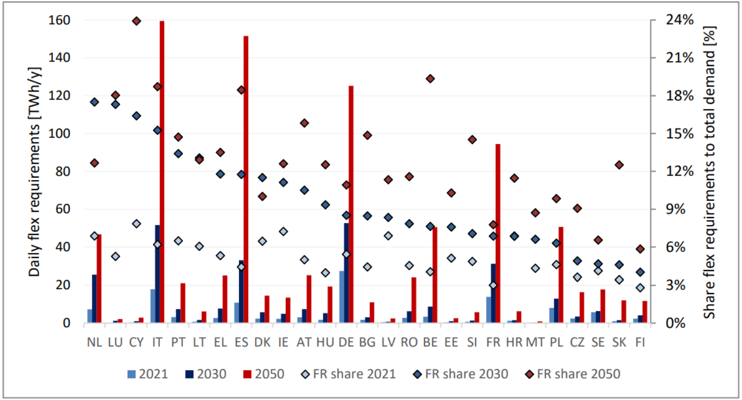
Operating envelope approach for grid-safe participation of distributed flexibility in balancing markets

Wicak Ananduta, L. Marques, A. Kaushal, A. Sanjab, T. Cuypers, and J. Vanschoenwinkel

Outline

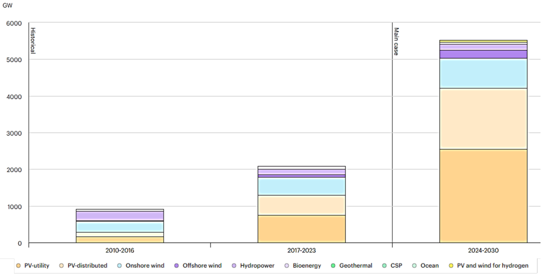
Outline

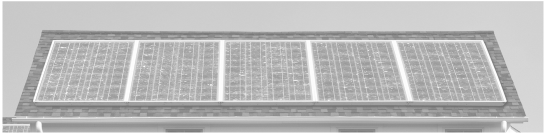
Flexibility requirements



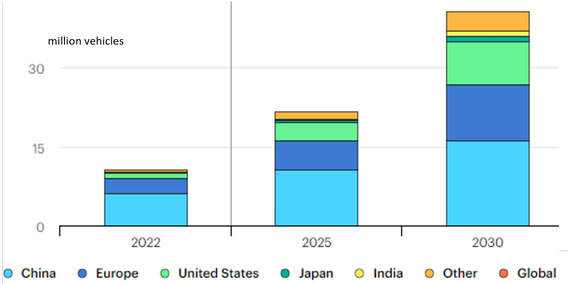
Daily flexibility requirements in Europe **[Koolen, et, al., '23]**

Distributed flexibility





Renewable energy production **[IEA '24]**



EV sale projection **[IEA '24]**

Balancing market

- Flexibility offers (upward/downward) in transmission (TN) and distribution (DN) networks: (price, p_n (active power quantity))

Balancing market

- Flexibility offers (upward/downward) in transmission (TN) and distribution (DN) networks: (price, p_n (active power quantity))
- Market clearing problem:

$$\min \sum_{n \in \text{Resources}} \text{price}_n \cdot p_n$$
$$\text{s. t.} \quad p_n \in \text{BidConstraint}_n, \quad \forall n \in \text{Resources},$$

Balancing market

- Flexibility offers (upward/downward) in transmission (TN) and distribution (DN) networks: (price, p_n (active power quantity))
- Market clearing problem:

$$
\begin{aligned}
\min \quad & \sum_{n \in \text{Resources}} \text{price}_n \cdot p_n \\
\text{s. t.} \quad & p_n \in \text{BidConstraint}_n, \quad \forall n \in \text{Resources}, \\
& ((p_n)_{n \in \text{ResourcesTN}}, \boldsymbol{z}) \in \text{TNConst},
\end{aligned}
$$

Balancing market

- Flexibility offers (upward/downward) in transmission (TN) and distribution (DN) networks: (price, p_n (active power quantity))
- Market clearing problem:

$$
\begin{aligned}
& \min \sum_{n \in \text{Resources}} \text{price}_n \cdot p_n \\
\text{s. t.}\quad & p_n \in \text{BidConstraint}_n, \quad \forall n \in \text{Resources}, \\
& ((p_n)_{n \in \text{ResourcesTN}}, \boldsymbol{z}) \in \text{TNConst}, \\
& \sum_{n \in \text{ResourcesDN}_\text{m}} p_n = z_m \in \text{InterfaceLimits}, \quad \forall m \in \text{DNs},
\end{aligned}
$$

