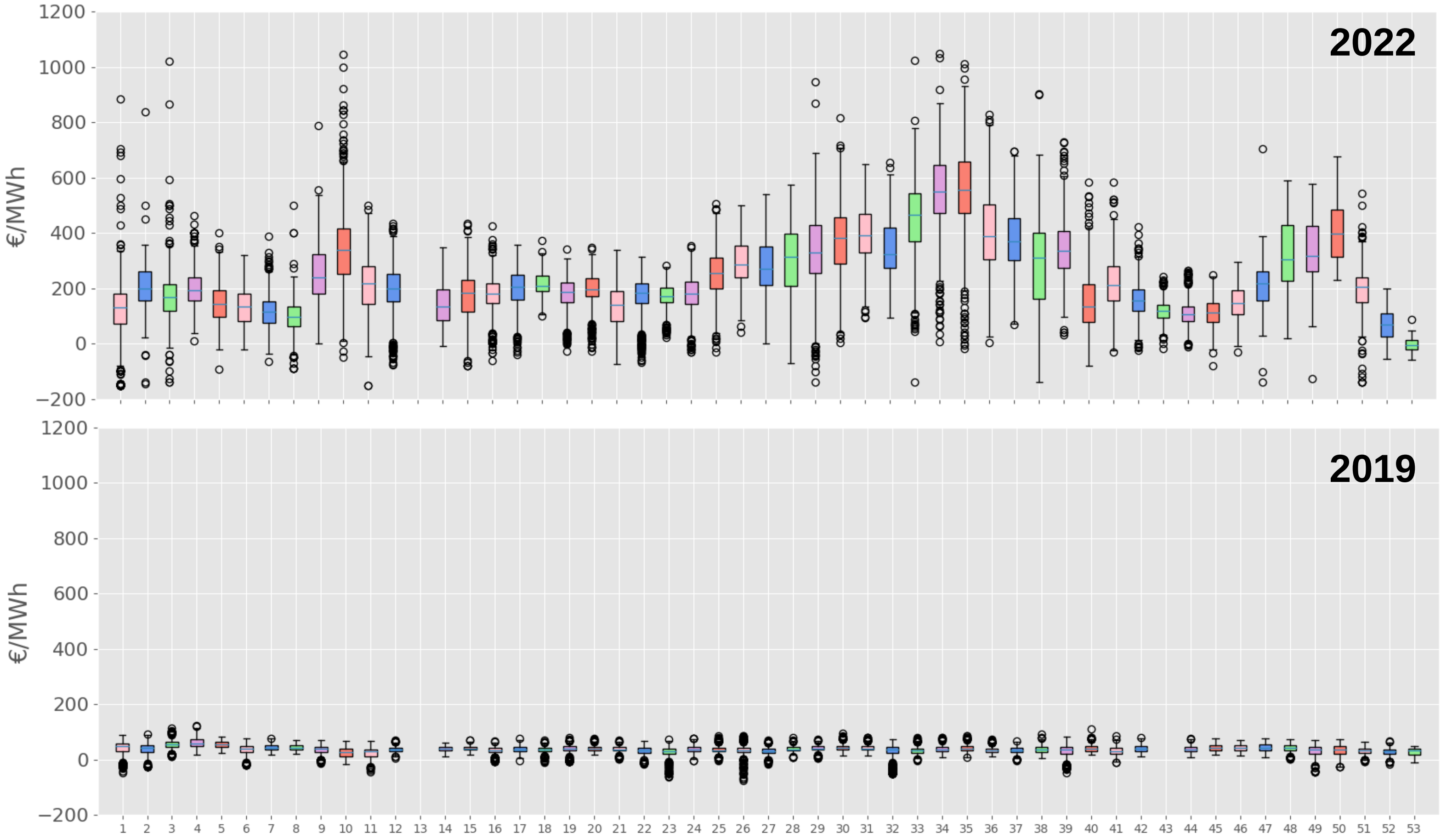
Motivation

- The operation of energy communities:
  - should be aligned with **market signals** of scarcity and excess.
  - respond the requirements of the **electricity grid**.
- Market volatilities incentivizes an operation aligned with market signals.

What are the benefits of the market-aligned operation of energy communities for the overall energy system?

Weekly fluctuation of day-ahead electricity prices in Germany [€/MWh]



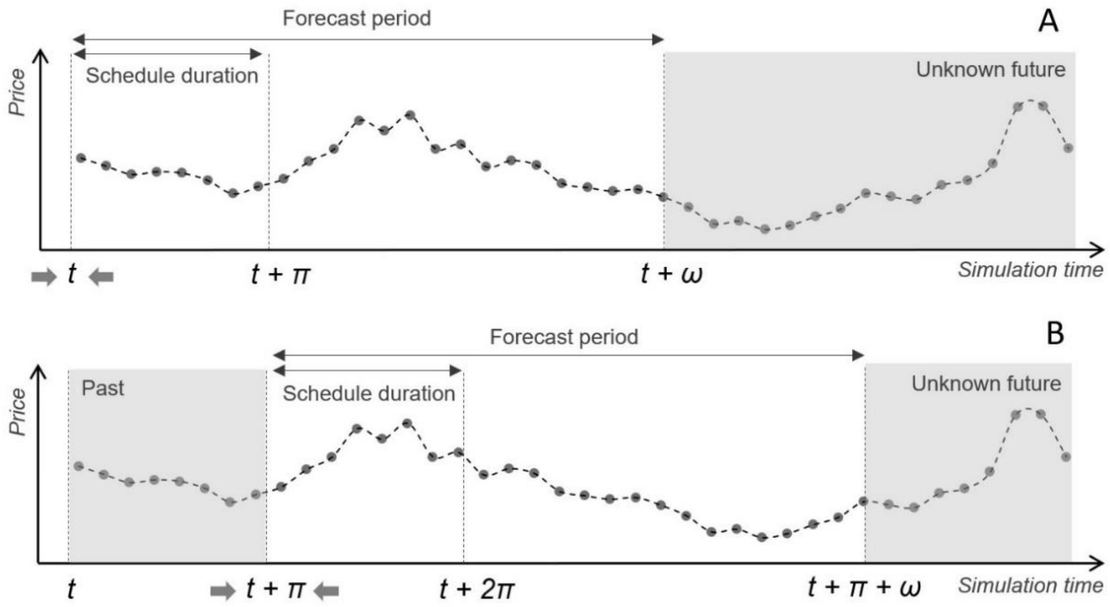
- Own representation based on the ENTSOE data
- For a better visualization prices above 1200 €/MWh are not shown.

