Data-driven Security-Constrained OPF

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ENTSO-e, 27-Feb-2019

Relevance to the ENTSO-e study

European Grid 2030 and 2050

- Run large-scale studies on a (reduced) ENTSO-e network of 7500 nodes, including TYNDP
- Assess impact of RES penetration and grid reinforcements on the nodal prices

European zonal markets (www.multi-dc.eu)

- Cost recovery of AC and HVDC losses: Develop a methodology to integrate both AC losses and HVDC losses in zonal markets

Redispatching (www.multi-dc.eu) (not in this presentation)

- Sharing reserves between areas to avoid redispatching due to N-1/low inertia

Data-driven Security-Constrained OPF

- Introduce a new market and operation framework that is scalable
- Can handle limitations such as uncertainty, flexible power flows, etc.

Developing the Business-as-Usual Scenario

ENTSO-E + **TYNDP** + **eHighway2050**

2030 Grid

+

~2016 Load and installed RES

ENTSO-e statistical factsheet 2016

Developing the Business-as-Usual Scenario

ENTSO-E + **TYNDP** + **eHighway2050**

2030 Grid
+
~2016 Load and installed RES

ENTSO-e statistical factsheet 2016

Add 2030 projections: (*EUCO30*)

- +20% Load
- +440% Offshore Wind
- +80% Onshore Wind
- +140% PV

Business-as-Usual 2030

The Business-as-Usual Network 2030

Characteristics

- ~7500 nodes
- 8900 AC lines
- ~1000 transformers
- 1269 generators
- 140 DC lines
- 270 converters

RES installed capacity: 63%

160 Hydro power plants

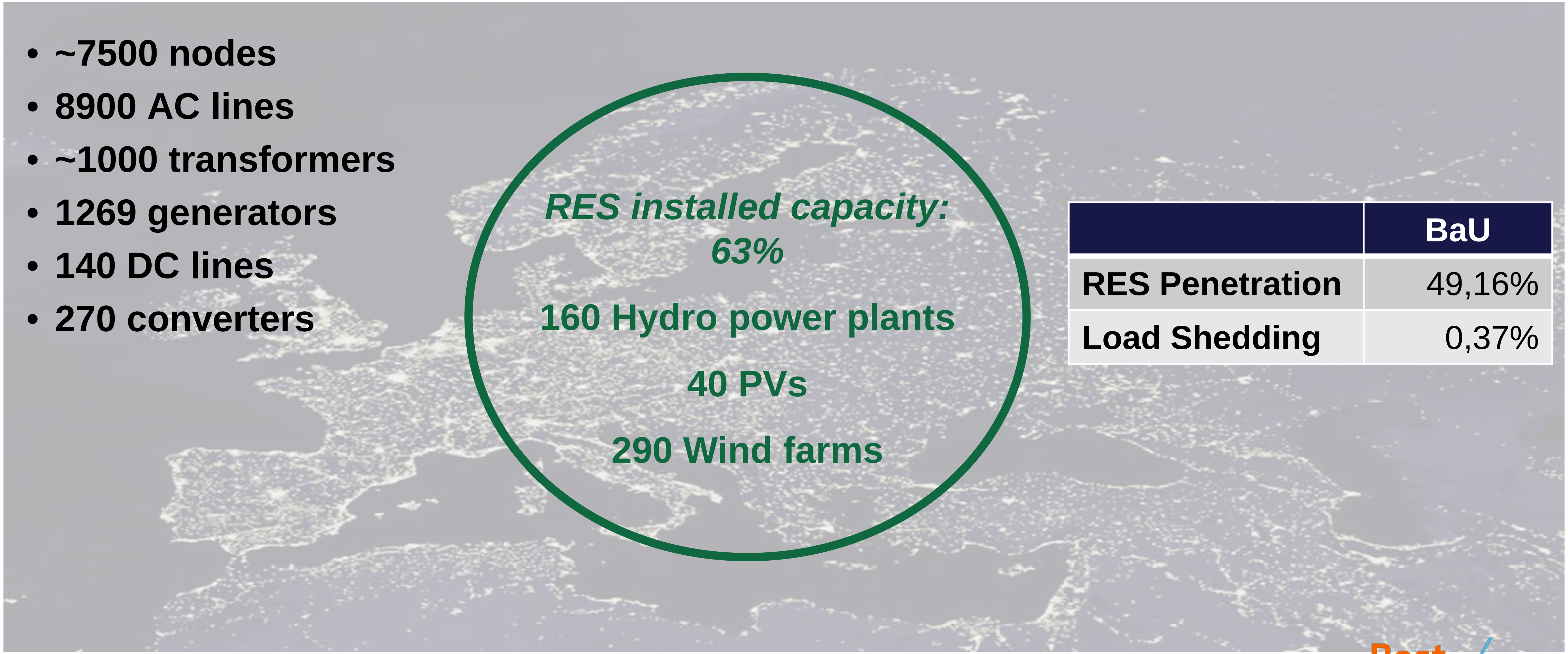
40 PVs

290 Wind farms

60% of RES in the distribution network

The Business-as-Usual Network 2030

Characteristics



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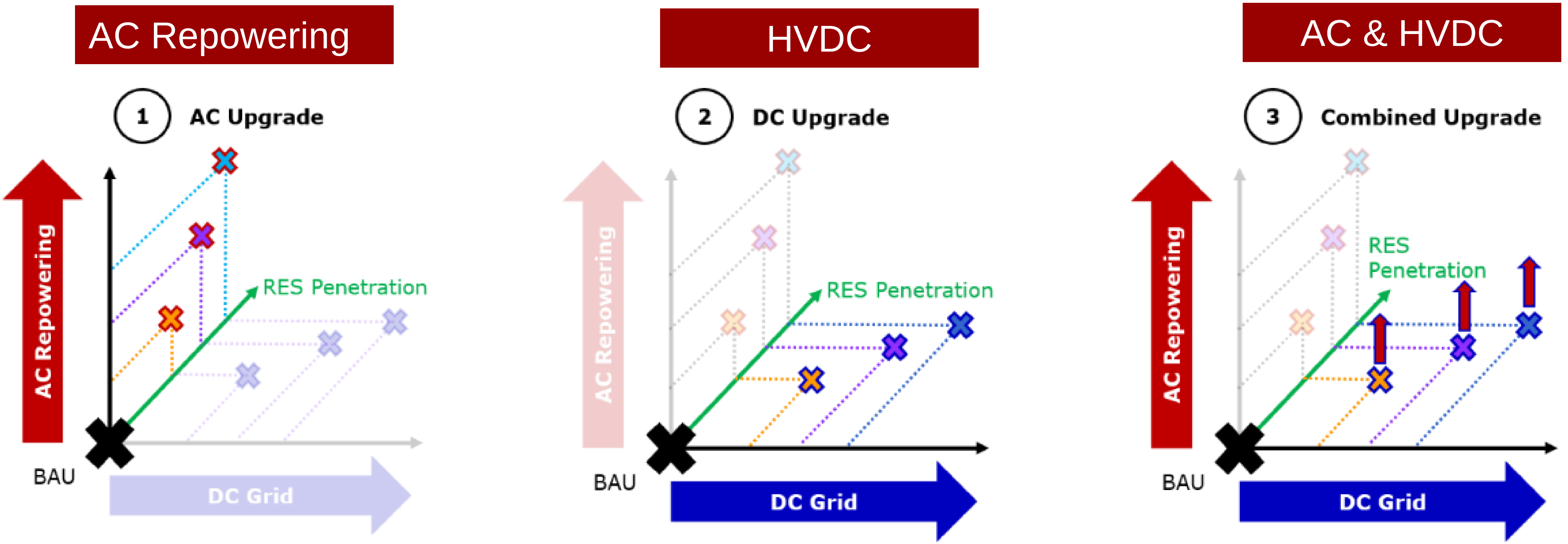
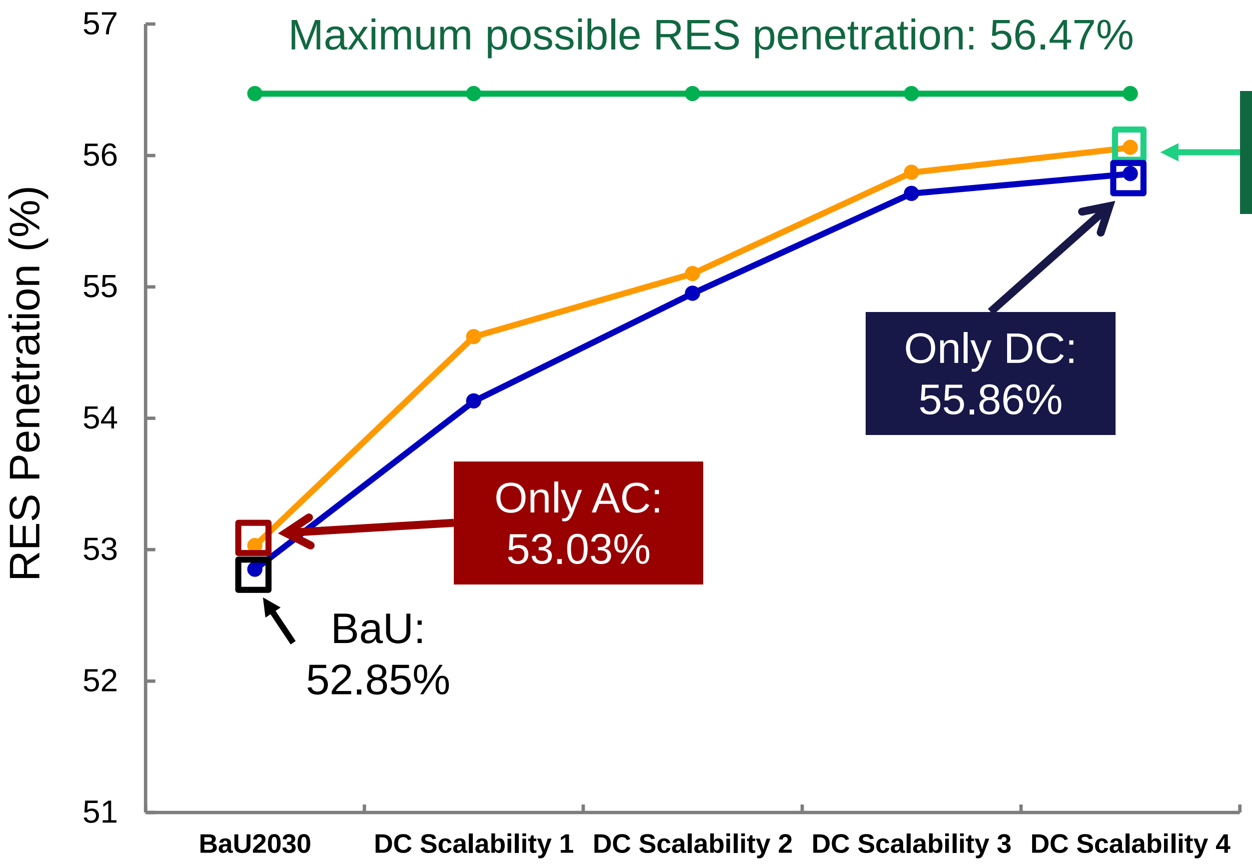
	BaU
RES Penetration	49,16%
Load Shedding	0,37%

