Breaking down the complexity of network operation

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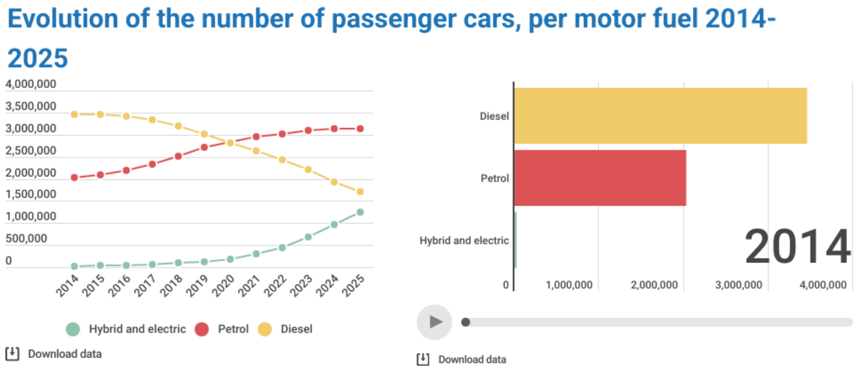
Introduction

- Increased electrification of industrial loads.
- Connection of new types of loads.
- RES have deeply penetrated the electricity mix.
- The number of EVs has increased drastically.
- The production schedules are subject to much higher uncertainty.



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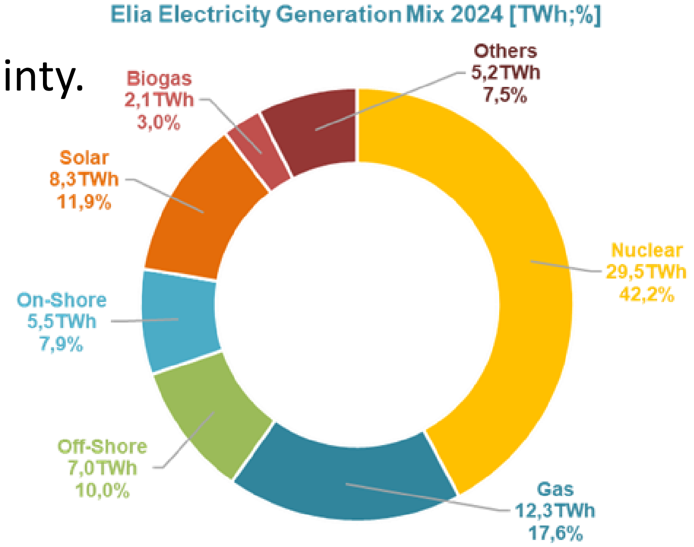


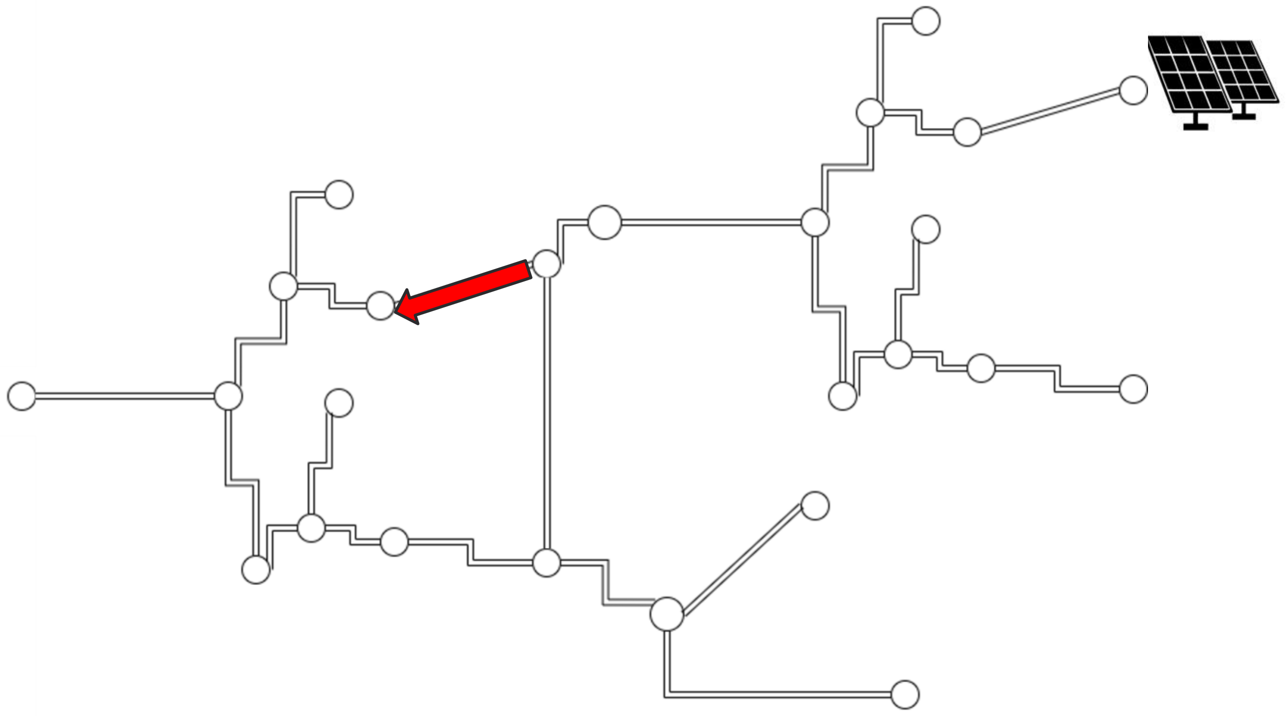
Elia

Network operation under uncertainty

- Requires building scenarios.
- Requires accurately modeling the network.
- Operation is based on complex optimization problems.
- Guaranteeing security may become intractable in practice.