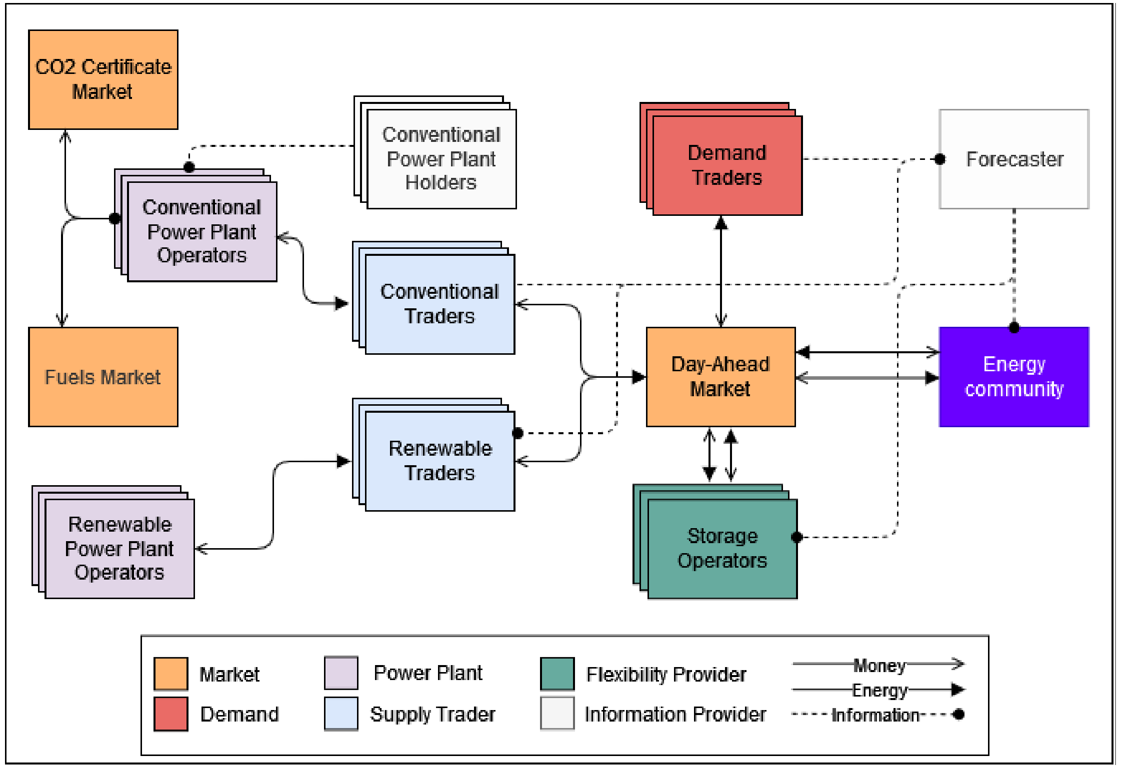
Methodology

Integration of energy community models in AMIRIS

AMIRIS:

- Open-source* agent-based model of the energy-only-market
- Market simulation based on the merit-order principle
- Actor behavior under a certain regulatory framework
- Rolling horizon optimization of the flexibility options.





AMIRIS in this analysis:

- German electricity market – One market zone
- No capacity expansion calculations
- Conventional power plants bid at their marginal costs
- No feed-in incentives for renewables

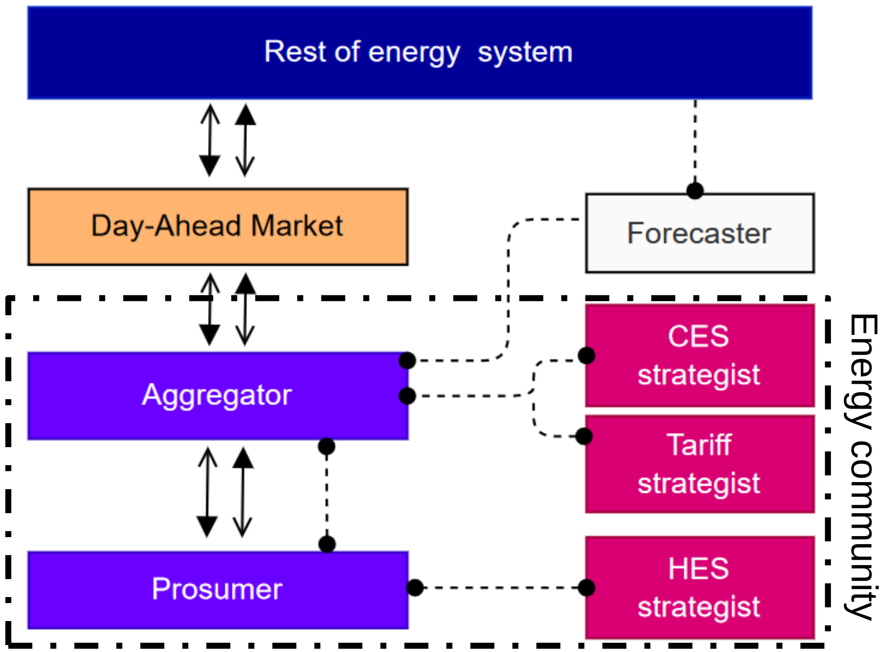
* The model developments in this study is not yet part of the open-source publication.