Best Paths: Scalability Assessment for 2030



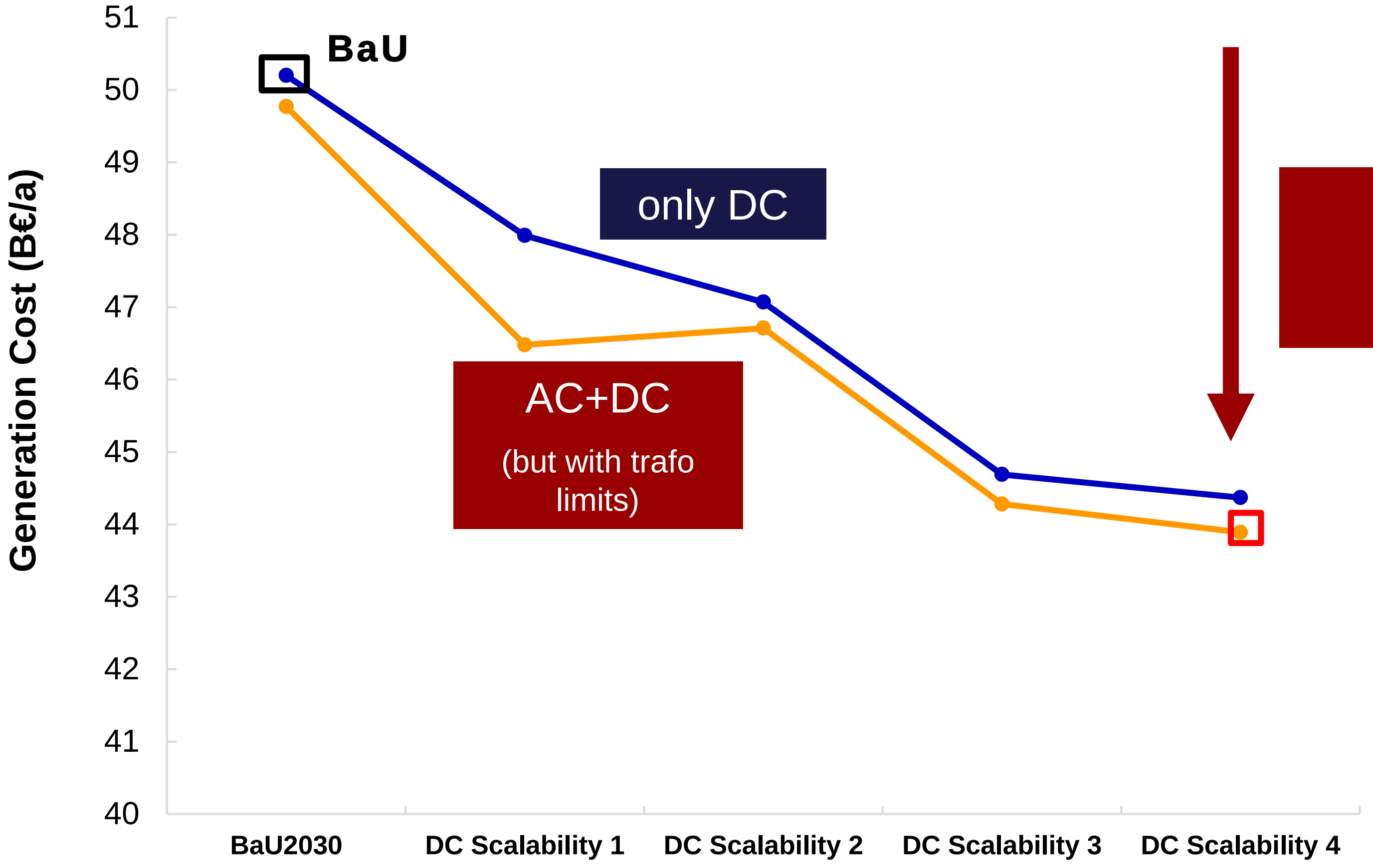
Transmission investments to increase RES penetration by 2030



Highest grid development stage, AC+DC upgrades: 56.06%

- 50 DC lines (150 GW)
- 56 AC lines require upgrade (63.62 GW)
- 20/56 lines: <20% increase

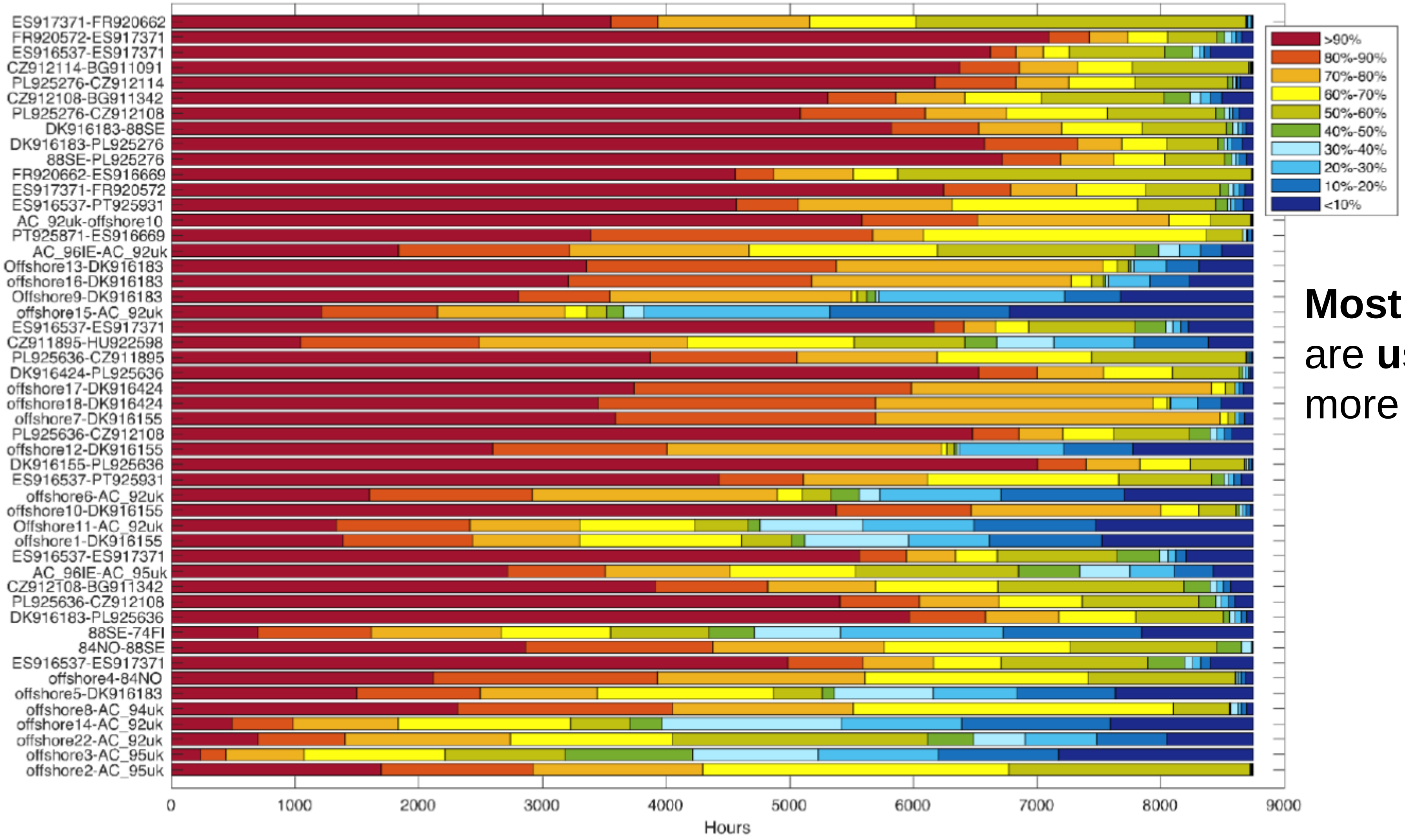
Reducing operating costs by 2030



Savings:

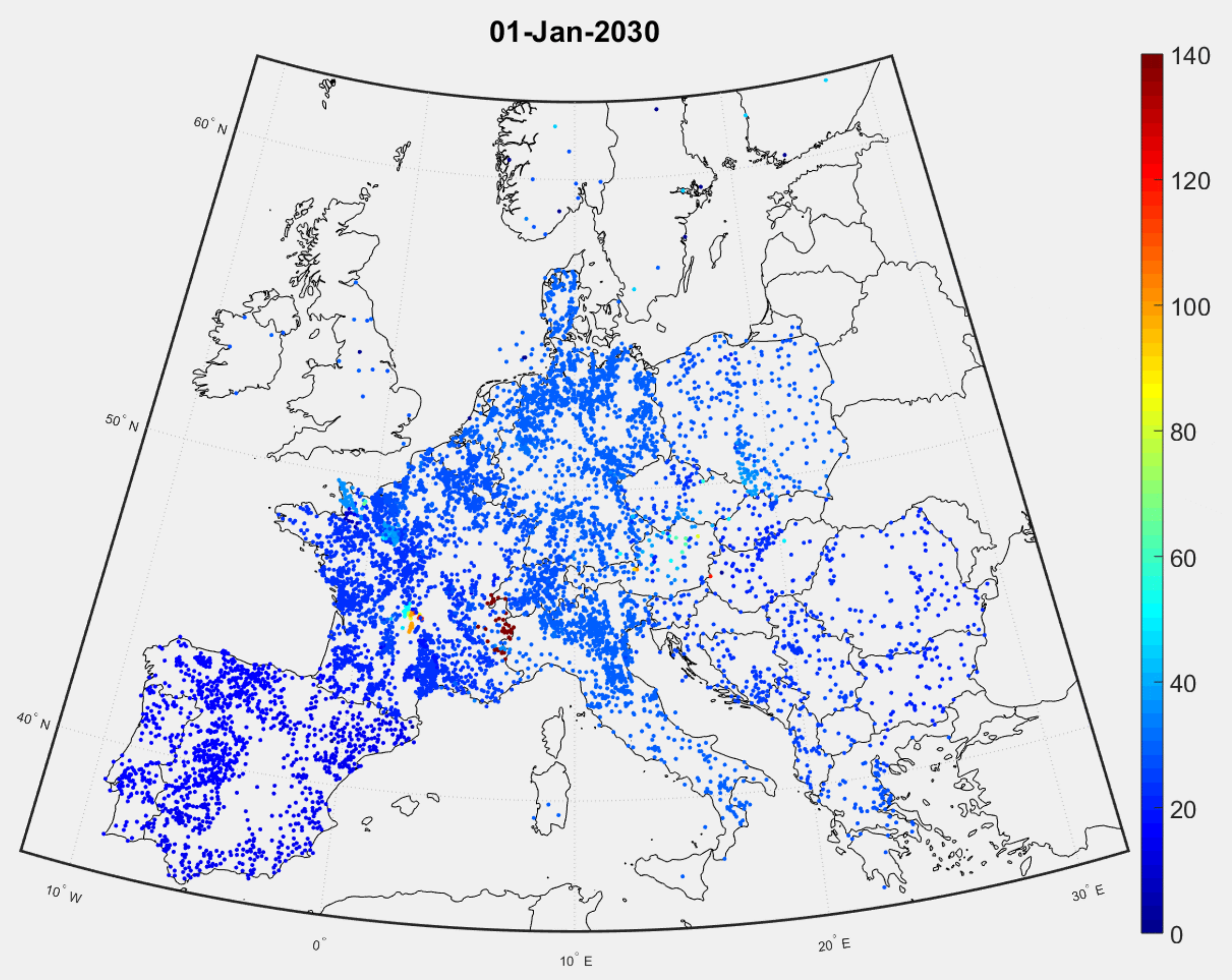
6.3 B€/a

DC Upgrade: Congestion Duration Curves

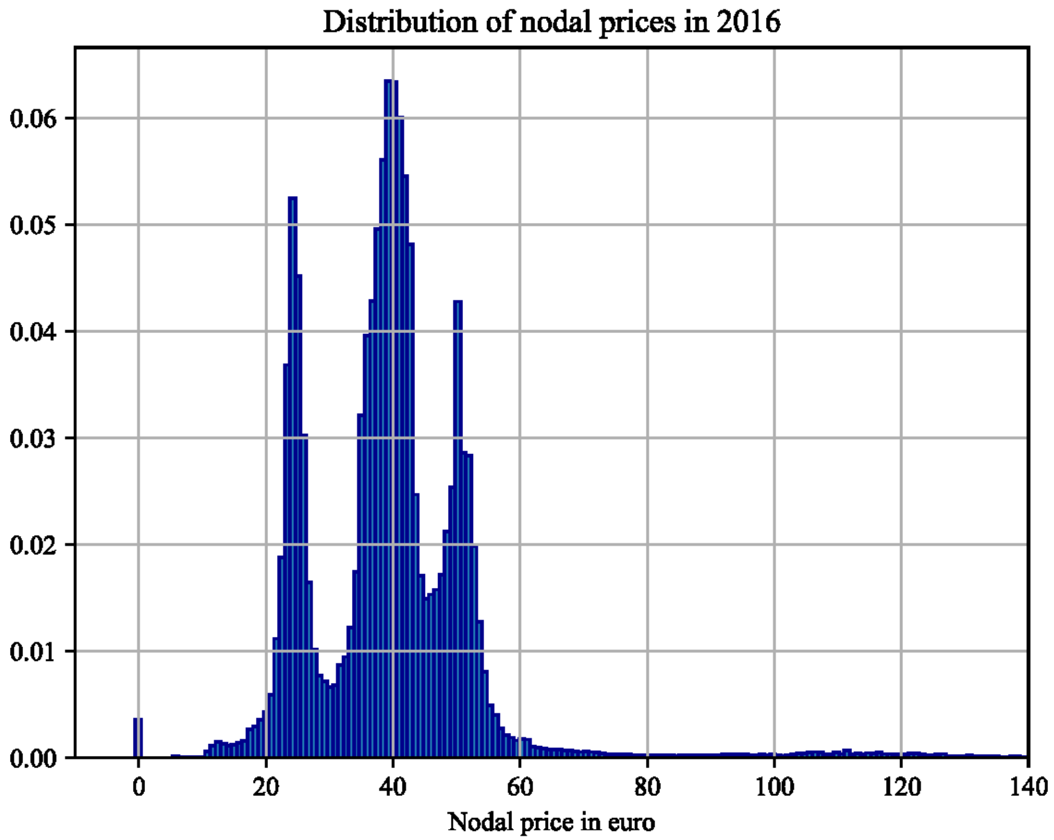


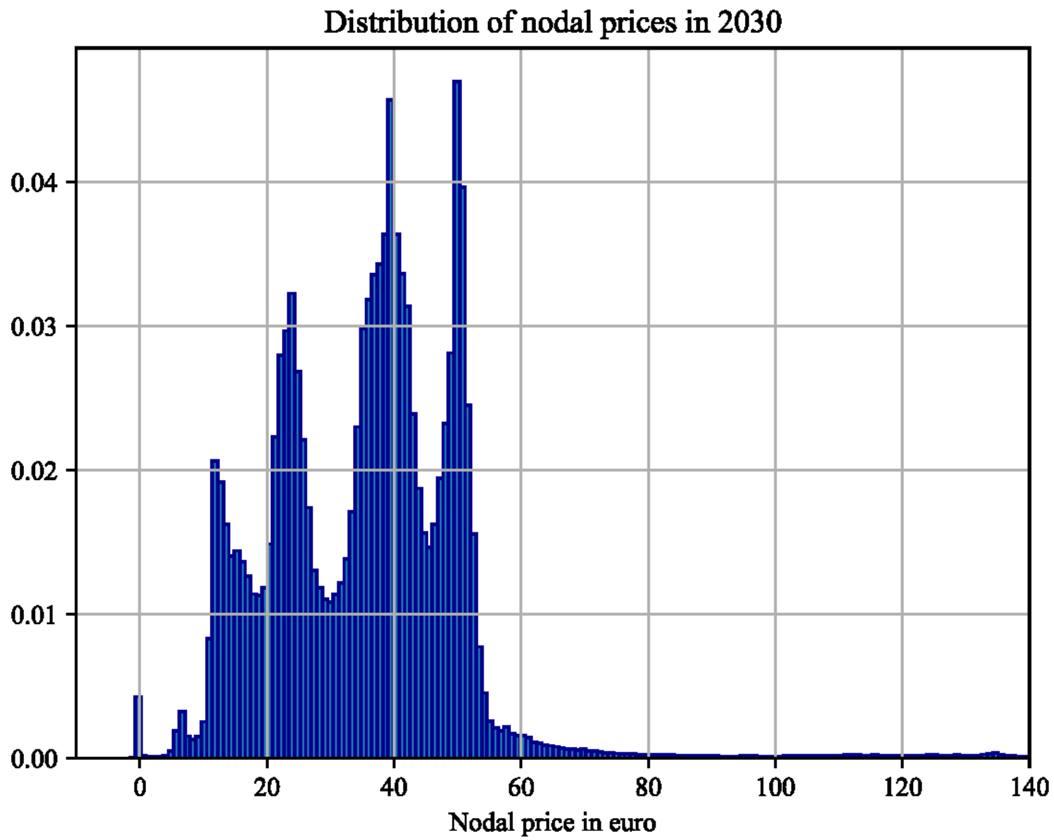
Most of the new **DC lines** are **used up to their limit** more than **50% of the time**

Nodal prices in 2030 (work in progress, no upgrades)



Nodal prices 2016 vs 2030 (work in progress)





- Increased RES presentation increases the variance of nodal prices
- Nodal prices follow a multi-modal distribution → from 3 modes to 4 modes
- Producer surplus decreases

Main Takeaways

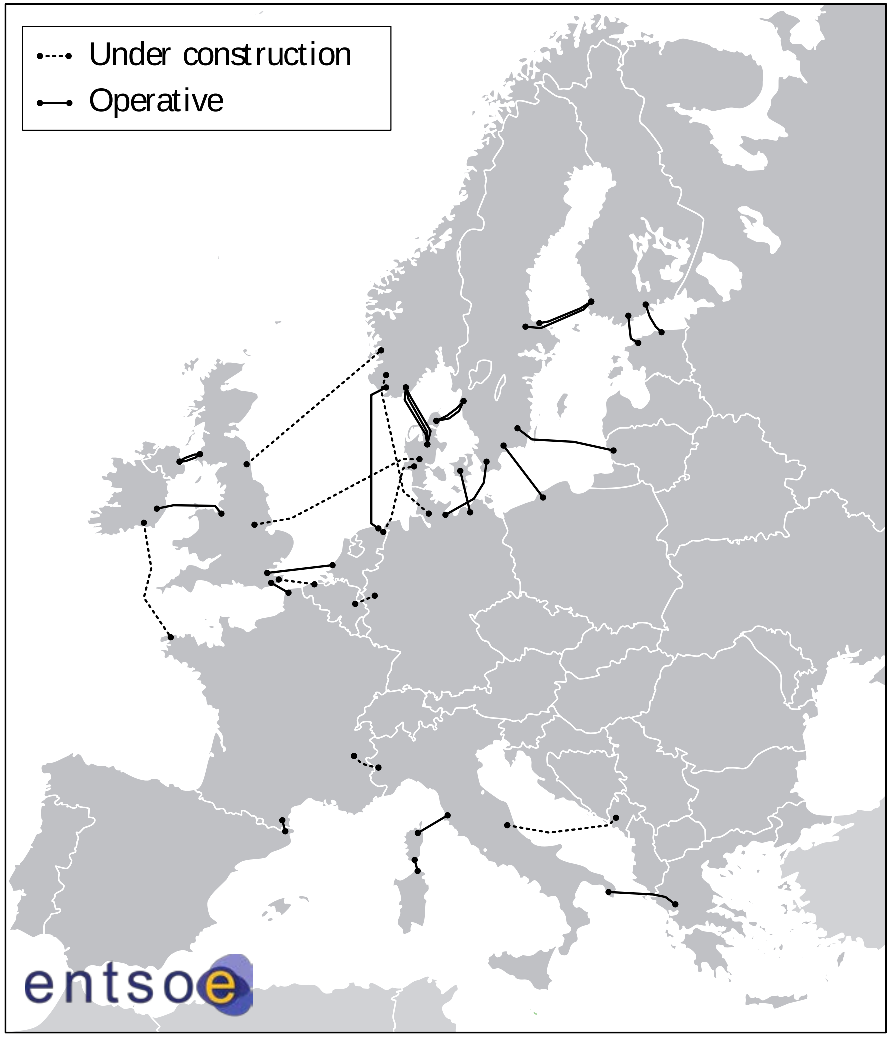
- Offshore wind capacity only deployable with additional corridors
- **Controllable flows are required**: DC upgrades have shown substantially better performance
- **Optimal grid development: AC & DC** → AC upgrades enable full potential of DC & vice versa
- Transformer bottlenecks need to be considered