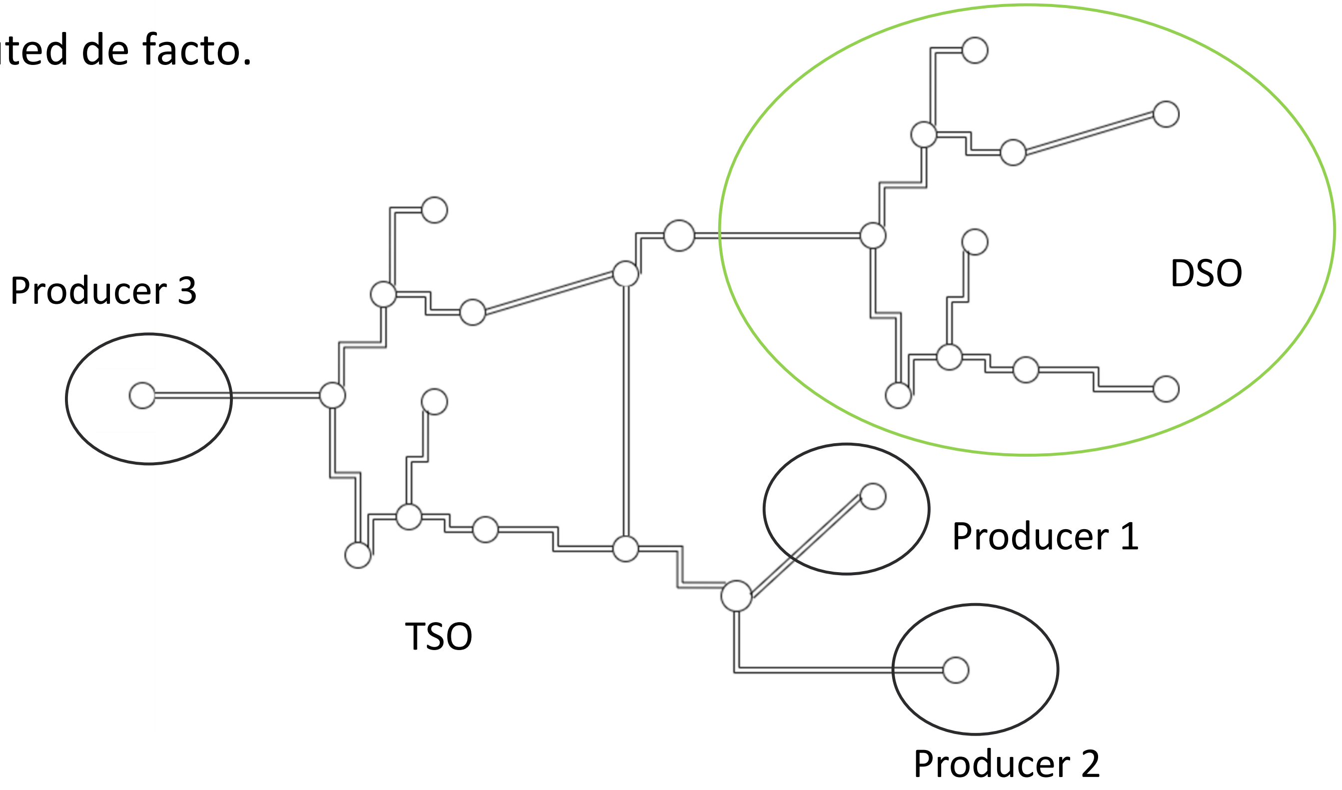
Observation 1
Uncertainty propagates

- Some parts of the network may be critical.
- Uncertainty on some security constraints is due to distant randomness.



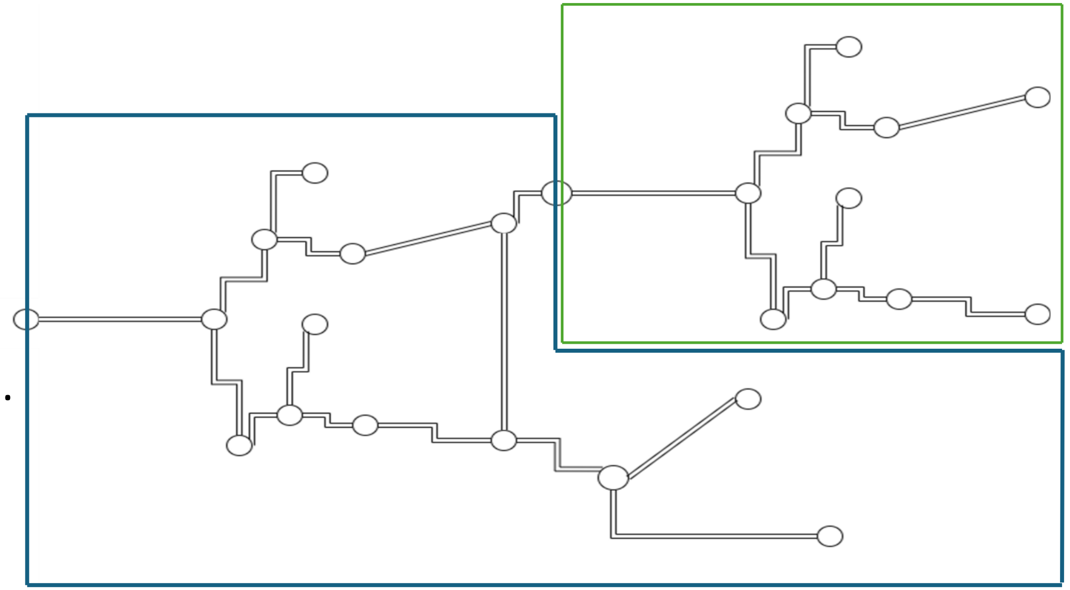
Observation 2
Operation is distributed

- Network operation is influenced by decisions taken by other actors.
- Creates additional uncertainty.
- Security management is distributed de facto.