Methodology

Integration of energy community models in AMIRIS

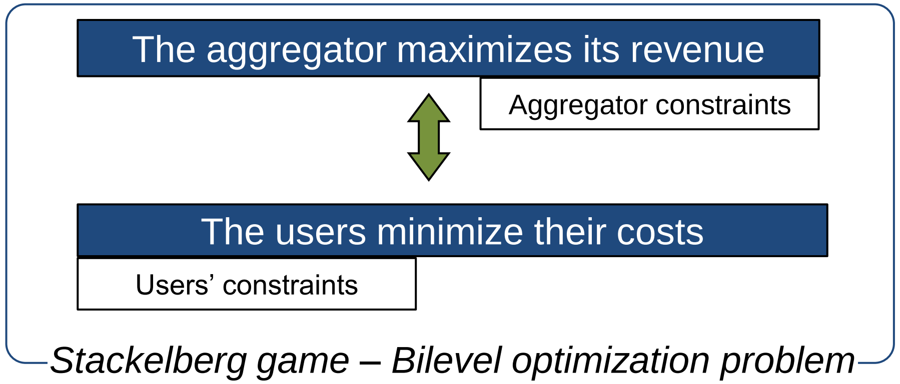
- Different energy community use-cases are defined based on the **storage operator**, **electricity tariff**, and storage optimization **goal**.

Use-case	Model	Storage	Electricity tariff	Goal
No storage	-	-	SP	-
CES-A	Single-level optimization	CES	SP	Autarky
CES-P	Single-level optimization	CES	SP	Profit
SP	Single-level optimization	HES	SP	Profit
ORTP	Bilevel optimization	HES	ORTP	Profit



ORTP problem formulation*:

- Single-level reduction by rewriting the lower-level problem using the Karush-Kuhn-Tucker optimality conditions and applying the strong duality theorem.
- Mixed-integer formulation through discretization of continuous variables and by using the big M technique.



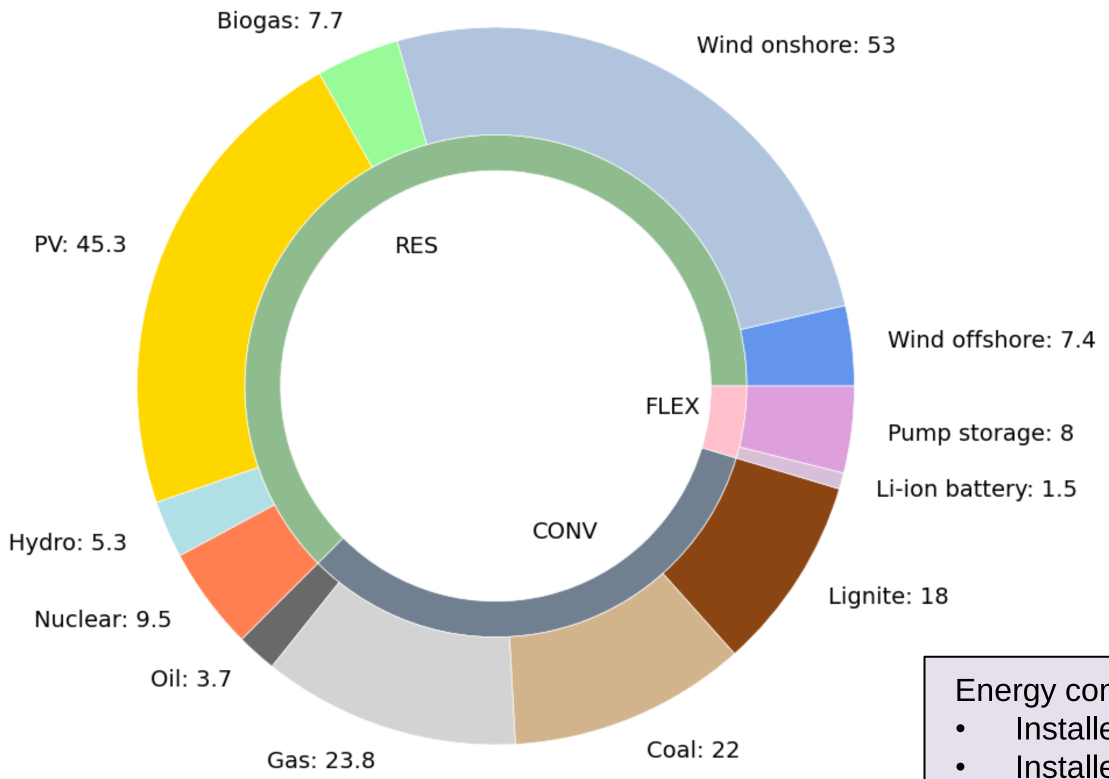
* Sarfarazi, Seyedfarzad, et al. "An optimal real-time pricing strategy for aggregating distributed generation and battery storage systems in energy communities: A stochastic bilevel optimization approach." International Journal of Electrical Power & Energy Systems 147 (2023): 108770.