Nodal pricing (preliminary insights)

- France seems to experience often extremely high prices at certain regions
- Prices within the former UCTE synchronous areas 1 and 2 seem to be more uniform
- Increased RES presentation increases the variance of nodal prices
- Nodal prices follow a multi-modal distribution

Market Integration of HVDC: Pricing losses

Motivation



- **HVDC interconnectors:**
  - usually longer than **AC** interconnectors
  - often connecting areas belonging to different TSOs (at least in Europe)
- **As a result**, the losses occurring on HVDC lines are not negligible, and the cost has to be shared among TSOs
- If **price difference** between areas is **small**, TSOs cannot recover the cost of HVDC losses, i.e. cost of losses higher than potential revenue

Some examples - Denmark

- In 2017 the **price difference** between **SE3** and **DK1** has been zero for more than 5300 hours (**61%**), resulting in **1.2 M€** losses.

- In 2017 the **price difference** between **DK1** and **DK2** has been zero for more than 6400 hours **(73%),** resulting in **0.8 M€** losses.

- In 2017 the **price difference** between **DK1** and **NO2** has been zero for more than 4000 hours **(47%)**, resulting in **3.2 M€** losses.

Source: https://www.nordpoolgroup.com/

Some examples - Finland

- In 2017 the **price difference** between **FI** and **EE** has been zero for more than 6600 hours (**76%**), resulting in **3 M€** losses.

- In 2017 the **price difference** between **FI** and **SE3** has been zero for more than 8600 hours (**99%**), resulting in **3.8 M€** losses.

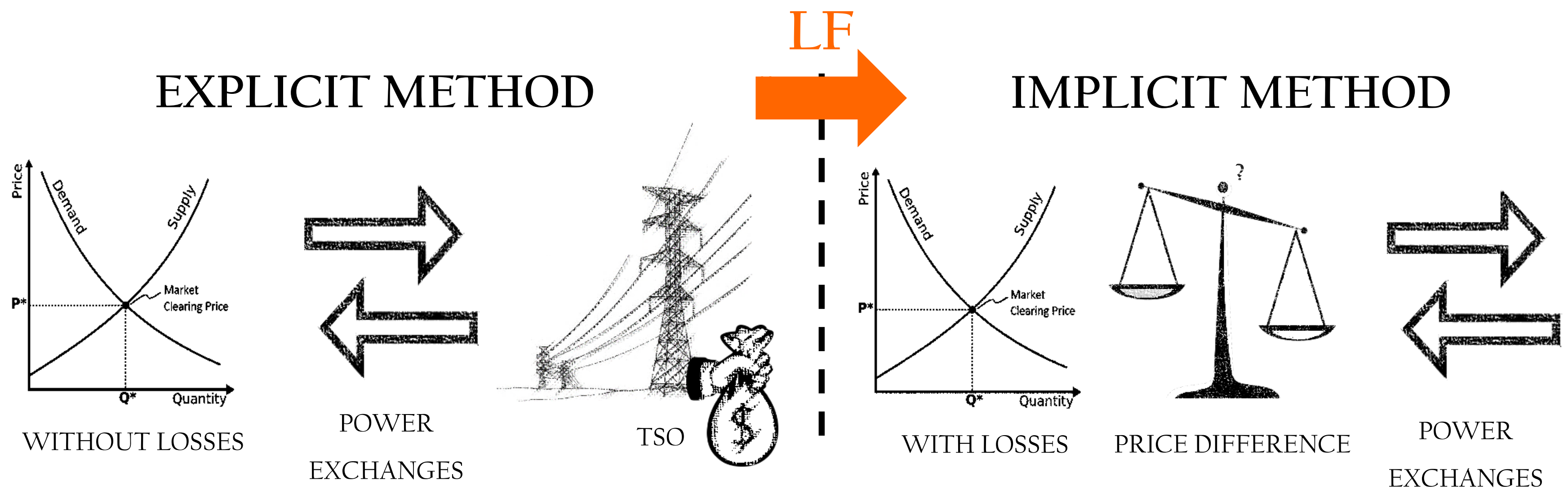
- For these **5 HVDC interconnectors**, losses amounts to **12 M€ per year.**

- Considering the number of HVDC interconnectors and all the new projects, this number is intended to **grow significantly.**

Source: https://www.nordpoolgroup.com/

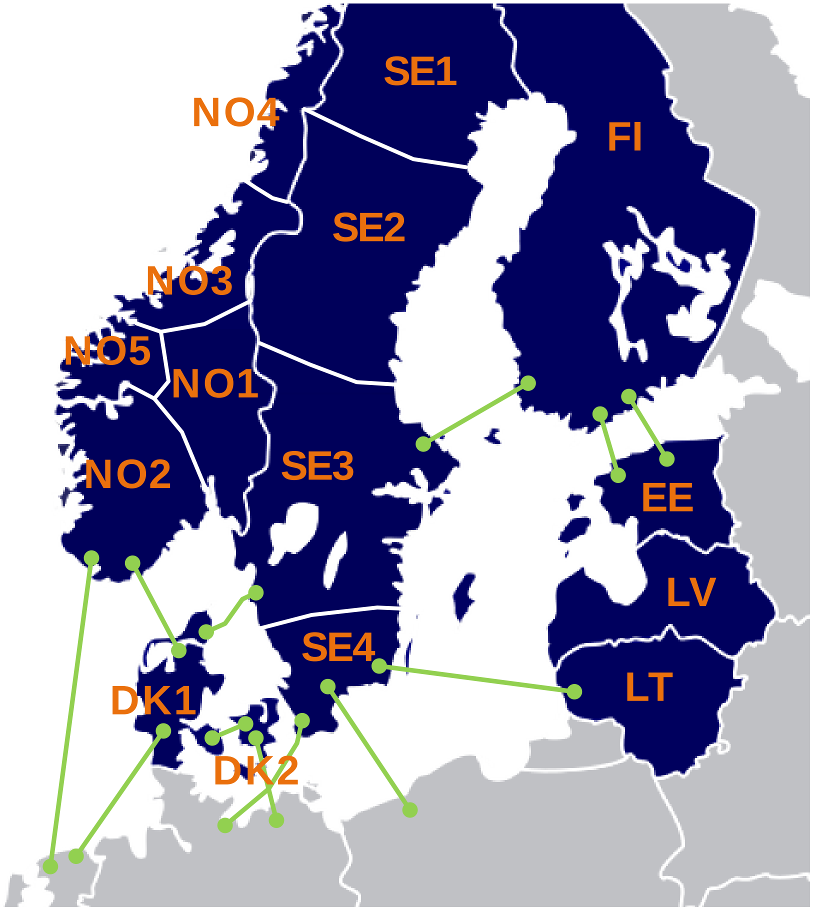
Problem statement

- **Losses** are handled in a different way for AC and HVDC lines.
- For **HVDC lines:**

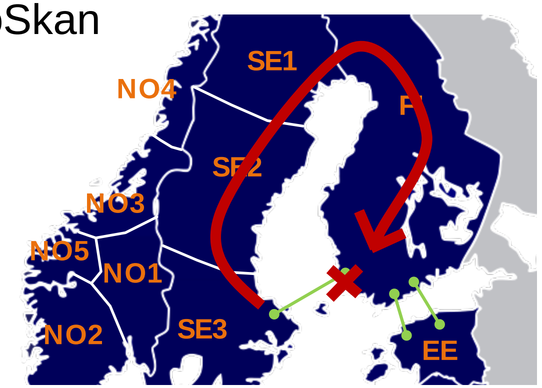


- To move from the explicit to the implicit method, a **loss factor** has to be included in the market clearing algorithm.
- **Is it a good idea to introduce a loss factor <u>only</u> for HVDC lines in meshed grids?**

Implicit grid losses - Nordic CCR



- Nordic TSOs, April 2018: *Analyses on the effects of implementing* ***implicit grid losses*** *in the* ***Nordic CCR***
- All simulations with implicit grid losses show an economic benefit
- One exception is FennoSkan

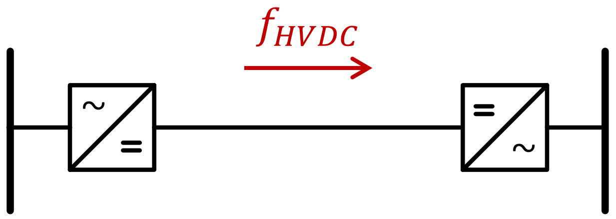


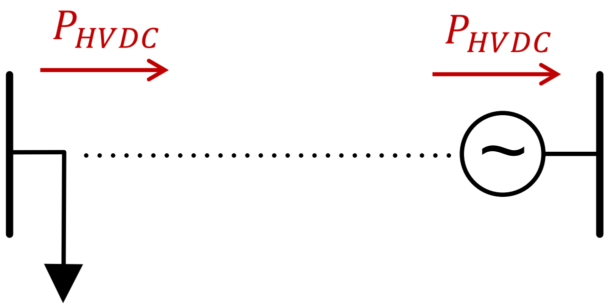
- The higher the number of lines with implicit losses implemented, the higher the benefit