Balancing market

- Flexibility offers (upward/downward) in transmission (TN) and distribution (DN) networks: (price, p_n (active power quantity))
- Market clearing problem:

$$
\begin{aligned}
\min \quad & \sum_{n \in \text{Resources}} \text{price}_n \cdot p_n \\
\text{s. t.} \quad & p_n \in \text{BidConstraint}_n, \quad \forall n \in \text{Resources}, \\
& ((p_n)_{n \in \text{ResourcesTN}}, \boldsymbol{z}) \in \text{TNConst}, \\
& \sum_{n \in \text{ResourcesDN}_\text{m}} p_n = z_m \in \text{InterfaceLimits}, \quad \forall m \in \text{DNs}, \\
& (p_n)_{n \in \text{ResourcesDN}} \in \text{DNConst}(\varphi^{\text{DN}_m}), \quad \forall m \in \text{DNs}\,.
\end{aligned}
\tag{BM}
$$

Alexander

Balancing market

- Flexibility offers (upward/downward) in transmission (TN) and distribution (DN) networks: (price, p_n (active power quantity))
- Market clearing problem:

$$
\begin{aligned}
\min \quad & \sum_{n \in \text{Resources}} \text{price}_n \cdot p_n \\
\text{s.t.} \quad & p_n \in \text{BidConstraint}_n, \quad \forall n \in \text{Resources}, \\
& ((p_n)_{n \in \text{ResourcesTN}}, \boldsymbol{z}) \in \text{TNConst}, \\
& \sum_{n \in \text{ResourcesDN}_\text{m}} p_n = z_m \in \text{InterfaceLimits}, \quad \forall m \in \text{DNs}, \\
& \cancel{(p_n)_{n \in \text{ResourcesDN}} \in \text{DNConst}(\varphi^{\text{DN}_m}), \quad \forall m \in \text{DNs}.}
\end{aligned}
\tag{BM}
$$

- Responsibility, data confidentiality, communication intensive

Balancing market

- Flexibility offers (upward/downward) in transmission (TN) and distribution (DN) networks: (price, p_n (active power quantity))
- Market clearing problem:

$$
\begin{aligned}
\min \quad & \sum_{n \in \mathrm{Resources}} \mathrm{price}_n \cdot p_n \\
\text{s. t.} \quad & p_n \in \mathrm{BidConstraint}_n, \quad \forall n \in \mathrm{Resources}, \\
& ((p_n)_{n \in \mathrm{ResourcesTN}}, \boldsymbol{z}) \in \mathrm{TNConst}, \\
& \sum_{n \in \mathrm{ResourcesDN_m}} p_n = z_m \in \mathrm{InterfaceLimits}, \quad \forall m \in \mathrm{DNs},
\end{aligned}
\tag{BM}
$$

Balancing market

- Flexibility offers (upward/downward) in transmission (TN) and distribution (DN) networks: (price, p_n (active power quantity))
- Market clearing problem:

$$
\begin{aligned}
\min \quad & \sum_{n \in \text{Resources}} \text{price}_n \cdot p_n \\
\text{s. t.} \quad & p_n \in \text{BidConstraint}_n, \quad \forall n \in \text{Resources}, \\
& ((p_n)_{n \in \text{ResourcesTN}}, \boldsymbol{z}) \in \text{TNConst}, \\
& \sum_{n \in \text{ResourcesDN}_\text{m}} p_n = z_m \in \text{InterfaceLimits}, \quad \forall m \in \text{DNs},
\end{aligned} \tag{BM}
$$

Unsafe activation

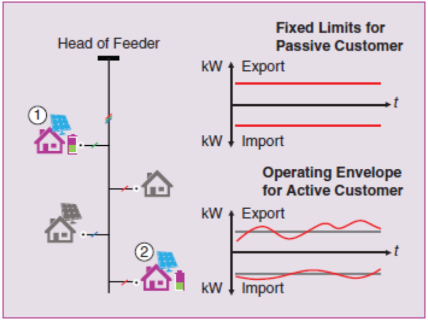
Cleared offers located in DNs causing network problems