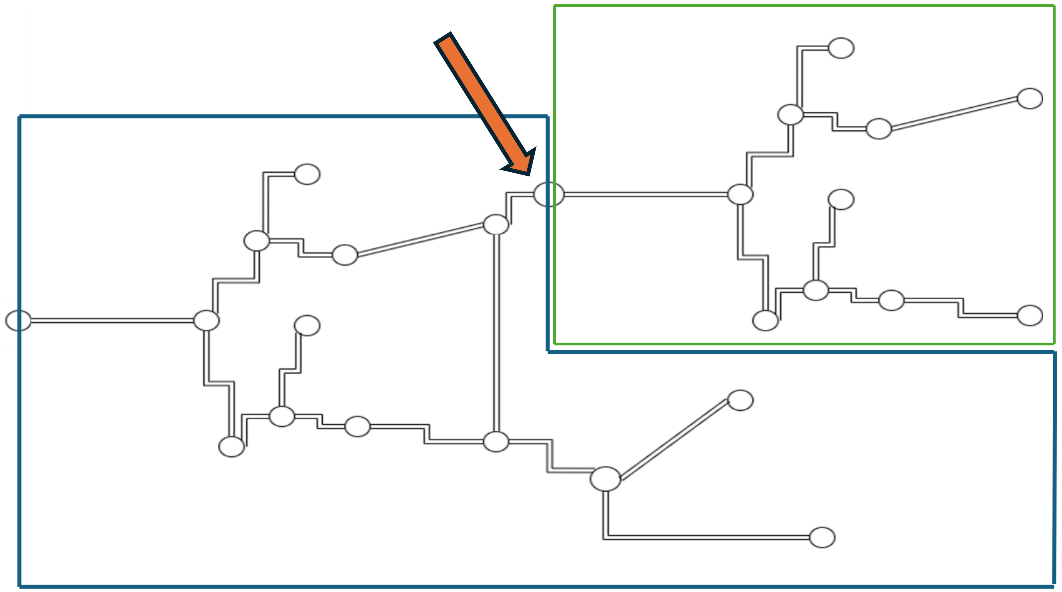
Network decoupling for efficient operation

- Divide network into different sub-networks.
- Decouple operation between sub-networks.
- Each network is presumably easier to operate.
- Uncertainty propagation is limited.
- Security management roles are clearly defined.

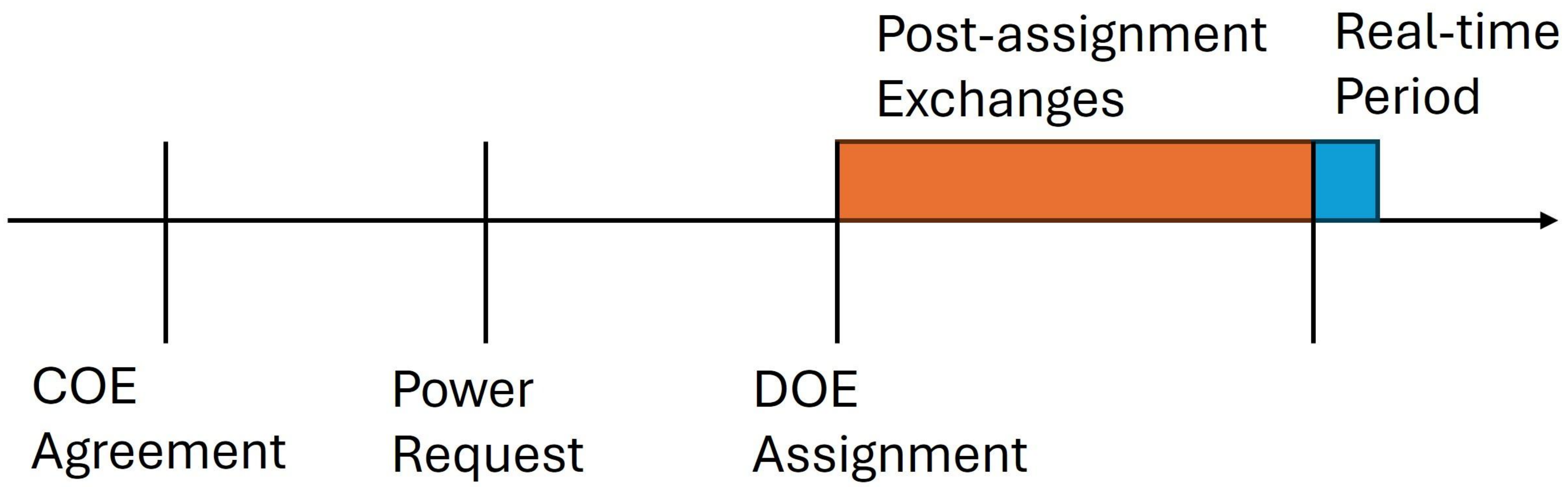


How to decouple sub-networks?

- Decoupling is possible through an exchange of guarantees at the interfaces.
- The parent graph (TSO) guarantees that the voltage at the interface is within an envelope (COE).
- The child graph (DSO/producer/consumer) guarantees that the power consumption at the interface is within an envelope (DOE).
- If the envelopes are respected, there exists a secure control rule for the parent graph.

