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Impact of network charge mechanisms on consumers, prosumers, and the energy system

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ENERGY, COVID, AND CLIMATE CHANGE

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Overview

Prosumers will play a major role in the transformation of the energy system – and impact the system as active market participants

- Transformation of our energy system towards zero net CO_2 emissions involves **distributed PV + battery** systems, operated by prosumers as active market participants.
- In principle, three prototypical battery operation modes possible:

1) Batteries can operate for **individual profit maximization** of the local operator, depending on the regulatory framework. This often equals self-consumption maximization; scope of analysis: n = one household.

2) Batteries can operate (distribution) **network-beneficially**, reducing peak-coincident network utilization; scope of analysis: n = tens to hundreds of households.

3) Batteries can operate **market-beneficially** to leverage portfolio effects for optimal renewable energy integration at the wholesale market (system) level; scope of analysis: n = thousands to millions of households.

Overview

Research question of this study

?

In what way do different network cost allocation schemes provide incentives for different battery operation modes, leading to

- different household energy bills (individual level),
- different utilizations of the distribution network (local level),
- and, ultimately, different system costs (global level)

Gliederung

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Methods

Workflow of analysis

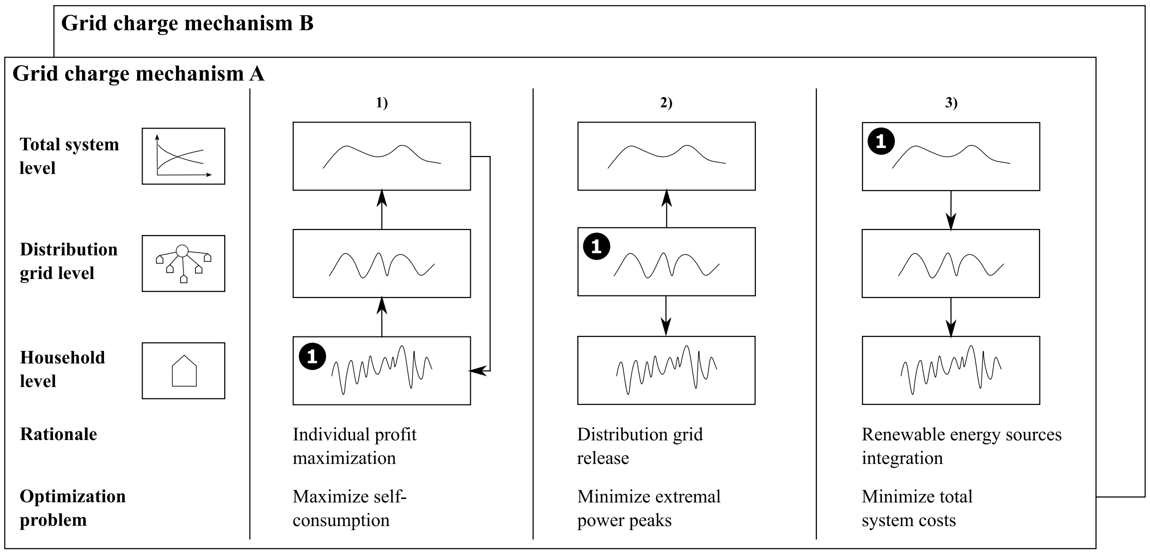


Figure 1: Workflow of analysis; circled "1" denotes technical starting point of analysis (first step in model chain), corresponding to the respective battery operation mode (1, 2, or 3).