Energy system scenarios

How do use-cases perform in a status quo and future energy system?

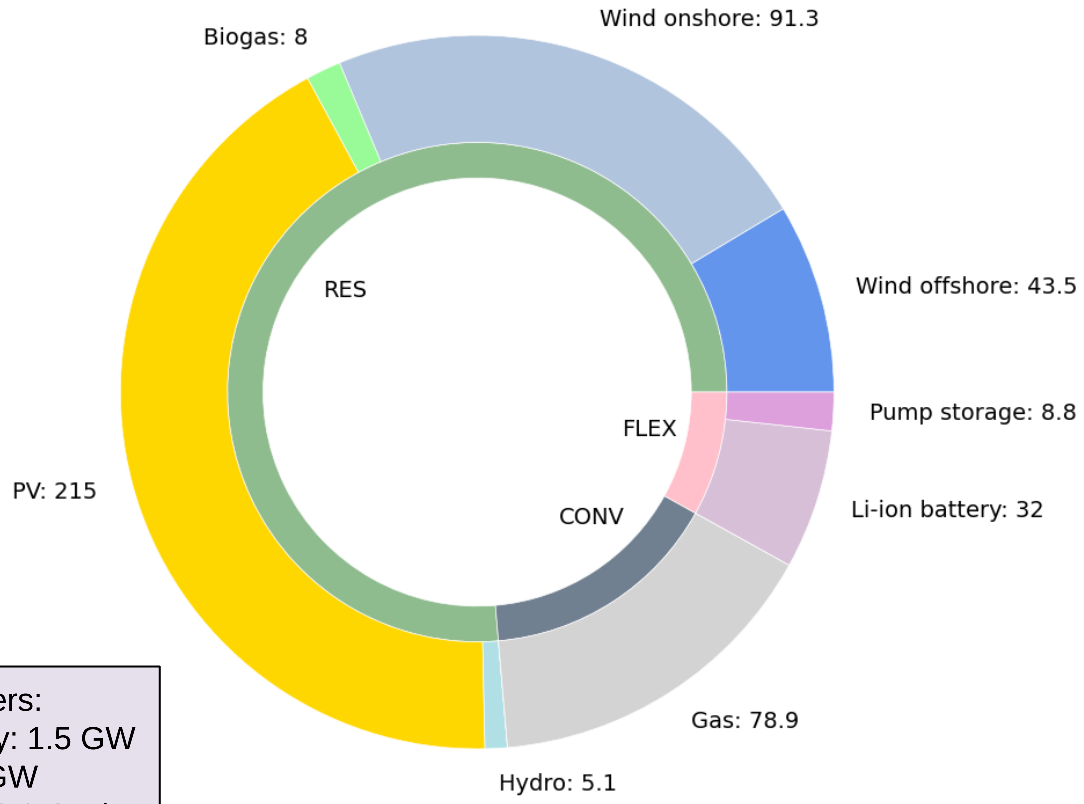
Status quo scenario

Based on German energy system in 2019



Future scenario

*Calculated by the energy system optimization model REMix for the year 2030**



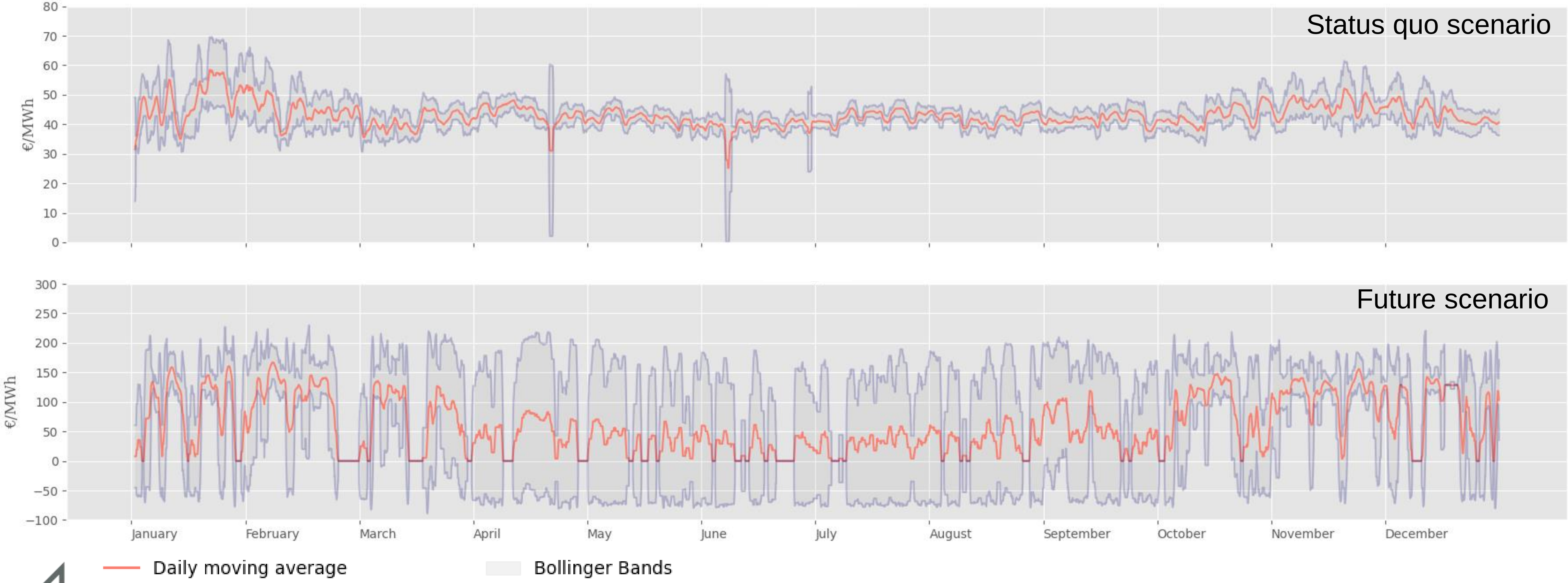
Energy community parameters:

- Installed battery capacity: 1.5 GW
- Installed PV system: 3 GW
- Average daily demand: 6.2 GWh

* Assumptions are made based on the Agora study „Klimaneutrales Stromsystem 2035“

Results
Market prices in energy system scenarios

Indicator	Status quo scenario	Future scenario
Share of renewables [-]	42%	82%
Operational system costs [B€]	9.228	14.004
Curtailed renewable generation [GWh]	0.9	92609.3

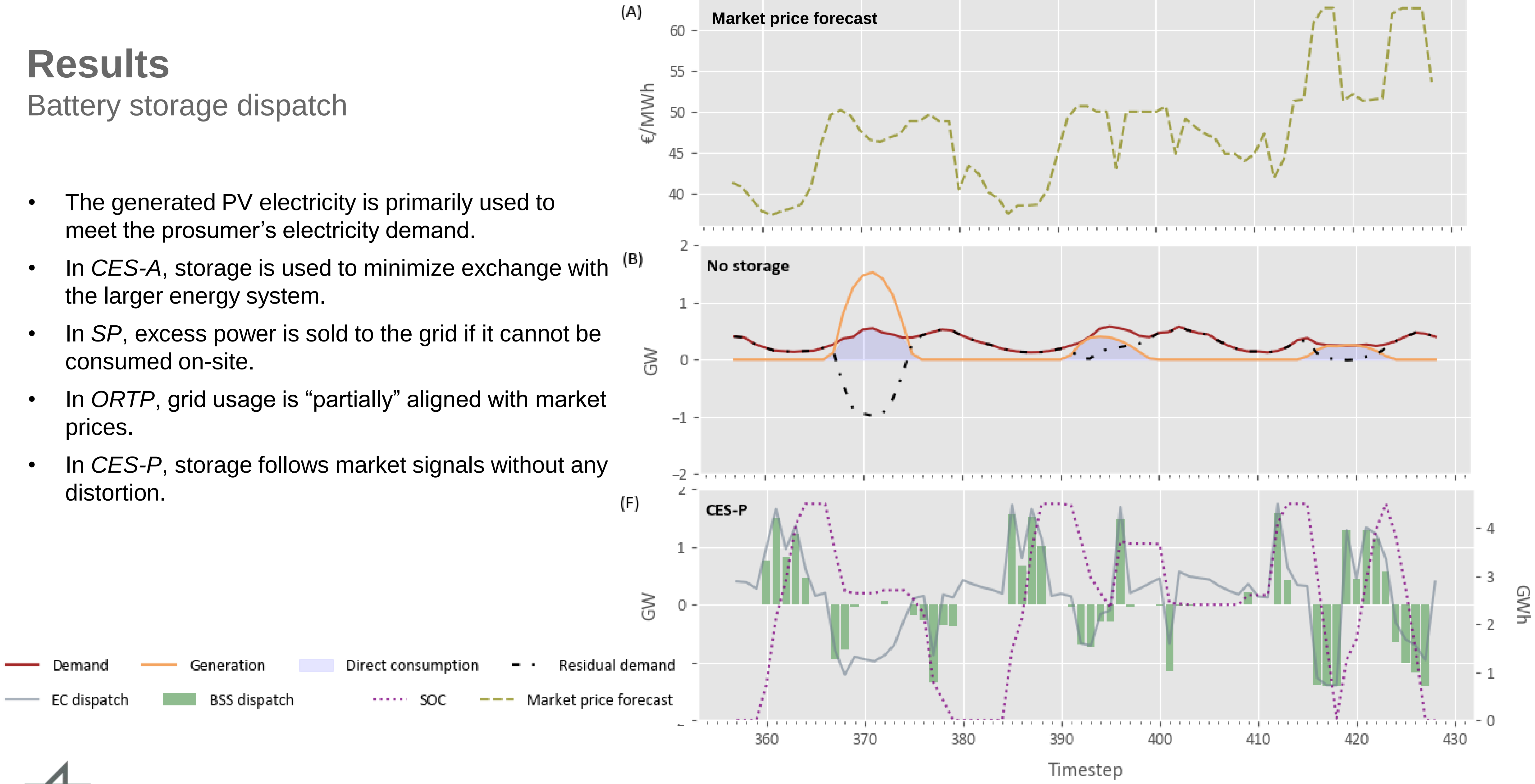


Results

Battery storage dispatch

- The generated PV electricity is primarily used to meet the prosumer’s electricity demand.
- In *CES-A*, storage is used to minimize exchange with the larger energy system.
- In *SP*, excess power is sold to the grid if it cannot be consumed on-site.
- In *ORTP*, grid usage is “partially” aligned with market prices.
- In *CES-P*, storage follows market signals without any distortion.