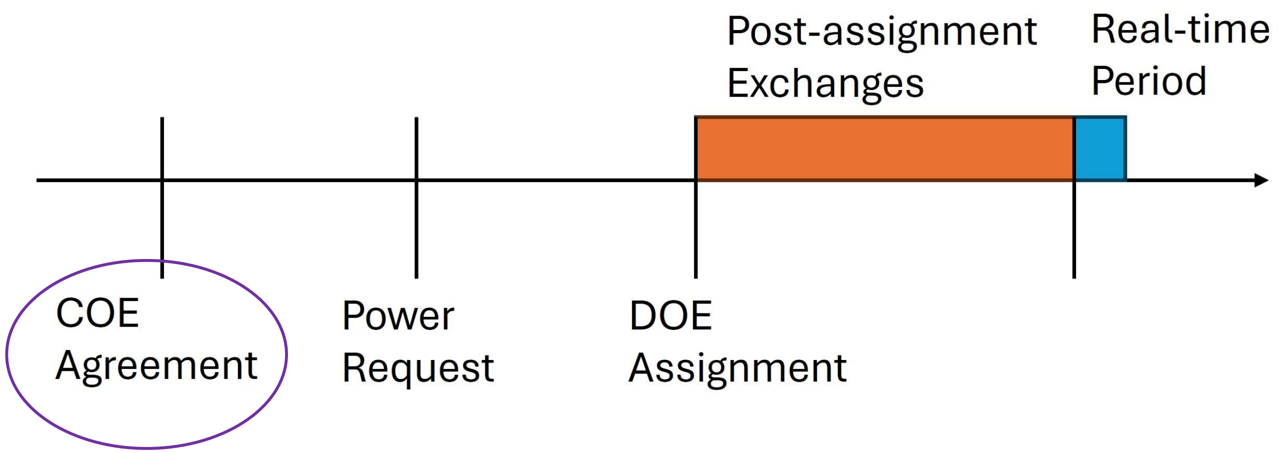


How to compute envelopes?



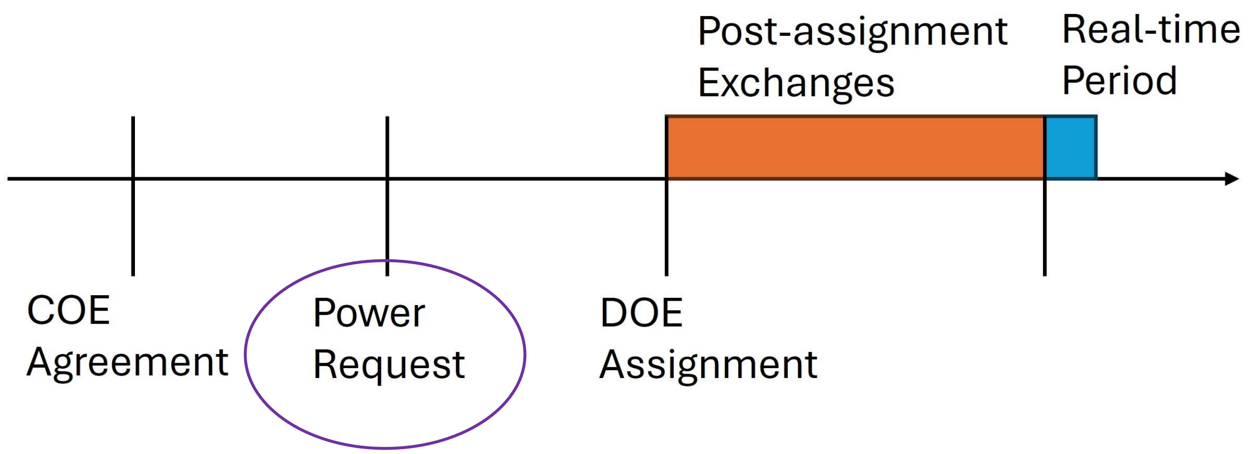
COE Agreement

- Contractual agreement on the voltage level.
- Simple process, done long in advance.
- There already exist constraints on voltage levels in practice.



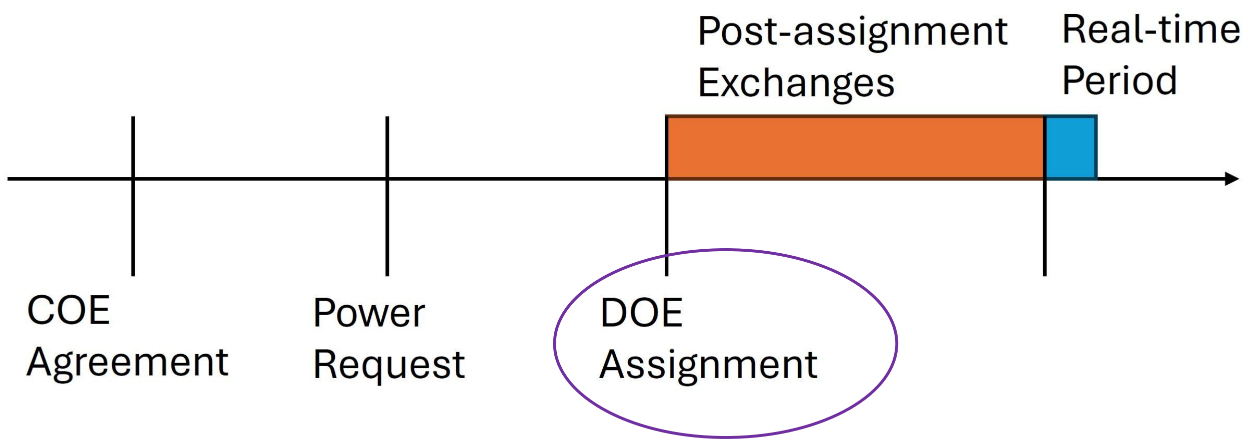
Power request

- The child graph requests a level of power.
- This part requires independent planning at the level of the child graph.