Closed-loop analysis of prosumer impacts at different levels of aggrgation, namely

- **Individual impacts**: Full costs of electricity (FCOE)
- **Local impacts**: Distribution network capacity utilization
- **Global impacts**: Total system costs

Methods

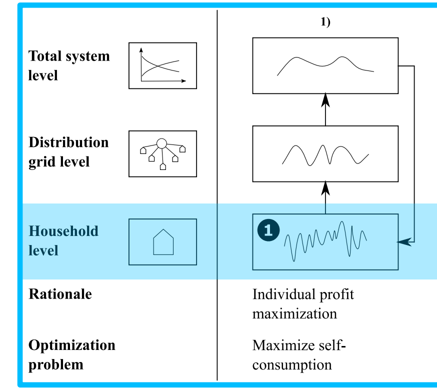
Overview of analyzed battery operating modes and network cost allocation schemes

	Volumetric network charges (VNC)	**Peak capacity charges, [5]** (PCC)
Battery Operation Mode 1: *Maximize self-consumption*		
Battery Operation Mode 2: *Minimize network capacity utilization*		
Battery Operation Mode 3: *Minimize total system costs*		

Table 1: Analyzed combinations of battery operation modes and network cost allocation schemes.

A) Battery Operation Mode 1

Battery operation



Chronological charging

- Predetermined prosumer heuristic maximizes self-consumption

Algorithm: Try 1); if not possibly, then try 2); …

In case of positive prosumer PV production:

1) Self-consume electricity directly.
2) Store surplus PV electricity into battery storage.
3) Feed surplus electricity into public grid, $fi(t_n)$

Other:

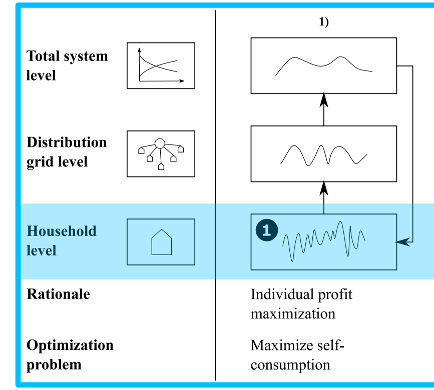
1) Discharge battery storage to cover electricity demand
2) Withdraw electricity from public grid, $gs(t_n)$

Output: **Prosumer residual load**

$$RL(t_n) = gs(t_n) - fi(t_n)$$

A) Battery Operation Mode 1

Full costs of electricity (FCOE)



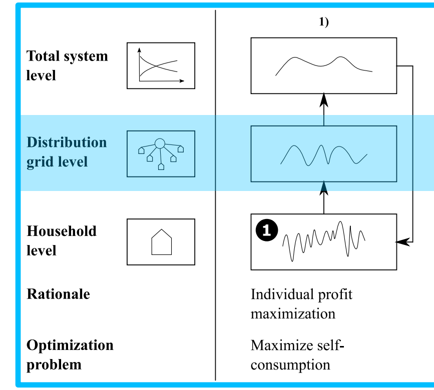
- Analysis of the full costs of electricity, containing annualized PV and battery investment costs, the wholesale market costs, and network charges

$$FCOE = \underbrace{c_{inv} \cdot x_{inv}}_{investment\ \ costs} + \underbrace{\bar{\lambda} \cdot (GS - MVF \cdot FI)}_{(wholesale)\ market\ costs} + \underbrace{f(\dots) \cdot c_{network}}_{network\ charges}$$

- λ: wholesale market price; here: 150 EUR/MWh
- GS: Annual grid supply, i.e., annual amount of electricity withdrawn from the grid
- MVF: (PV) market value factor (50%)
- FI: Annul feed-in
- $f(\dots)$: Functional dependency of network charges with either volume or capacity
- $c_{network}$: Specific network charges

A) Battery Operation Mode 1

Gaussian smoothing



- Calculation of residual load on network node under consideration of **simultaneity effects** ….

$$\widehat{RL}(t_0) = \int_{-\infty}^{\infty} RL(t) \cdot \frac{1}{\sqrt{2\pi\sigma^2}} \cdot e^{-\frac{(t-t_0)^2}{2\sigma^2}} dt$$