Status quo scenario, No regulatory induced charges



Results

Interaction with the larger energy system and community welfare

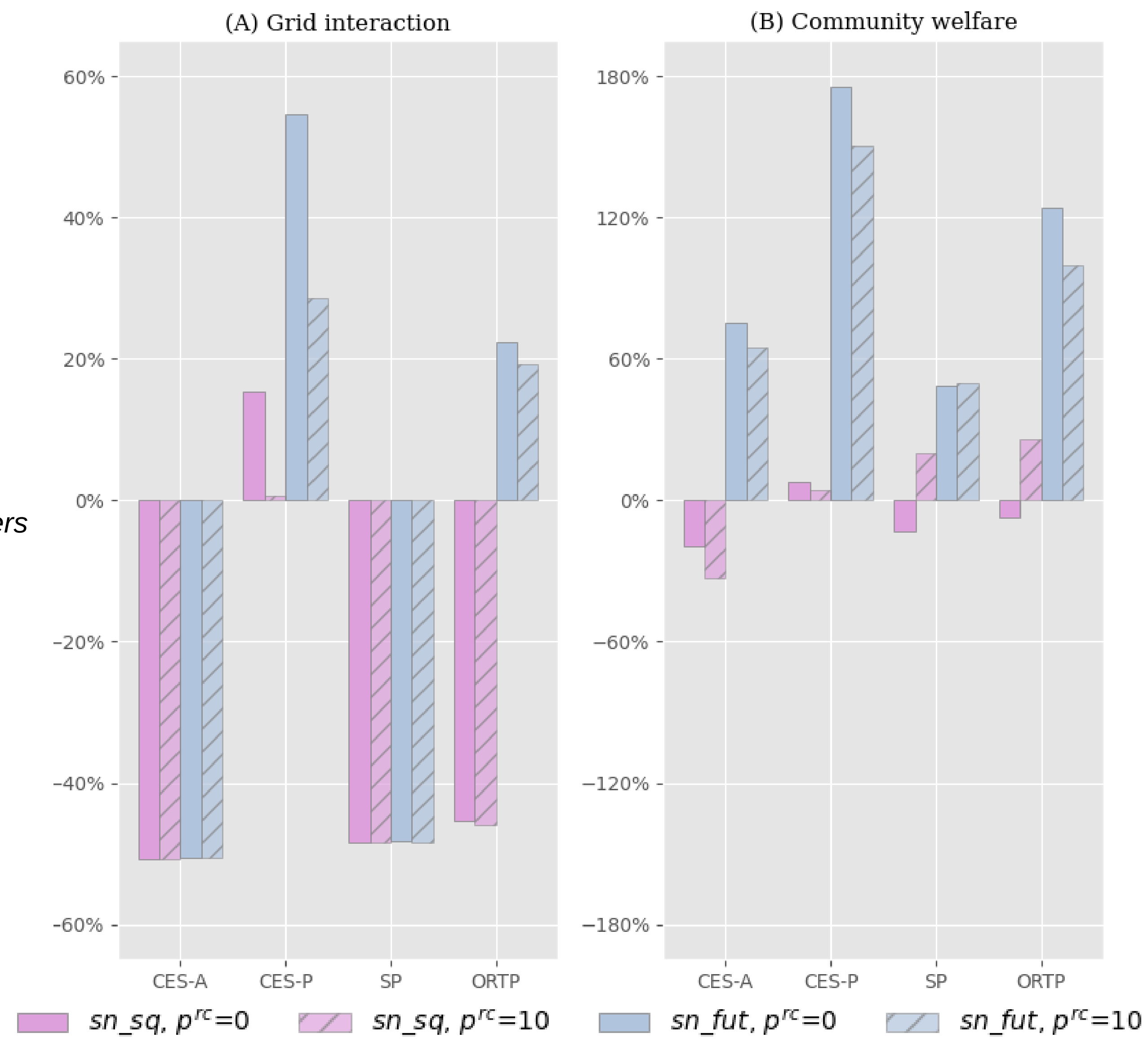
Grid interaction → *Annual electricity usage and feed-in*

- *SP* and *CES-A:* independent from regulatory charges and scenario.
- *ORTP*: Contrary behavior depending on the scenario.
- *CES-P:* Significantly higher exchange with the market.

Community welfare → *Aggregated profit of the aggregator and prosumers*

- Generally higher in Future scenario.
- Efficient market trading in case of market-aligned optimization.
- Regulatory induced charges:
  - inefficient market trading.
  - saving potential with behind-the-meter self-consumption