DOE assignment

- An active field of research with open questions.
- How to maximize welfare, include fairness, etc?



Maximum total utility DOE assignment

$$\max_{\overline{P}^{\mathcal{C}}, O} U^{DOE}(\overline{P}^{\mathcal{C}}, O, P^{o}) \tag{1a}$$

Utility function (e.g., norm of DOEs)

$$\text{s.t. } \forall P^{-,\mathcal{C}} \in \overline{P}^{\mathcal{C}}, \forall V^{\mathcal{P}} \in \overline{V}^{\mathcal{P}}, \exists V^{o}, I^{o}, P^{+,\mathcal{P}}, E^{o} :$$

$$C(P^{o}, E^{o}) \leq O \tag{1b}$$

Cost function (e.g., curtailment cost)

$$PowerFlow(V^{o}, I^{o}, E^{o}, P^{+,\mathcal{P}}, P^{-,\mathcal{C}}) = 0 \tag{1c}$$

Physical constraints

$$Security(V^{o}, I^{o}, E^{o}, P^{+,\mathcal{P}}, P^{-,\mathcal{C}}) \leq 0 \tag{1d}$$

Security constraints

$$V^{\mathcal{C}} \in \overline{V}^{\mathcal{C}} \tag{1e}$$

Voltage envelope

$$P^{+,\mathcal{P}} \in \overline{P}^{\mathcal{P}}, \tag{1f}$$

Power envelope

$$E^{o} - P^{o} \in \overline{\Delta E} \tag{1g}$$

Curtailment limits

Utility function

- The quality of the envelopes is measured with a utility function.

$$Volume\left(\bar{P}_n{}^C\right) - \beta \cdot \left|Barycenter\left(\bar{P}_n{}^C\right) - \hat{P}_n{}^C\right|$$

- The utilities of envelopes are aggregated into the total utility.
- The aggregation may account for the lexicographic order and implement fairness.
- The aggregation may be the sum.

$$\max_{\bar{P}^C, O}\left(\sum_n Volume\left(\bar{P}_n{}^C\right) - \beta \cdot |Barycenter\left(\bar{P}_n{}^C\right) - \hat{P}_n{}^C|\right) - \alpha \cdot O$$