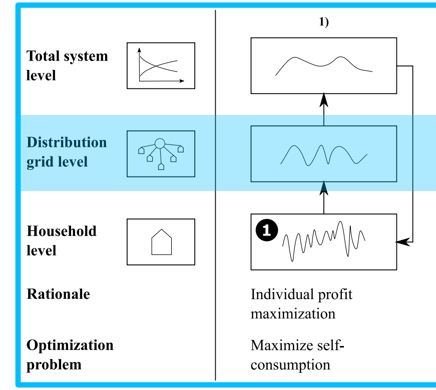
- … and **superposition** of prosumer and consumer residual loads:

$$RL_{Node}(t) = n \cdot \left(\rho \cdot \widehat{RL}(t)_{Pros} \cdot (1-\rho) \cdot \widehat{RL}(t)_{Cons}\right)$$

- In the following: ρ = 75% as prosumer penetration ratio, σ = 7 (distribution network level).

A) Battery Operation Mode 1

Consideration of simultaneity effects



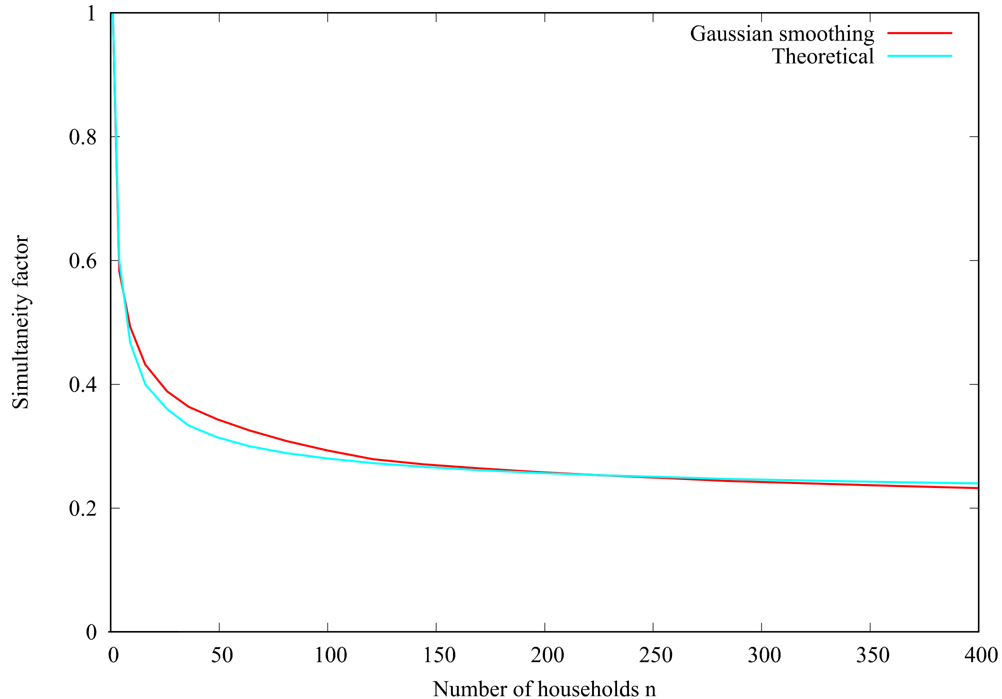


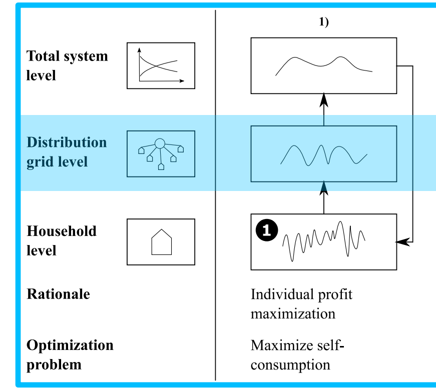
Figure 2: Simultaneity factor resulting from Gaussian smoothing versus theoretical simultaneity factor (g_∞ = 0.20).