* Fingrid, Energinet, Statnett, Svenska Kraftnät, *Analyses on the effects of implementing implicit grid losses in the Nordic CCR*, April 2018

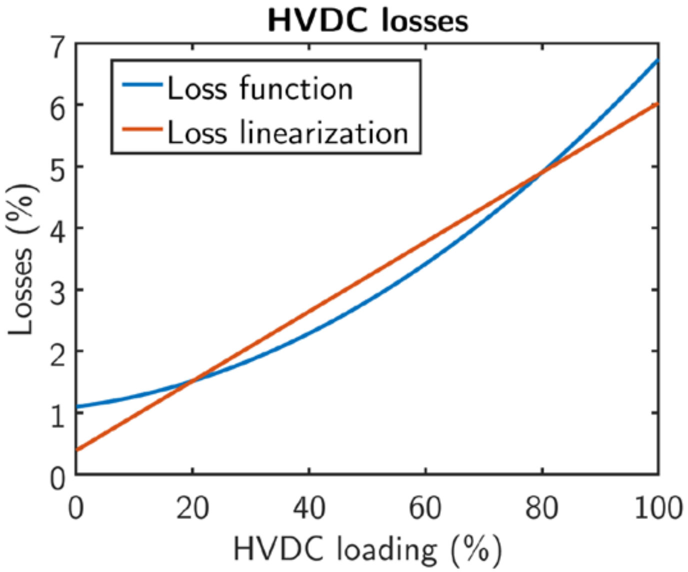
HVDC line model

- Simple linear model





- Losses
  - **Quadratic losses** for HVDC converters and HVDC lines
  - Losses are considered as an **extra load equally shared** by the sending and the receiving node
  - **Linearization** of losses for their introduction in the market clearing algorithm



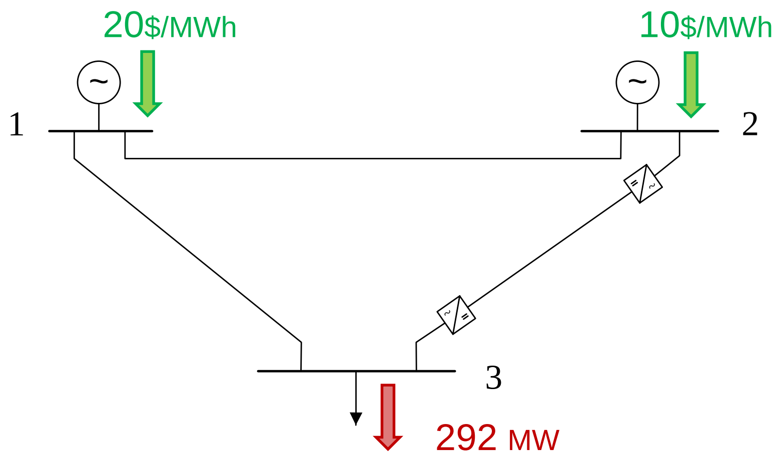
Example: impact on prices

No Congestion

Prices	without LF ($/MWh)	with LF ($/MWh)
Zone 1	10.00	10.00
Zone 2	10.00	10.00
Zone 3	10.00	10.38

With Congestion → Loss is absorbed in the congestion rent

Prices	without LF ($/MWh)	with LF ($/MWh)
Zone 1	20.00	20.00
Zone 2	10.00	10.00
Zone 3	20.00	20.00

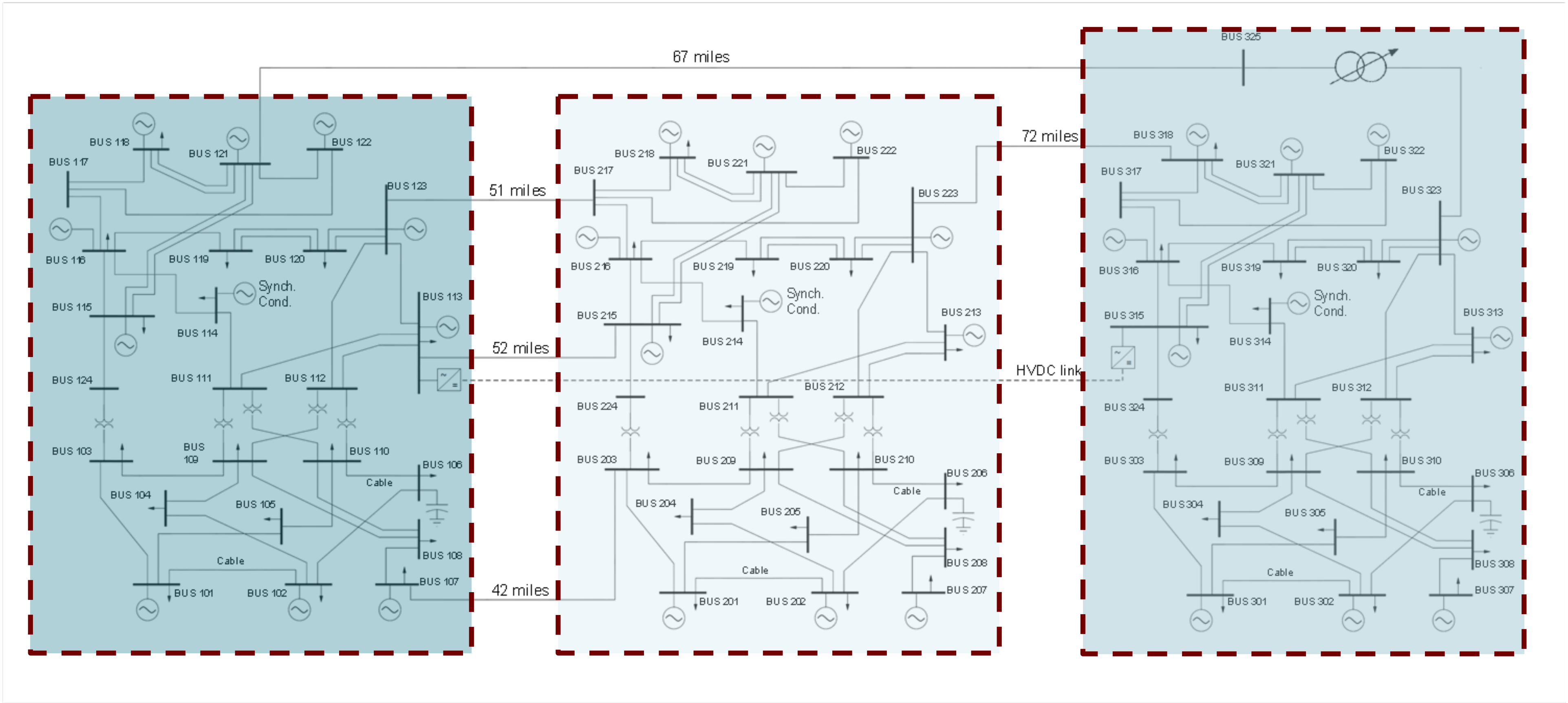


2 DC lines: 1-2, 2-3

Inter-TSO compensation

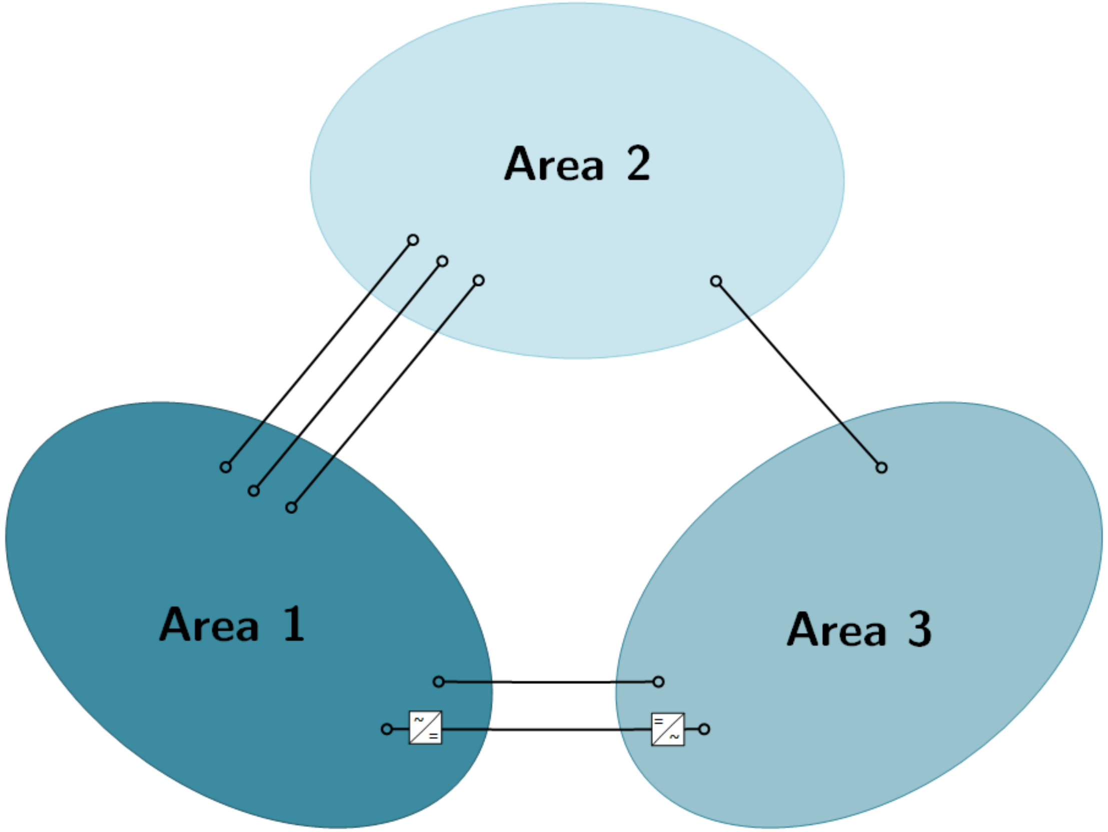
Prices	without LF ($/MWh)	with LF ($/MWh)
Zone 1	20.00	20.00
Zone 2	20.00	20.82
Zone 3	20.00	21.61