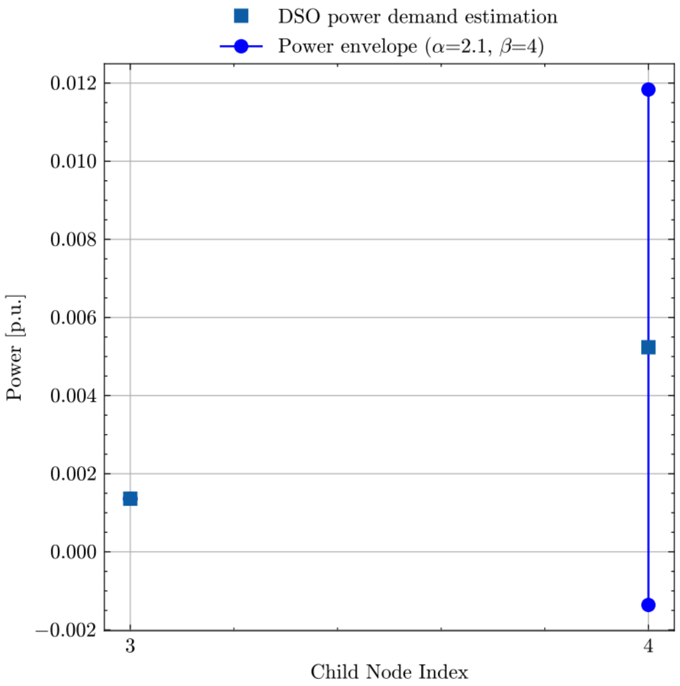
$O =$ Curtailment in the worst case

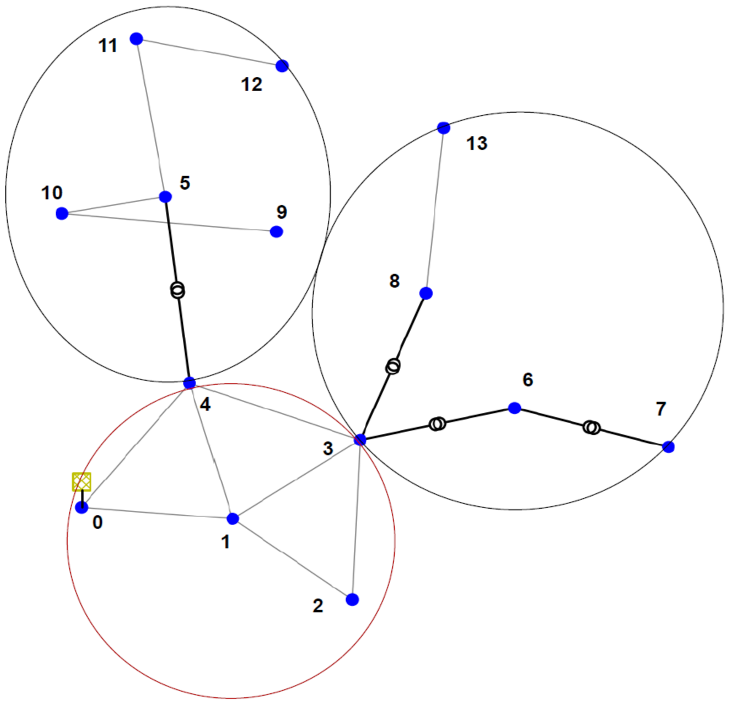
Practical complexity

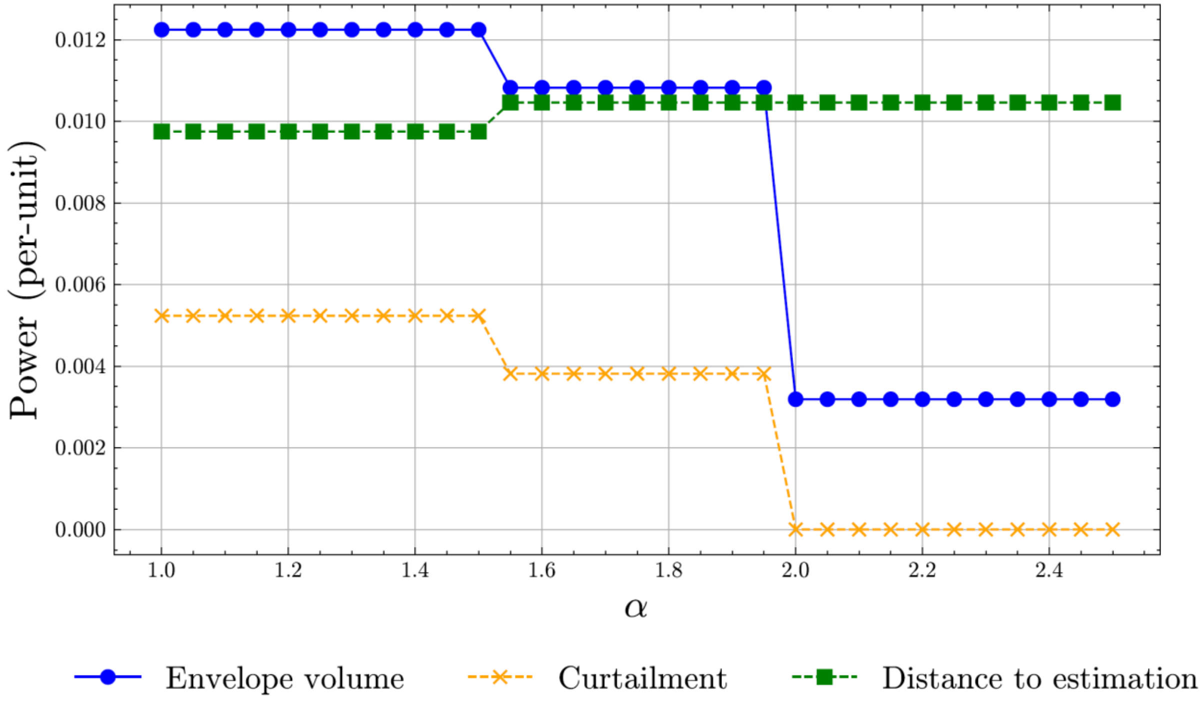
- A reformulation exists if the envelopes are polyhedra and constraints are convex.
- The previous equations must then be verified for all combinations of the vertices of voltage and power envelopes.

Illustration

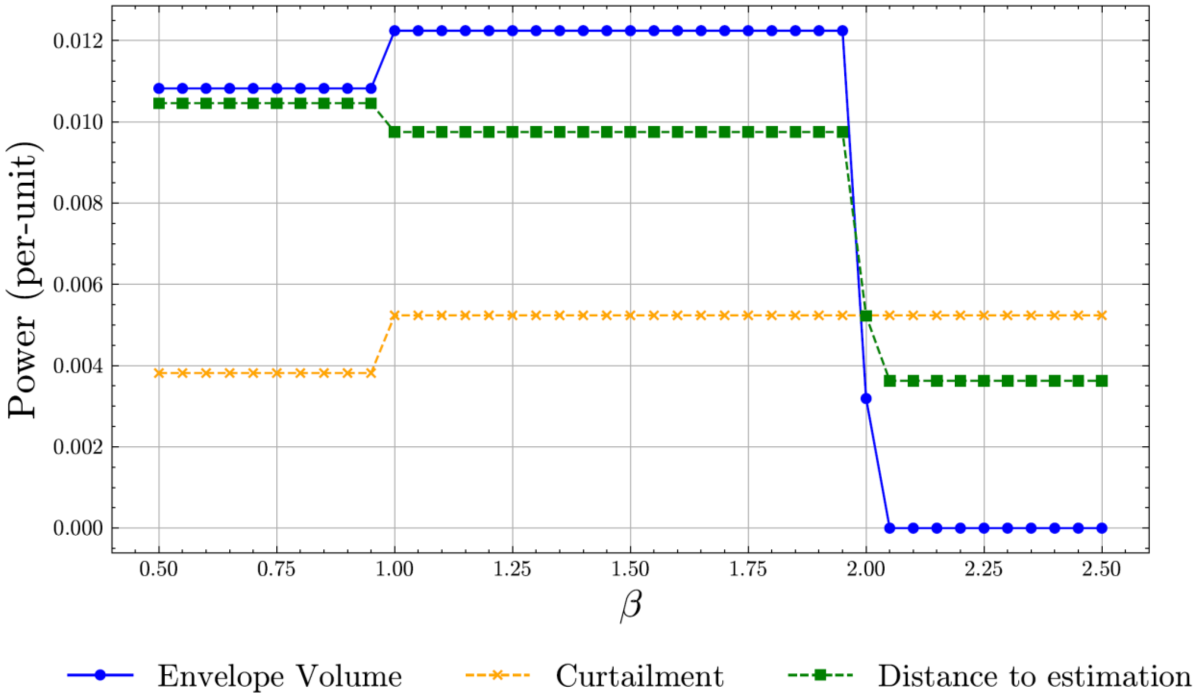
- We decouple a TSO from its two DSOs.
- COE are fixed and power requests are the total consumptions.
- DOEs are computed using DC powerflow equations.