- Gaussian smoothing is in asymptotical accordance with theoretical functional dependency of simultaneity factor, [7]:

$$g(n) = g_\infty + (1 - g_\infty) \cdot \frac{1}{\sqrt{n}}$$

A) Battery Operation Mode 1

Network charges – definition of *f(…)*



Volumetric network charges (VNC)

$$VNC = GS \cdot c_{network}^{vol}$$

- $c_{network}^{vol}$: Specific volumetric network charges [EUR/kWh]; here: 50 EUR/MWh
- GS : Annual grid supply [kWh]

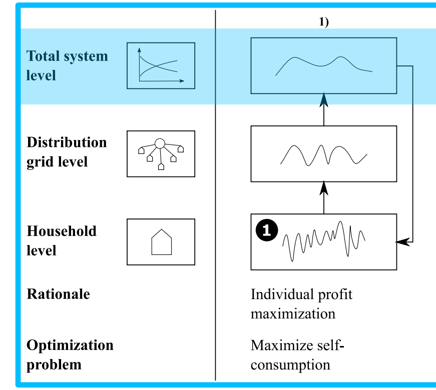
Peak-coincident capacity charges (PCC), [5]

$$PCC = \overline{RL^{peak}} \cdot c_{network}^{peak} + C_{network}^{per\ customer}$$

- $\overline{RL^{peak}}$: Prosumer/consumer residual load [kW] as average over top 30 residual power peaks at distribution grid node
- $c_{network}^{peak}$: Specific capacity charges [EUR/kW]; here: 100 EUR/kW
- $C_{network}^{per\ customer}$: Fixed network charge per customer compensating for the residuum between total network costs and refinancing carried out through capacity charges [EUR/p.c.]

A) Battery Operation Mode 1

System analysis



- Application of a fundamental linear optimization model of the European electricity market, the European Electricity Market Model, E2M2, [8]
- Model structure and parameter setting (cost vector c^T and decision variable vector x) as in [4]

$$\min_{x \in \mathbb{R}_+^n} C_{sys}^{total} = \min_{x \in \mathbb{R}_+^n} c^T \cdot x$$

- Aggregated (and further smoothed) residual load enters system model as exogenous time series
- Model depicts several characteristics of electricity market, such as load coverage, system adequacy, and RES investment paths

B) Battery Operation Mode 2

Reduction of peak capacity network utilization

Objective function

$$SC = D_{Pros} - \sum_t gs(t) \rightarrow \text{max}$$

- Actual battery operation mode is adjusted to reduce peak-coincident network utilization
- For this purpose, battery operation is formulated as linear optimization problem

Restrictions

- Load coverage
- Capacity (power) and storage constraints
- Peak capacity restrictions for aggregated residual load at node

$$gs(t_n) \cdot \rho + d_{Cons}(t_n) \cdot (1 - \rho) \leq UpperBound_i \quad \forall\, t_n \in T$$
$$fi(t_n) \cdot \rho \leq UpperBound_{\,i} \quad \forall\, t_n \in T$$

- Output: Residual load of prosumer, following steps as for Battery Operation Mode 1

C) Battery Operation Mode 3

Minimization of total system costs

- Analysis begins with minimization of total system costs
- Battery operation is left as degree of freedom for the system
- Actual battery operation is endogenous result of the system optimization
- Output: Prosumer residual load profile (at wholesale market level)
- Analysis of network utilization and FCOE as for Operation Modes 1 and 2
- Main difference: Smooth profiles from system modeling need to be made “sharper”; this is performed using theoretical functional dependency of simultaneity factor (p.11)