Test case: IEEE RTS system



AREA 1 **AREA 2** **AREA 3**

Test case: IEEE RTS system



A. Tosatto, T. Weckesser, S. Chatzivasileiadis, *Market Integration of HVDC lines*, Submitted. Available: https://arxiv.org/abs/1812.00734

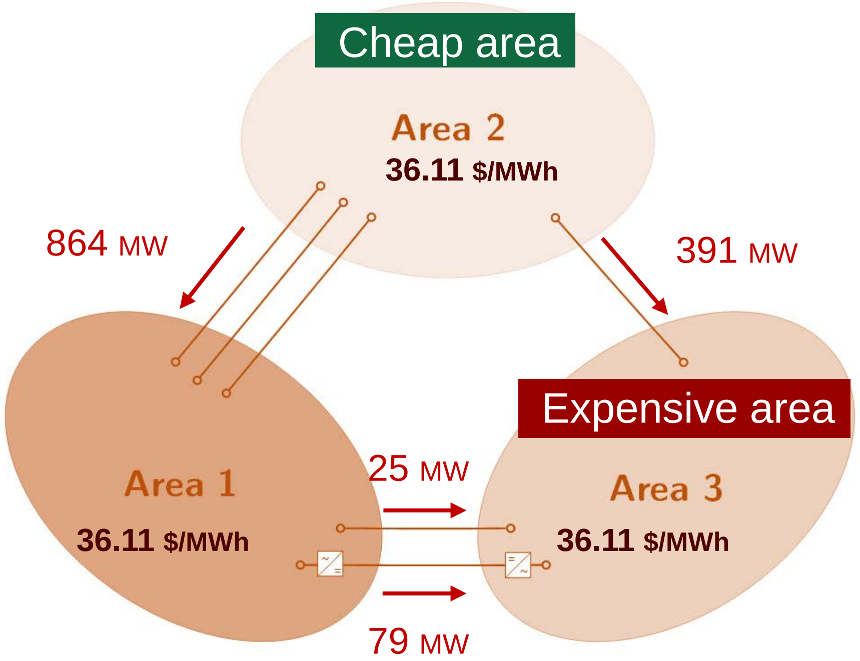
For **each area**:

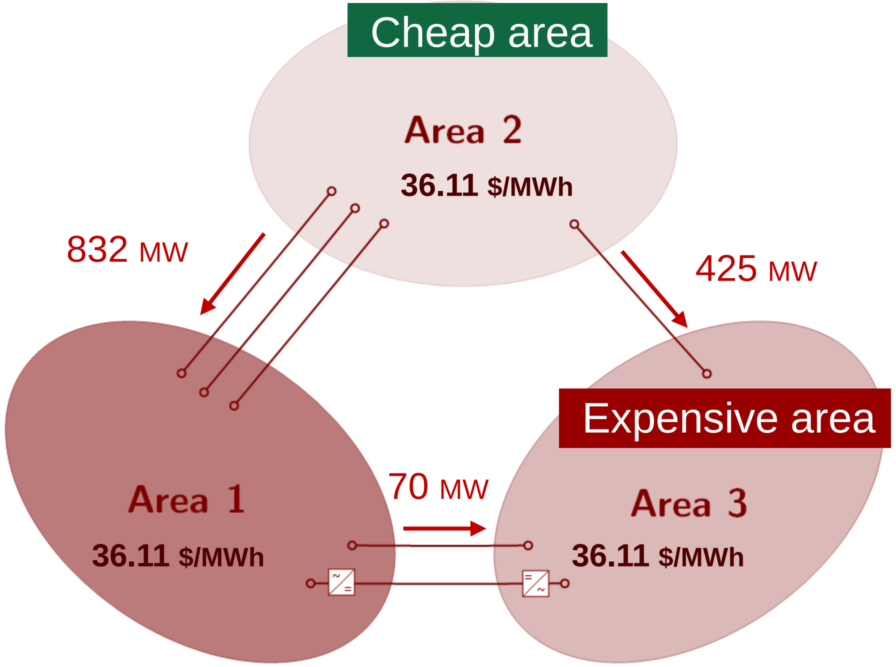
- 32 producers and 17 consumers

Flow-based market coupling

- Estimation of the PTDF matrix: marginal variations in one generator at a time
- Emulate how TSOs purchase the required power to cover their losses
- Equilibrium problem: each market participant seeks to maximize its profit

Test case 1: some results



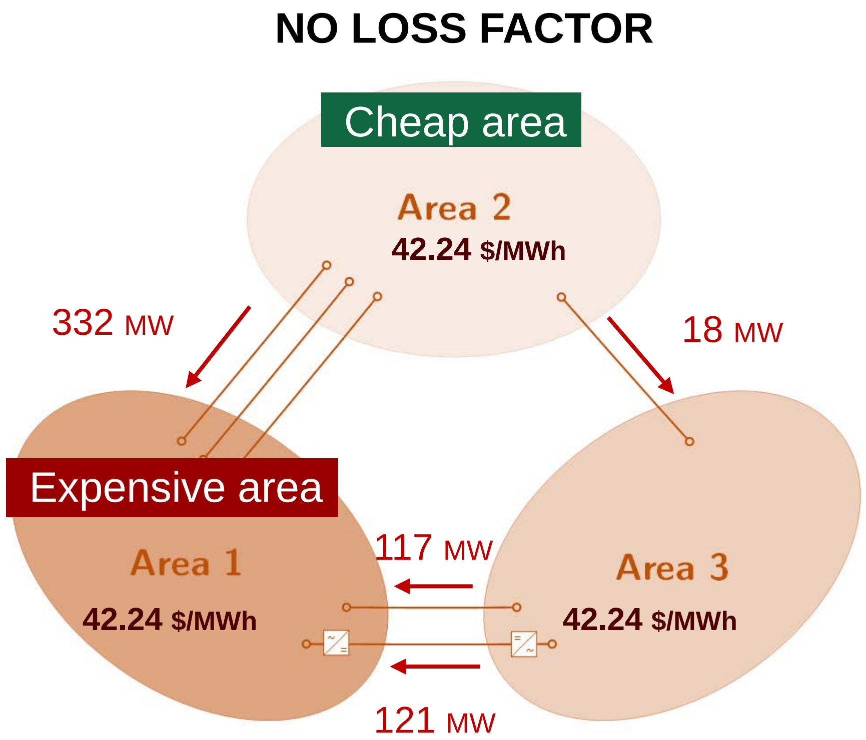


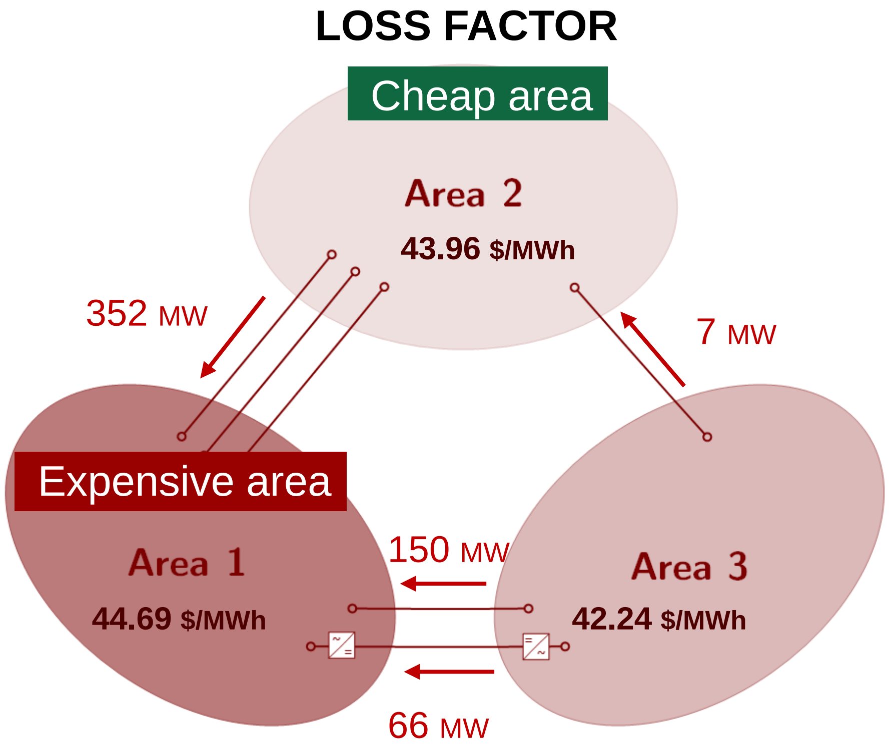
Loss factor	AC losses	HVDC losses
NO LF	254.6 MW	4.5 MW
HVDC LF	250.5 MW	2.2 MW

Δ Cost HVDC	Δ Cost AC
84.58 $/h	151.39 $/h

Economic benefit: 235.97 $/h

Test case 1: some results





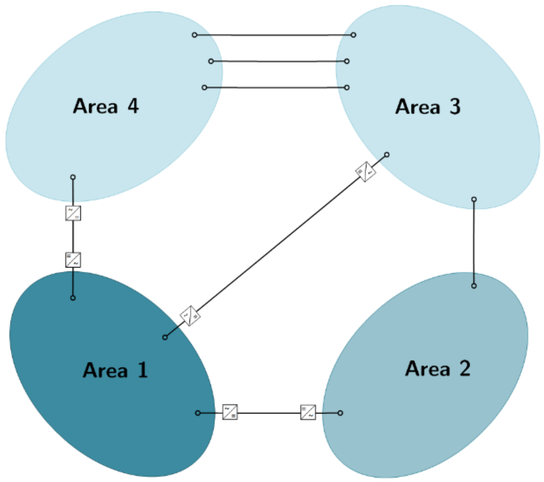
Loss factor	AC losses	HVDC losses
NO	182.5 MW	6.9 MW
HVDC	186.9 MW	4.0 MW