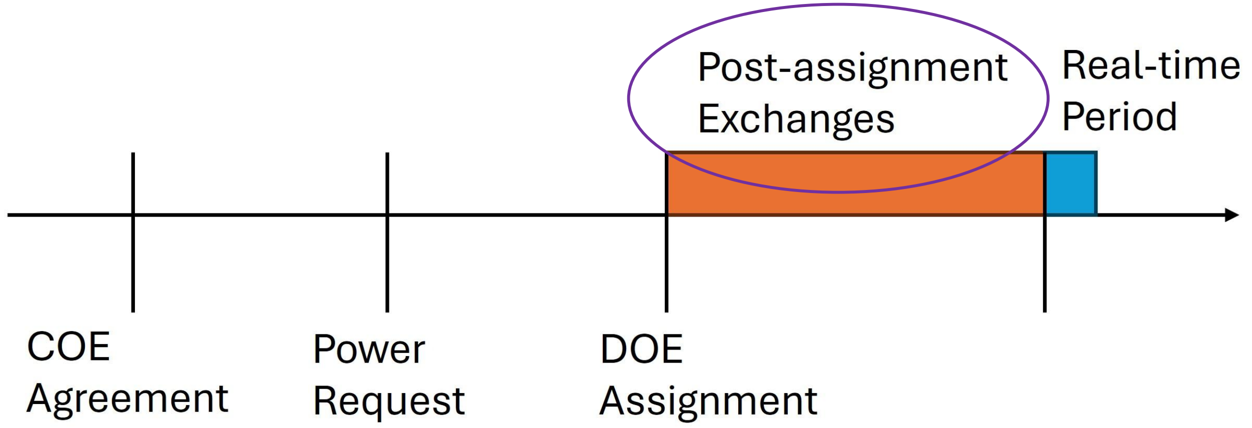
$$\max_{\bar{P}^C, O} \left(\sum_n Volume\left(\bar{P}_n{}^C\right) - \beta \cdot \left|Barycenter\left(\bar{P}_n{}^C\right) - \hat{P}_n{}^C\right| \right) - \alpha \cdot O$$



$$\max_{\bar{P}^C, O} \left(\sum_n Volume\left(\bar{P}_n{}^C\right) - \beta \cdot \left| Barycenter\left(\bar{P}_n{}^C\right) - \hat{P}_n{}^C \right| \right) - \alpha \cdot O$$

Post-assignment exchanges: SecuLEx

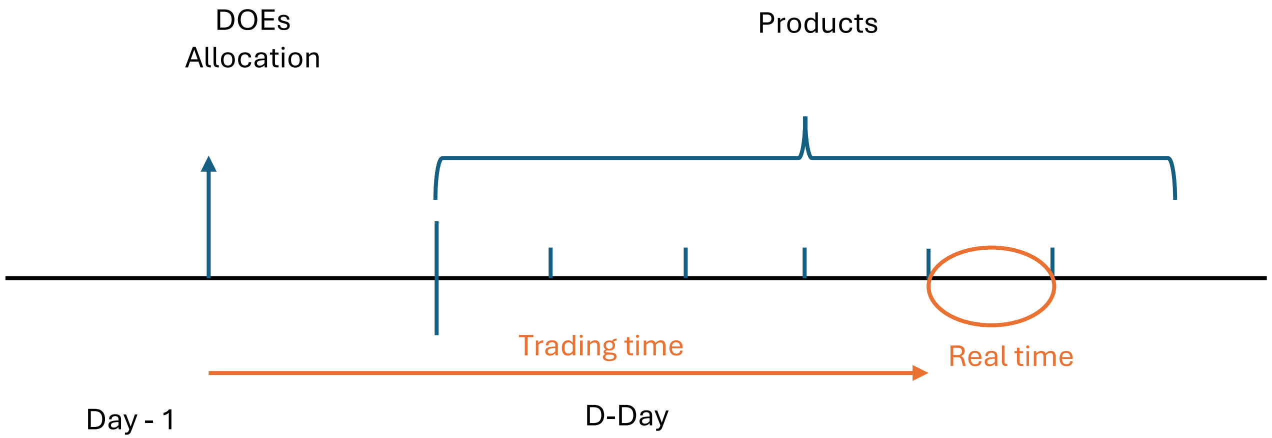
- Sub-graphs may be willing to modify their DOE as time evolves.
- Sub-graphs may exchange their DOE limits on a market.

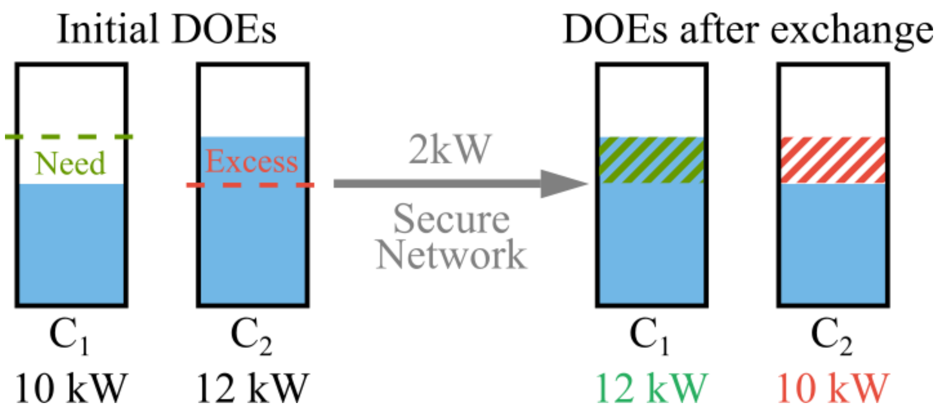


V. Maurizio, A. Bolland, et al. SecuLEx: a Secure Limit Exchange Market for Dynamic Operating Envelopes. *arXiv preprint arXiv:2510.08172* (2025).