Relative results compared to "No storage" case

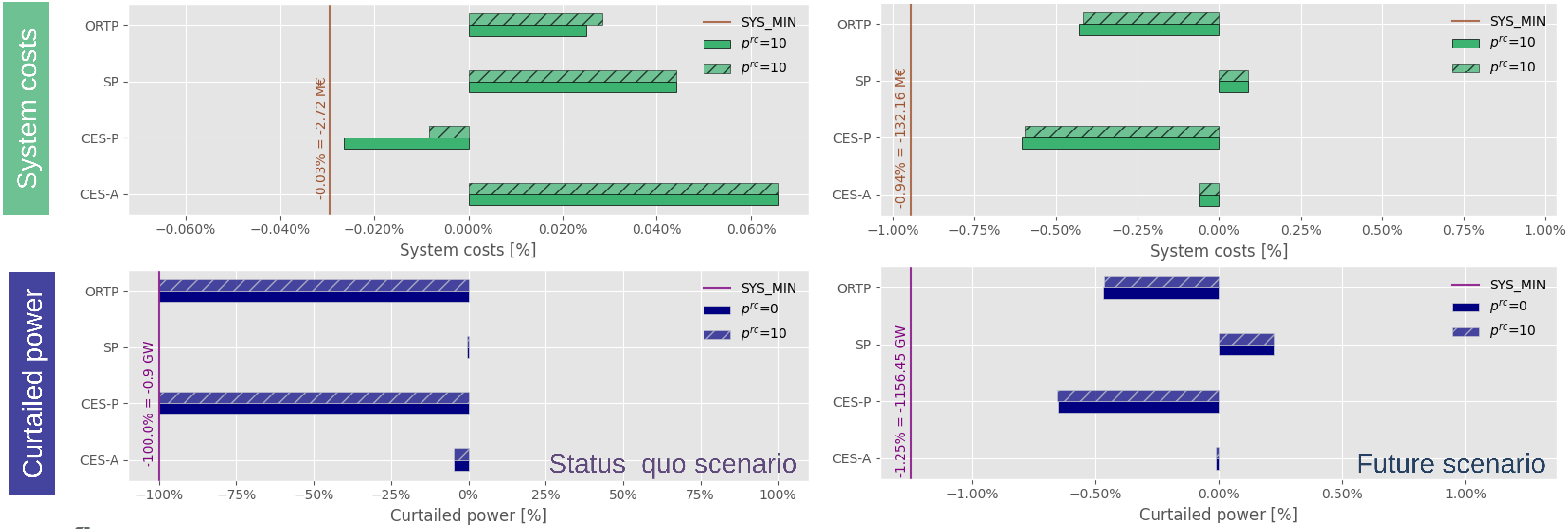


Results

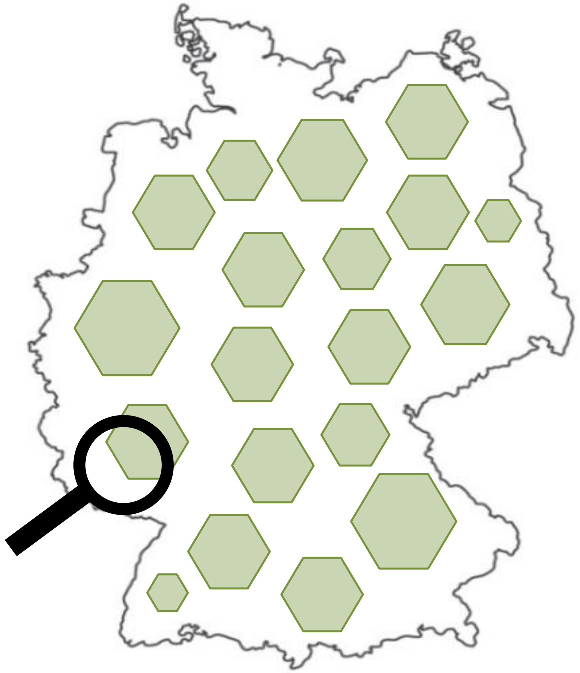
System costs and power generation curtailment

- More significant contributions in Future scenario.
- Inefficient usage of storage flexibility in *SP* and *CES-A.*
- *CES-P* shows the most efficient performance → yet not as good as the system cost minimizing storage.

- Contrary system effects of *ORTP* due to high price fluctuations in Future scenario.



Limitations



- Energy community:
    - Neglecting the **heterogeneity of actors** in the energy community.
    - **Welfare distribution** inside the energy community is not considered.
    - Focus solely on **load shifting** potential with battery storage systems.
- Overall system:
    - Consideration of the energy community as the **only flexibility option** in system.

Key take-aways

- High volatility in the power market incentivizes investment and efficient operation of storage systems.
- Autarky orientation of energy communities doesn‘t allow the full exploitation of the storage potential.
- Optimized electricity tariffs for energy communities benefits both the overall energy system and the energy community.
- Assumption of system cost minimizing operation of storage systems can lead to underestimation the required flexibility in future energy system.

Thanks for your attention!