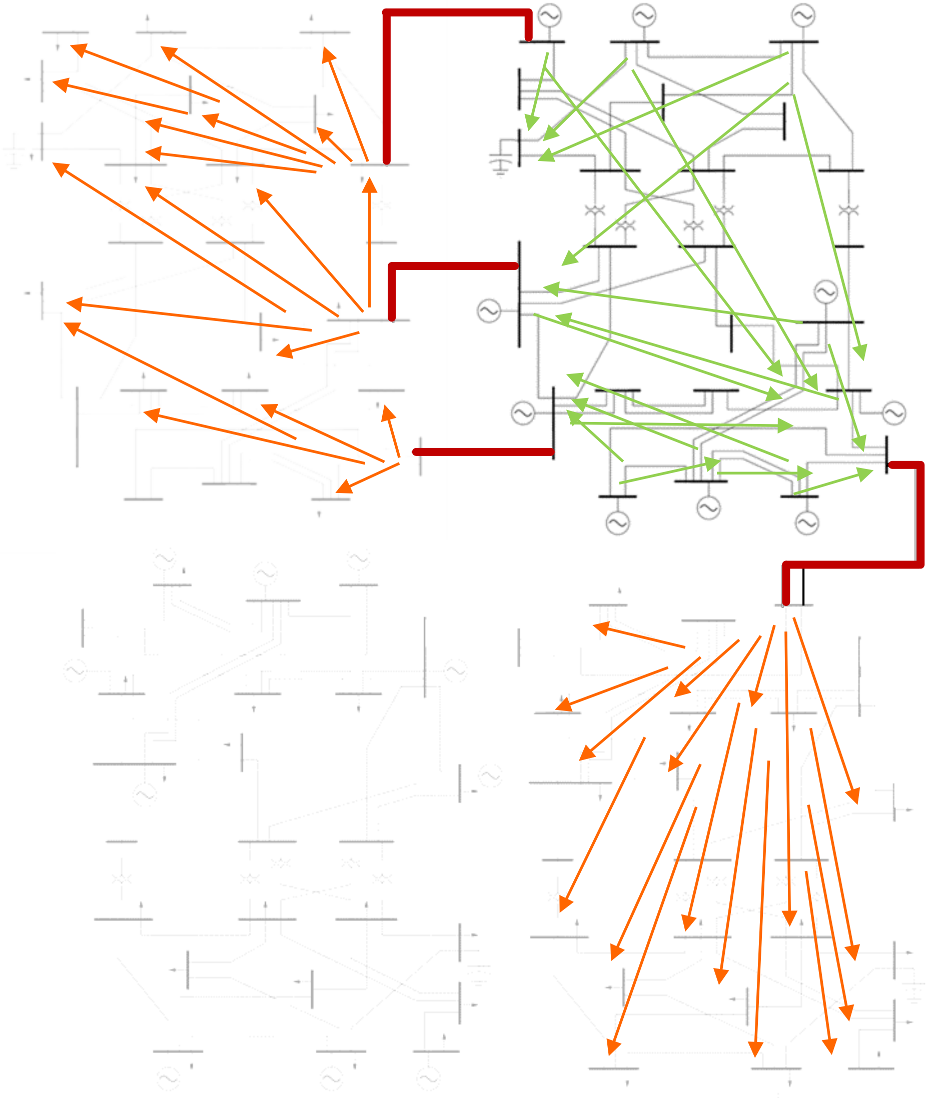
Δ Cost HVDC	Δ Cost AC
282.66 $/h	-484.25 $/h

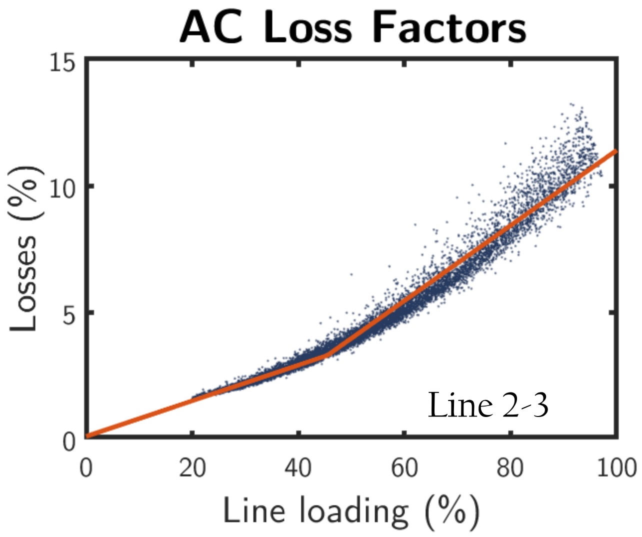
Economic loss: 201.59 $/h

AC loss factors

System emulating DK1, DK2, SE, NO







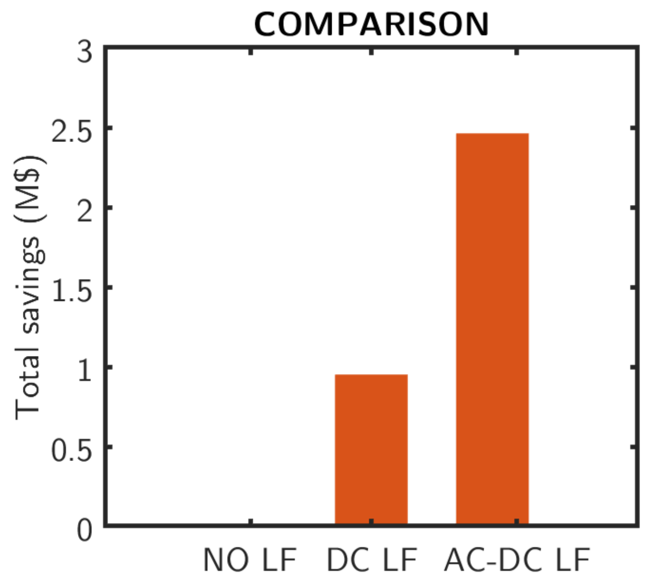
More info:

A. Tosatto, T. Weckesser, S. Chatzivasileiadis, *Market Integration of HVDC lines*, available: https://arxiv.org/abs/1812.00734

www.multi-dc.eu

Economic evaluation

- The results show that the introduction of HVDC loss factors for this specific system is **beneficial** for most of the time.
- However, there are cases where the social welfare is **decreased** (**>14%**).
- Theory guarantees that this does not happen with LFs for **both AC** and **DC** systems
- The introduction of AC-LFs **double** the benefit.



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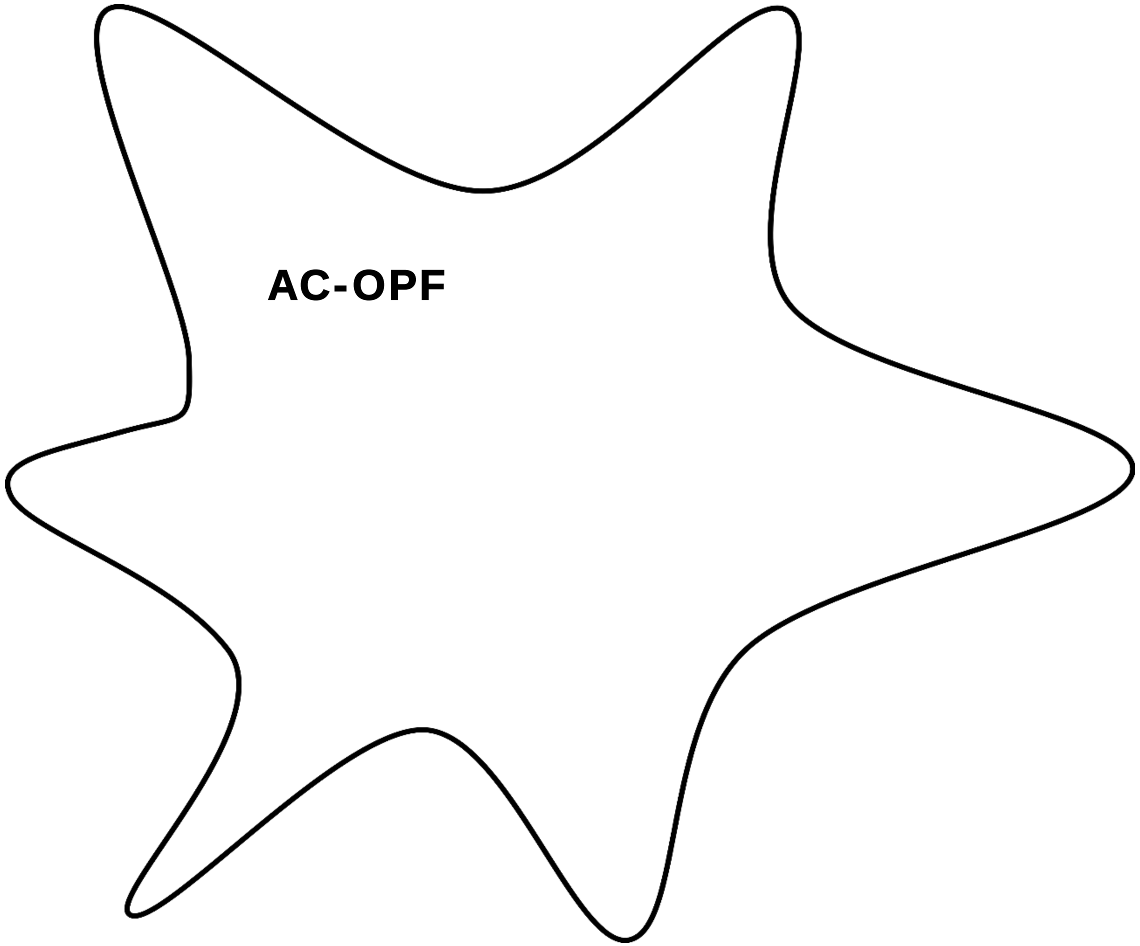
www.multi-dc.eu

Conclusion

- **Is it a good idea to introduce a loss factor only for HVDC lines in meshed grids?**
- The HVDC loss factor can act positively or negatively w.r.t. the amount of system losses depending on the **system under investigation**.
- If to be introduced in the market clearing algorithm, the recommendation is to consider the losses in **both AC** and **DC systems**.