SecuLEx implementation

- Once allocated, limits can be exchanged according to evolving needs.
- Exchanges happen through orders to buy (or sell) upper or lower limits of envelopes.
- Orders are cleared only when the new allocation is secure.
- The market is continuously operated until real-time.





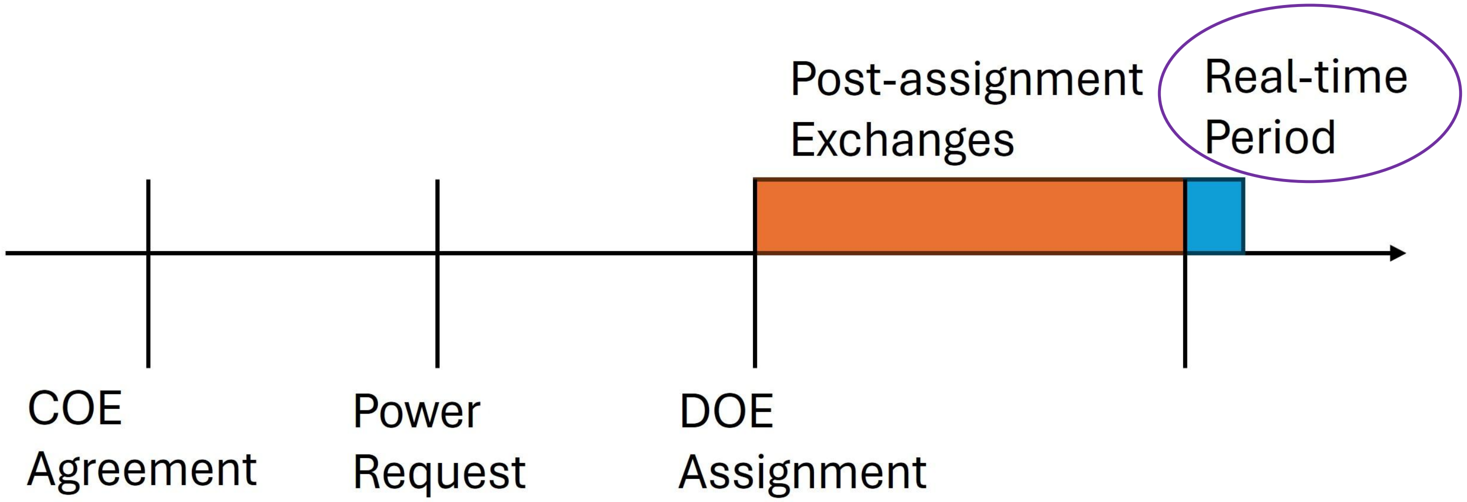
SecuLEx clearing

- Continuously cleared with pay-as-bid settlement.
- Maximum welfare clearing under security constraints.

$$
\begin{aligned}
\max_{a,\mathbf{L}'} \quad & \sum_{b\in\mathcal{B}} \pi_b a_b - \sum_{s\in\mathcal{S}} \pi_s a_s \;, \\
\text{s.t.} \quad & 0 \le a_o \le \Delta P_o && \forall o \in \mathcal{O} \;, \\
& \underline{P}'_c = \underline{P}_c + \sum_{\substack{s\in\mathcal{S}\cap\mathcal{L}:\\ c_s=c}} a_s - \sum_{\substack{b\in\mathcal{B}\cap\mathcal{L}:\\ c_b=c}} a_b && \forall c \in \mathcal{C} \;, \\
& \overline{P}'_c = \overline{P}_c - \sum_{\substack{s\in\mathcal{S}\cap\mathcal{U}:\\ c_s=c}} a_s + \sum_{\substack{b\in\mathcal{B}\cap\mathcal{U}:\\ c_b=c}} a_b && \forall c \in \mathcal{C} \;, \\
& \underline{P}'_c \le \overline{P}'_c && \forall c \in \mathcal{C} \;, \\
& \mathbf{L}' = [\underline{P}', \overline{P}'] \;, \\
& VerifyLimits(\mathfrak{G}, \mathbf{L}') \le 0 \;.
\end{aligned}
$$

Real-time operation

- Each sub-graph operates independently.
- They must respect their envelopes.
- The parent graph can be operated securely.
- The worst-case cost is known.



Recursive approach

- Child graphs are decoupled from the complexity of their parents.
- So far, there is no security guarantee for child graphs!
- They can apply the same decoupling method recursively.
- Eventually, consumers and producers must respect envelopes.

Advantages

- Every computation is limited to a sub-graph.
- Security is ensured by construction.
- Uncertainty sources may be isolated using envelopes.
- Operation and planning are distributed based on local information.
- Operation and planning are effectively simplified and coordinated.

Disadvantages

- Computational and practical overhead for decoupling.
- Decentralized operation under worst-case conditions.
- Open questions on the “network services” needed to respect the envelopes.
- Open research questions on DOE computation, time coupling, etc.
- Open regulatory questions.

Conclusion

- Disruptive solution to simplify secure operation.
- Allows decoupling network operation.
- DOE can be exchanged according to evolving needs.