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Results

System perspective

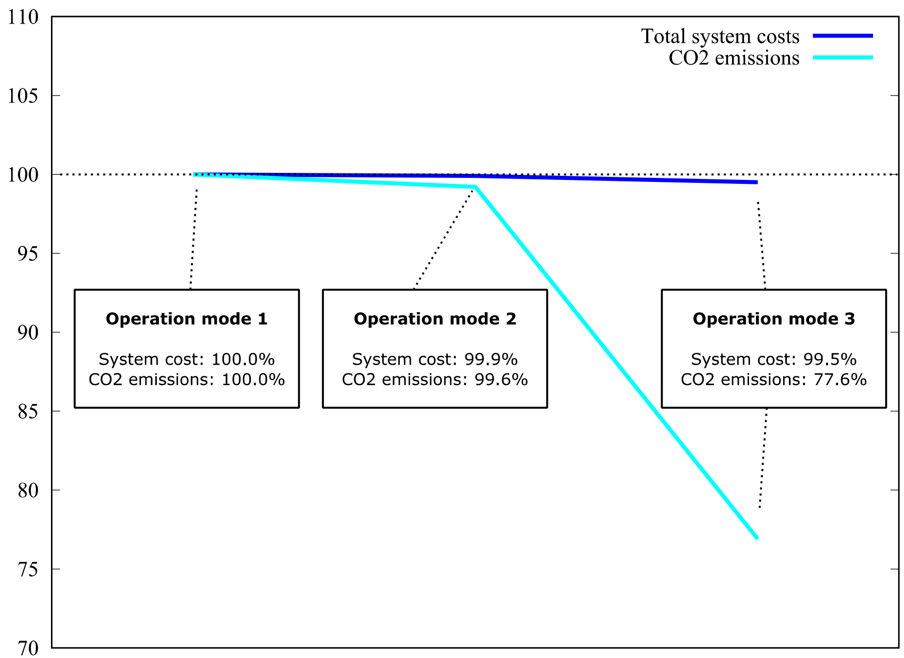


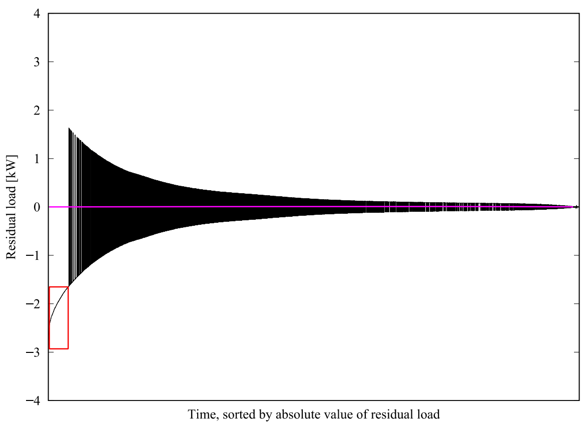
Figure 3: Annualized total system costs and CO_2 emissions, normalized in % of respective values for battery Operation Mode 1, by battery operation mode.

- Total system costs are highest for Operation mode 1 (chronological charging) and lowest for operation mode 3 (market beneficial battery operation)
- System cost delta is 0.5%, corresponding to 230 MN EUR p.a. with a system cost base of ca. 50 BN EUR p.a.
- Effect is driven by reduced RES integration in case of static battery operation, correspondingly, increased fuel and CO_2 costs
- Even stronger differences in CO_2 emissions; underlying cause is, again, different RES integration levels