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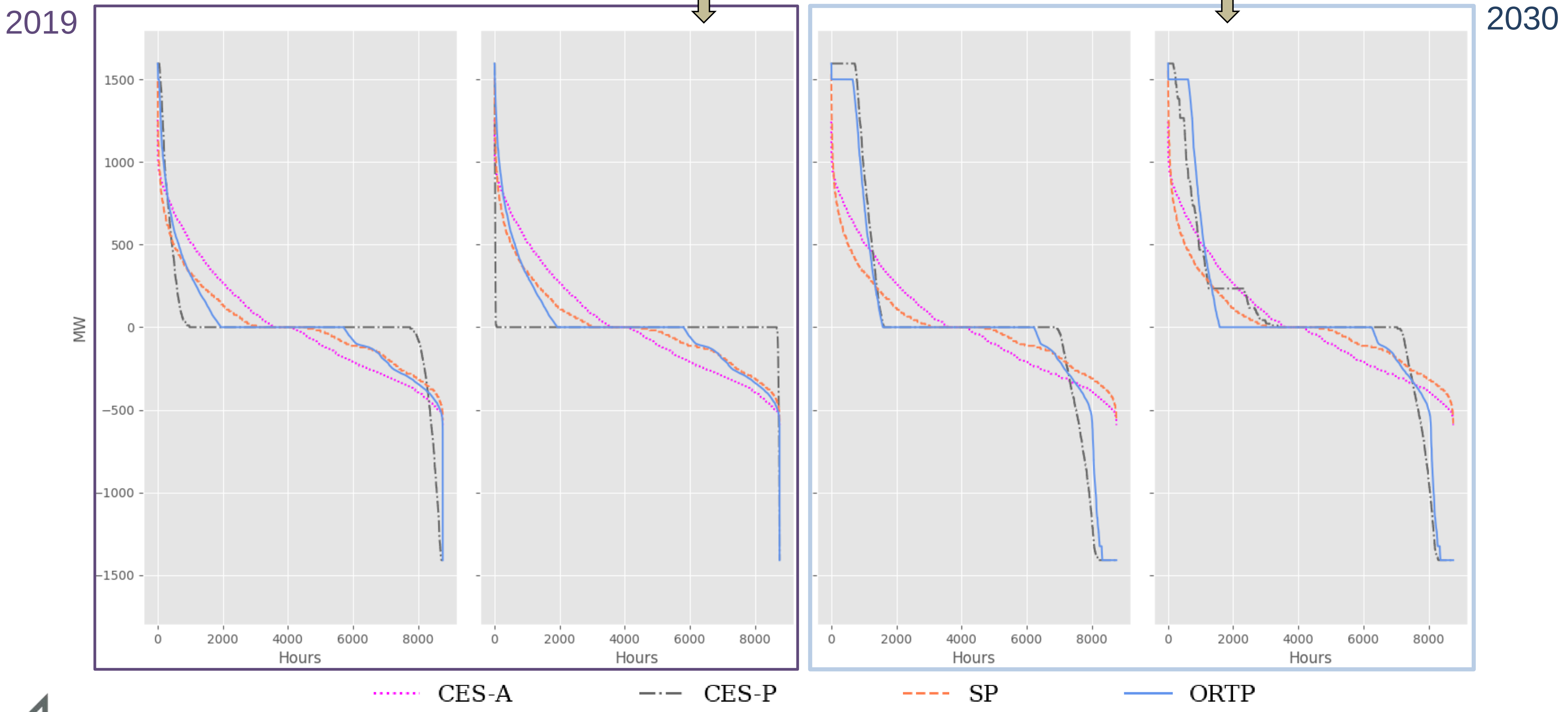
Results

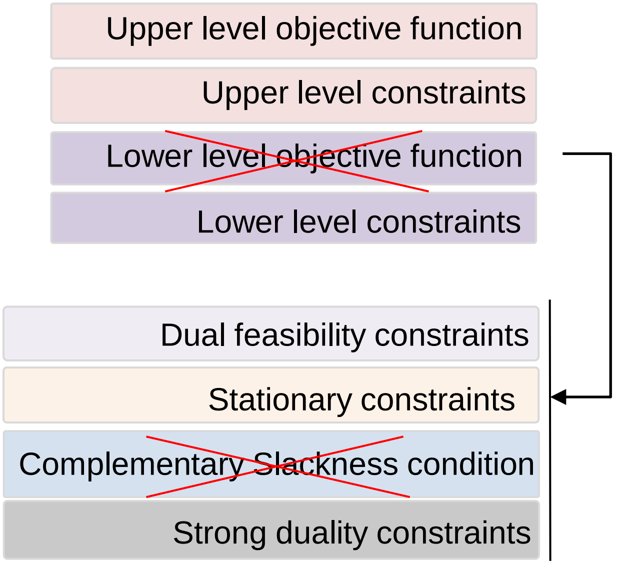
BSS dispatch – duration curve

Regulatory induced charges = 10 cents/kWh



Bilevel optimization problem

Problem reformulation



- Since the lower level is a linear problem, it can be represented by **Karush-Kuhn-Tucker (KKT) optimality condition**.
- The complementary slackness conditions consist of many bilinear terms. It can be therefore replaced by **strong duality theorem**.

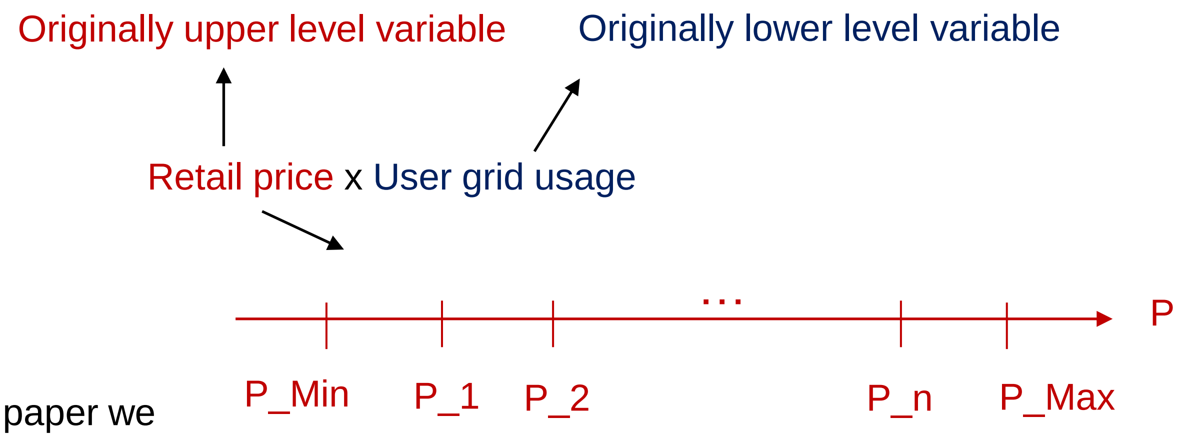
→ a single ***non-linear*** *optimization problem* → Cannot be solved efficiently

- We discretize one of the variables to eliminate the non-linearity
- We use binary variables to force the solver to adopt discrete values (Big M approach)

→ *Mixed Integer Linear Problem*

↓

Can be solved with commercial solvers like CPLEX



- To increase the efficiency of the optimization even further, in our paper we propose a novel solution that applies a linear quasi-relaxation approach.