Outline

Operating envelopes (OEs)

Definition

Allowable *dynamic* limits without causing network issues



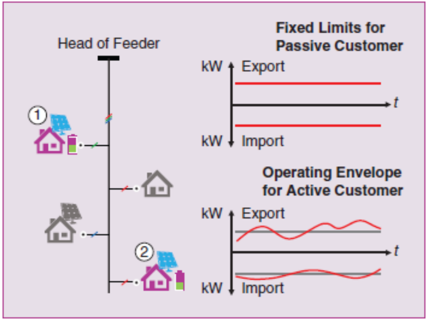
[Liu, et. al., PEM'21]

- Depends on network current states

Operating envelopes (OEs)

Definition

Allowable *dynamic* limits without causing network issues



[Liu, et. al., PEM'21]

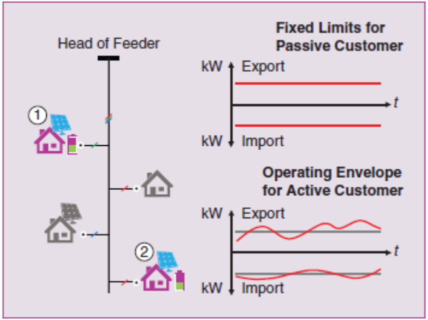
- Depends on network current states
- Adapted to flexibility resources:

$$\mathrm{OE}_n : \{p_n | 0 \leq p_n \leq \varepsilon_n\}$$

Operating envelopes (OEs)

Definition

Allowable *dynamic* limits without causing network issues



[Liu, et. al., PEM'21]

- Depends on network current states
- Adapted to flexibility resources:

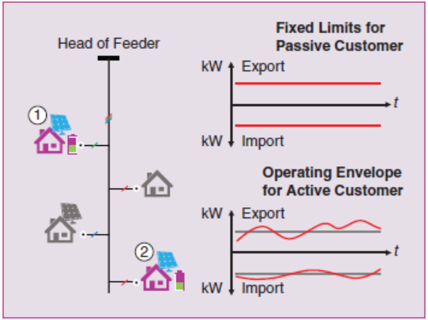
$$\mathrm{OE}_n : \{p_n | 0 \leq p_n \leq \varepsilon_n\}$$

- Calculation methods:
  - OPF-based: [Petrou, et. al., TSG'21], [Liu, et. al., TSG'22], [Liu, et. al., 2023], [Feng, et. al., TSG'24],
  - Scenario/sampling based: [Riaz & Mancarella, '19], [Wang, et. al., AE'20], [Lankeshwara, et. al., TPS'24]

Operating envelopes (OEs)

Definition

Allowable *dynamic* limits without causing network issues



[Liu, et. al., PEM'21]

- Depends on network current states
- Adapted to flexibility resources:

$$\text{OE}_n : \{p_n | 0 \leq p_n \leq \varepsilon_n\}$$

- Calculation methods:
  - OPF-based: [Petrou, et. al., TSG'21], [Liu, et. al., TSG'22], [Liu, et. al., 2023], [Feng, et. al., TSG'24],
  - Scenario/sampling based: [Riaz & Mancarella, '19], [Wang, et. al., AE'20], [Lankeshwara, et. al., TPS'24]

Research gaps

- How OEs impact balancing market outcomes
- Fundamental analysis

OE-based balancing market

- Redefined market clearing problem:

$$
\begin{aligned}
\min \quad & \sum_{n \in \text{Resources}} \text{price}_n \cdot p_n \\
\text{s. t.} \quad & p_n \in \text{BidConstraint}_n, \quad \forall n \in \text{Resources}, \\
& ((p_n)_{n \in \text{ResourcesTN}}, \boldsymbol{z}) \in \text{TNConst}, \\
& \sum_{n \in \text{ResourcesDN}_\text{m}} p_n = z_m \in \text{InterfaceLimits}, \quad \forall m \in \text{DNs}, \\
& p_n \in \text{OE}_n, \quad \forall n \in \text{ResourcesDN}_m, \quad \forall m \in \text{DNs}
\end{aligned}
\tag{BM-OE}
$$

- No DNConst needed!