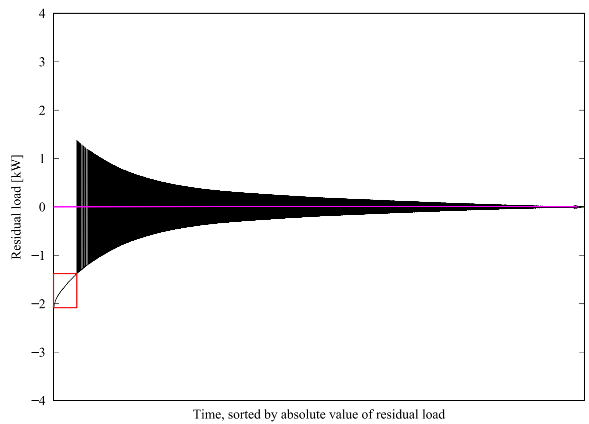
Results

Network utilization

Operation mode 1



Operation mode 2



Operation mode 3

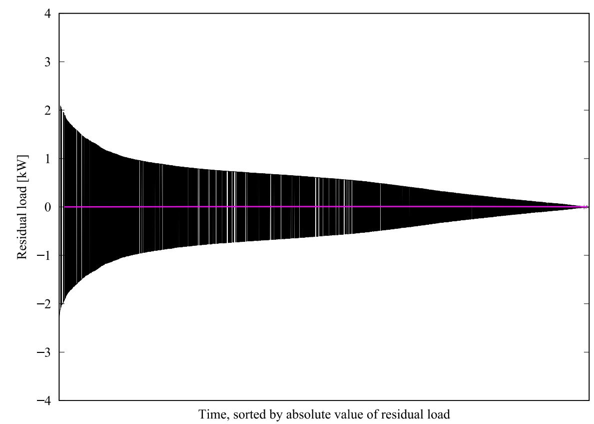


Figure 4a: Annual residual load duration curves; by battery operation mode.

- Highest residual load peak: 2.9 kW per household
- Network utilization purely driven by feed-in for the situations of highest thermal network stress

- Lowest residual load peak: 2.2 kW per household
- Network utilization purely driven by feed-in for the situations of highest thermal network stress

- Residual load peak lower than for operation mode 1, but higher than for operation mode 2: 2.3 kW per household
- Highest network utilization caused both by feed-in and grid load

Results

Network utilization

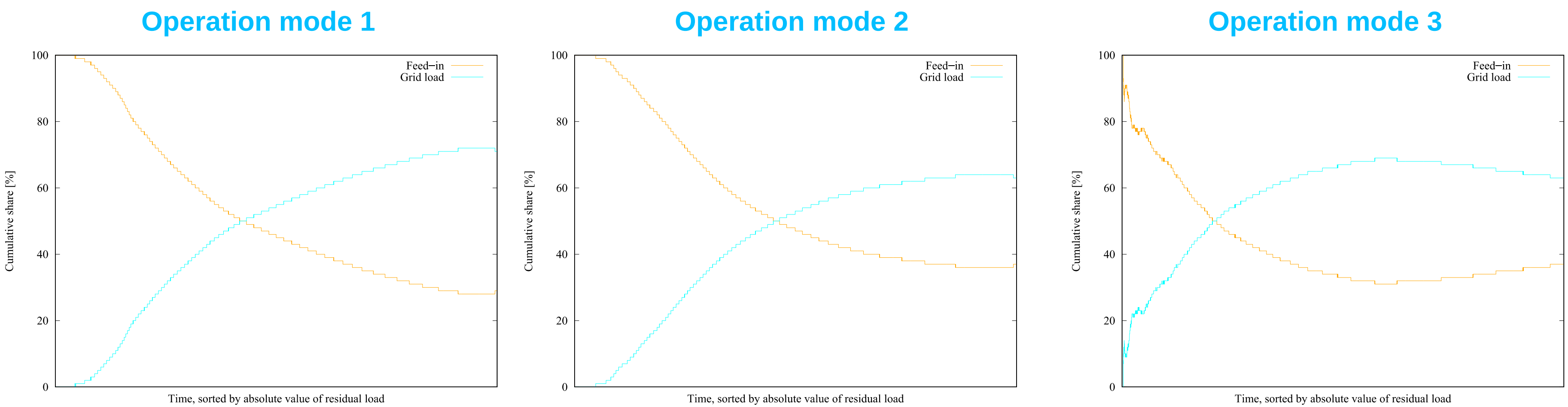


Figure 4b: Cumulative shares of feed-in (orange) and grid load (cyan) in the residual load duration curves

- Intersections of curves represent points in (reordered) time up to which feed-in peaks and demand peaks have equally contributed to the network capacity utilization, starting from the situations of highest network stress

Results

End customer effects

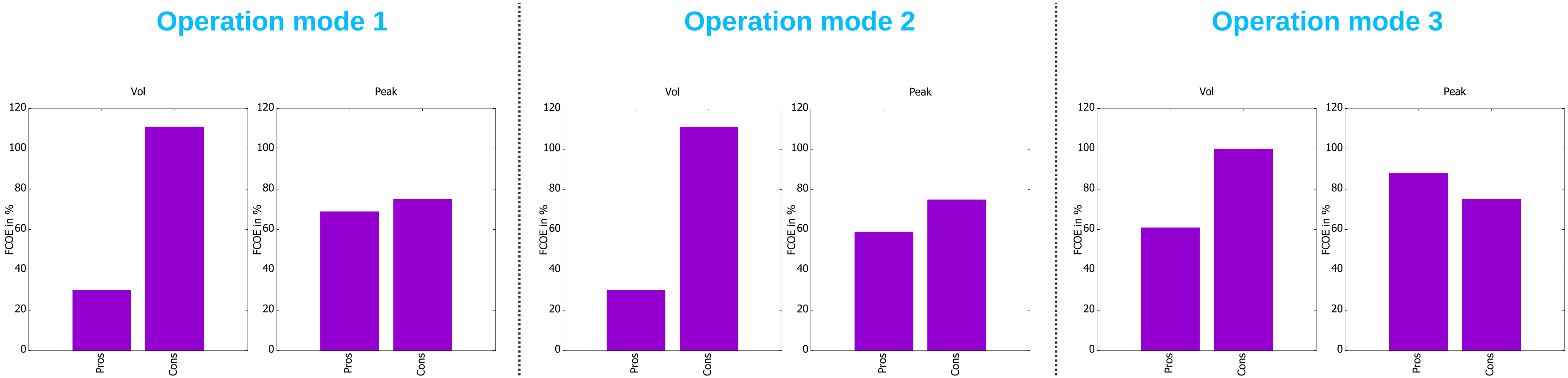


Figure 5: FCOE for prosumers (Pros) and consumers (Cons), in % and normalized to 800 EUR/a, by network cost allocation scheme (Vol: volumetric network charges; Peak: peak-coincident capacity charges); by battery operation mode.

- Investments in distributed PV and battery systems are economically viable both under volumetric and peak capacity network charges, in principle
- Peak capacity charges generally tend to reduce the FCOE gap between prosumers and consumers
- Market-beneficial battery operation (Operation Mode 3) is neither favorable for volumetric nor peak capacity network charges

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Conclusions

- This manuscript evaluates the impact of prosumer behavior at the individual level (electricity bill), local level (distribution network stress), and the system level (total system costs).
- Volumetric network charges tend to favor battery operation modes that are neither grid- nor market-oriented.
  - Such battery operation modes can lead to significantly higher thermal stress on the distribution network nodes.
  - Additionally, these modes can cause overall higher system costs and CO2 emissions because of reduced RES integration. Moreover, volumetric network charges can amplify the gap between prosumer and consumer household electricity bills.
- Peak capacity charges could constitute an incentive for different battery operation modes.
  - These could reduce inequalities between prosumer and consumer electricity bills and simultaneously release the distribution network.
- It is unclear from this analysis whether (and to what extent) a grid-oriented battery operation mode also results in corresponding positive market effects.
- In this study, market-oriented battery operation displays significantly better RES integration, resulting in overall lower system costs and CO2 emissions.
- In a subsequent journal paper we will evaluate further aspects, first and foremost improvements to the prosumer heuristic presented in this paper that explicitly account for a prosumer response to a changed regulatory framework.

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Thank you!

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