OE-based balancing market

- Redefined market clearing problem:

$$
\begin{aligned}
\min \quad & \sum_{n \in \text{Resources}} \text{price}_n \cdot p_n \\
\text{s.t.} \quad & p_n \in \text{BidConstraint}_n, \quad \forall n \in \text{Resources}, \\
& ((p_n)_{n \in \text{ResourcesTN}}, \boldsymbol{z}) \in \text{TNConst}, \\
& \sum_{n \in \text{ResourcesDN}_\text{m}} p_n = z_m \in \text{InterfaceLimits}, \quad \forall m \in \text{DNs}, \\
& p_n \in \text{OE}_n, \quad \forall n \in \text{ResourcesDN}_m, \quad \forall m \in \text{DNs}
\end{aligned}
\tag{BM-OE}
$$

- No DNConst needed!
- OEs as *simple* prequalification measure
- Network feasibility study in Belgium: static OE
- Compatible with existing regulation [Marques, et. al., Alexander D3.2, 2024]

Optimization-based operating envelope calculation

- Optimize OE_n for all DN resources
- Include DNConst $\rightarrow$ network model is crucial!
- Done for each DN

Optimization-based operating envelope calculation

- Optimize OE_n for all DN resources
- Include DNConst $\rightarrow$ network model is crucial!
- Done for each DN

One-step method [Petrou, et. al., TSG'21]

- Compute OE_n for all resources
- Quadratic objective function:

$$\min \sum_{n \in \mathrm{ResourcesDN_m}} w_n(\varepsilon_n - p_n^{\max})^2$$

Optimization-based operating envelope calculation

- Optimize OE_n for all DN resources
- Include DNConst $\rightarrow$ network model is crucial!
- Done for each DN

One-step method [Petrou, et. al., TSG'21]

- Compute OE_n for all resources
- Quadratic objective function:

$$\min \sum_{n \in \mathrm{ResourcesDN_m}} w_n(\varepsilon_n - p_n^{\max})^2$$

Two-step method [Liu, et. al., TSG'22]

- Compute OE_n for downward and upward resources separately
- Linear objective function:

$$\max \sum_{n \in \mathrm{ResourcesDN_m}} w_n \cdot \varepsilon_n$$

Optimization-based operating envelope calculation (+)

- Different weight w_n types:
  - Equal,
    $$w_n = 1, \quad \text{for all resources}$$
  - Price-based:
    $$w_n \propto \begin{cases} |\,\text{price}_n\,|, & \text{for all downward resources} \\ 1/|\,\text{price}_n\,|, & \text{for all upward resources} \end{cases}$$
  - Quantity-based:
    $$w_n = p_n^{\max}, \quad \text{for all resources}$$

Outline

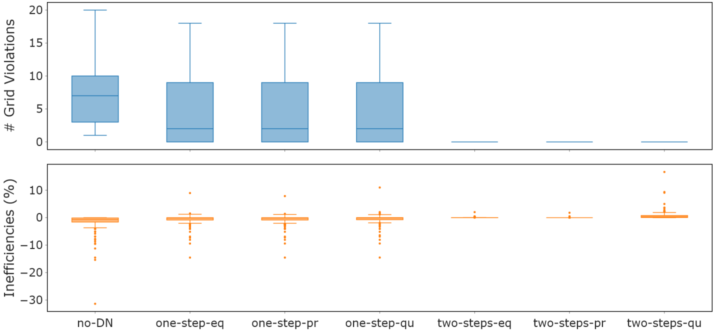
Numerical tests [Kaushal, et. al. ISGT'24]

Assessing performance of integrating OEs into balancing market:

- Grid safety of cleared offers
  - Satisfaction of voltage and line flow limits (DNConst)
  - DNConst uses linearized branch flow model
- Market efficiency
  - Total flexibility procurement cost
  - Benchmarked with idealized formulation
- Volume of unqualified DN offers

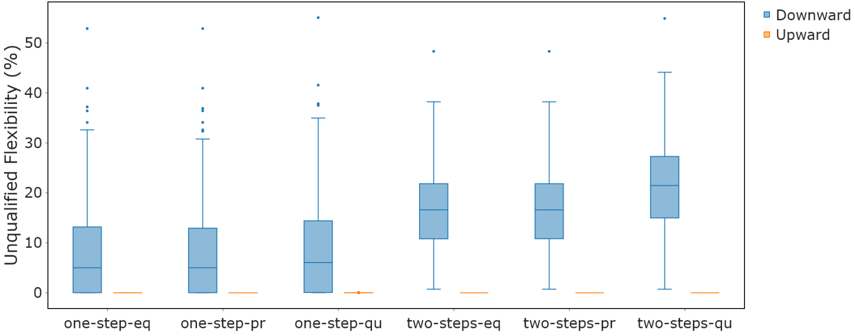
Numerical tests (+) [Kaushal, et. al., ISGT'24]

- $\sim$ 300 cases (downward scenario) where (BM *no-DN*) is not grid safe
  - IEEE 14-bus TN coupled with Matpower 69-bus and 141-bus DNs
  - Monte Carlo simulations: randomly generated loads, generation, flexibility offers



- 2-step OE **always** provides grid-safe (but possibly suboptimal) outcomes
- 1-step OE does not always provide grid-safe outcomes
- Price-based weight is best in market efficiency

Numerical tests (++) [Kaushal, et. al., ISGT'24]



- 2-step OE provides more restricted limits than 1-step OE

Theoretical results

- DNConst is linearized branch flow model [Sanjab, et. al., '21]
- Distribution networks are radial
- Prices of upward resources are more expensive than downward resources

Theoretical results

- DNConst is linearized branch flow model [Sanjab, et. al., '21]
- Distribution networks are radial
- Prices of upward resources are more expensive than downward resources

(Theorem) Grid safety guarantee

If OE_n calculated with **2-step method**, outcomes of (BM-OE), $(p_n^*)_{n\in\mathrm{Resources}}$ are grid safe, i.e.,

$$\exists \varphi^{\mathrm{DN}_m} \mid (p_n^*)_{n\in\mathrm{ResourcesDN}_m} \in \mathrm{DNConst}(\varphi^{\mathrm{DN}_m}), \quad \forall m \in \mathrm{DNs}\,.$$

Theoretical results

- DNConst is linearized branch flow model [Sanjab, et. al., '21]
- Distribution networks are radial
- Prices of upward resources are more expensive than downward resources

(Theorem) Grid safety guarantee

If OE_n calculated with **2-step method**, outcomes of (BM-OE), $(p_n^*)_{n\in\mathrm{Resources}}$ are grid safe, i.e.,

$$\exists \varphi^{\mathrm{DN}_m} \mid (p_n^*)_{n\in\mathrm{ResourcesDN}_m} \in \mathrm{DNConst}(\varphi^{\mathrm{DN}_m}), \quad \forall m \in \mathrm{DNs}\,.$$

(Proposition) Suboptimality

Outcomes are suboptimal and inefficiency of (BM-OE) can be upper-bounded by

$$\sum_{m\in\mathrm{DNs}} \sum_{n\in\mathrm{ResourcesDN_m}} \mathrm{price}_n(p_n^* - \hat{p}_n),$$

where $(\hat{p}_n)_{n\in\mathrm{Resources}}$ are outcomes of (BM).

Outline

Alexander

Conclusion

- Integration of operating envelopes into balancing market *can** ensure grid safety
- OE calculation method impacts performance
- 2-step OE calculation method with price-based weight is the best tested option

Conclusion

- Integration of operating envelopes into balancing market *can** ensure grid safety
- OE calculation method impacts performance
- 2-step OE calculation method with price-based weight is the best tested option
- Further research directions:
  - Understanding (theoretical) limitations when other (more realistic) power flow models are considered
  - Uncertainties in the OE calculation: what kind of guarantees can we have?

Conclusion

- Integration of operating envelopes into balancing market *can** ensure grid safety
- OE calculation method impacts performance
- 2-step OE calculation method with price-based weight is the best tested option
- Further research directions:
  - Understanding (theoretical) limitations when other (more realistic) power flow models are considered
  - Uncertainties in the OE calculation: what kind of guarantees can we have?

Publications:

- "Development of a novel, grid safe concept for flexibility provision from the LV grid," Alexander D3.2.
- "Embedding operating envelopes in the market design to unlock the flexibility potential of distribution grids," CIRED Vienna Workshop, 2024.
- "Operating envelopes for the grid-constrained use of distributed flexibility in balancing markets," ISGT Europe Conference, 2024. Best paper award!
- "Grid-safe flexibility market design based on the operating envelope approach," in preparation for journal submission.

This project has received funding from Energy Transition Fund 2021 FPS Economy, SMEs, Self-employed and Energy.

https://alexander-project.vito.be/en
alexander@energyville.be