Data-driven Security-Constrained OPF

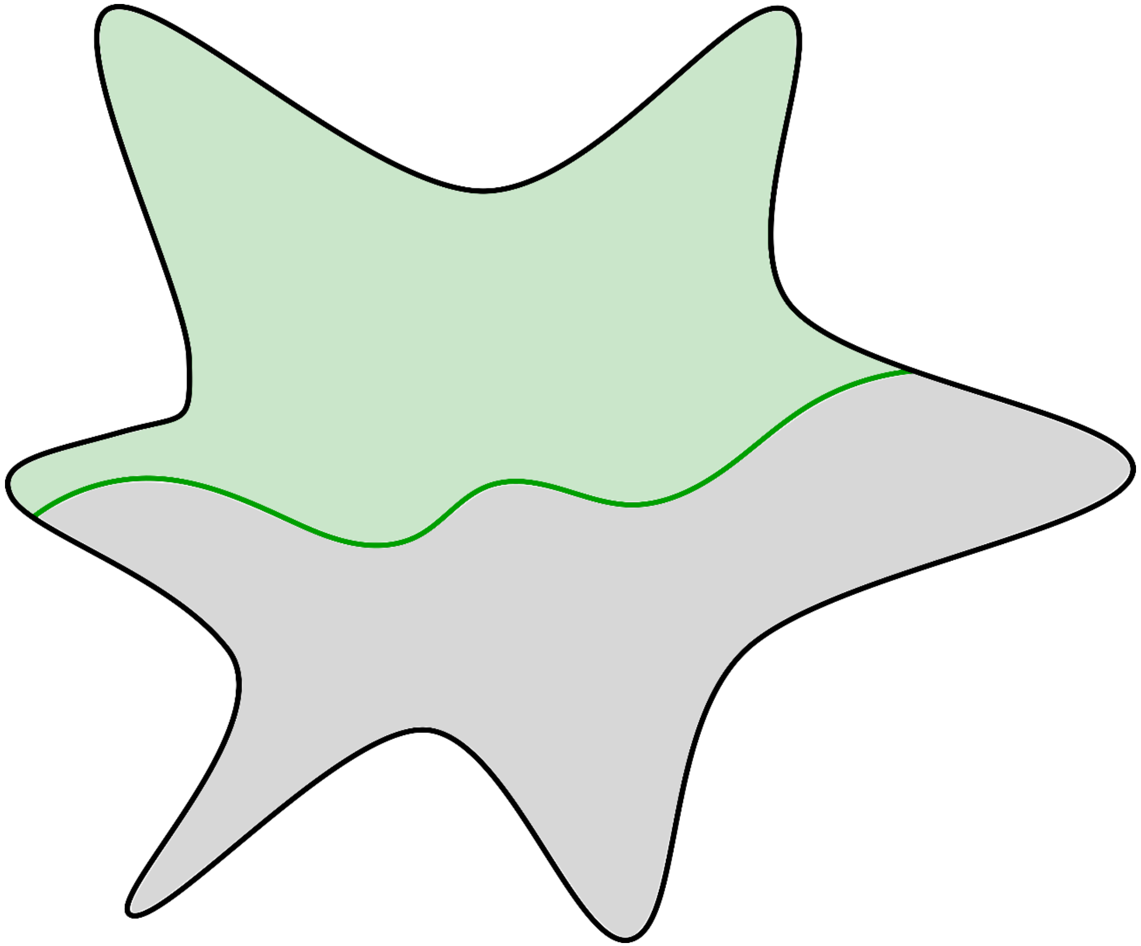
The feasible space of power system operations



- Nonlinear and nonconvex

  AC power flow equations
- Component limits

The feasible space of power system operations



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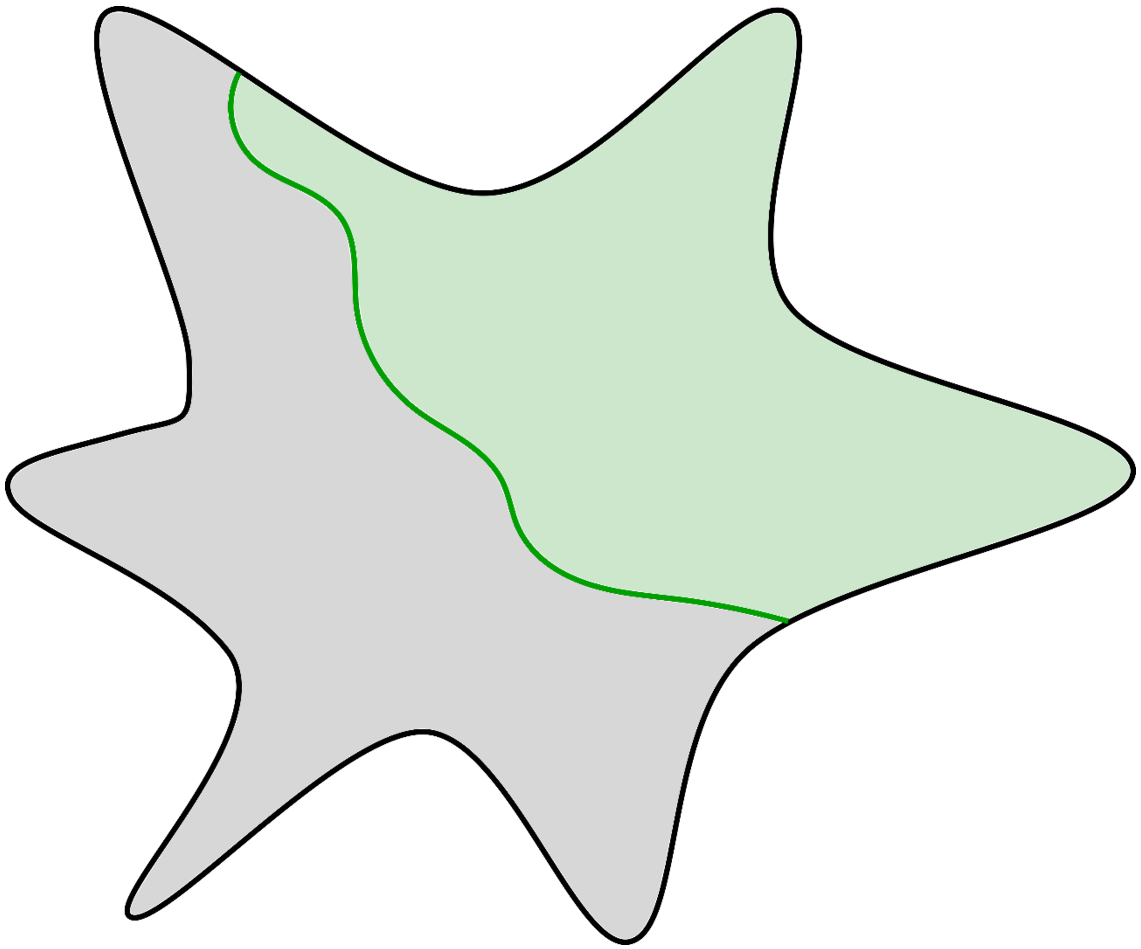

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\+ Other security criteria (e.g., N-1)

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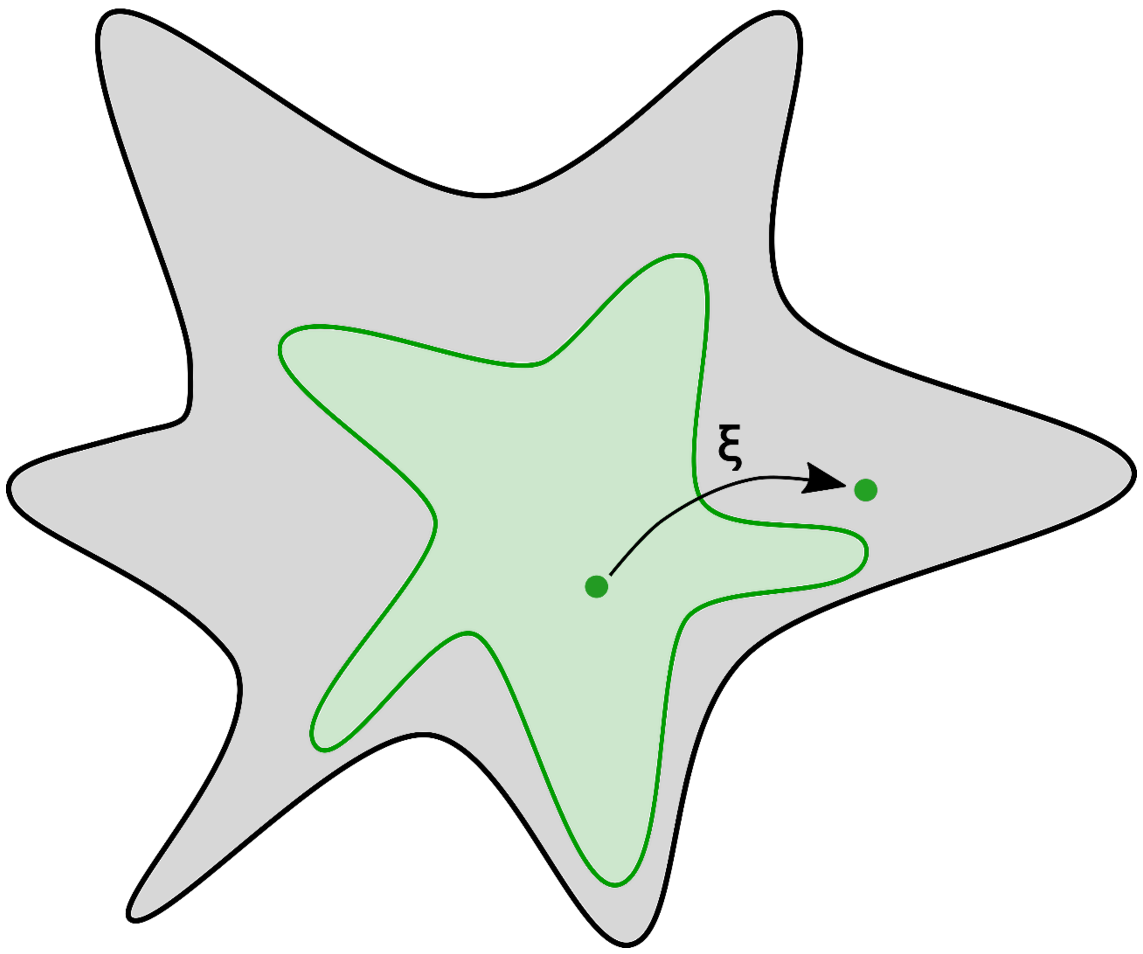

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\+ Uncertainty **ξ** in nodal power injections

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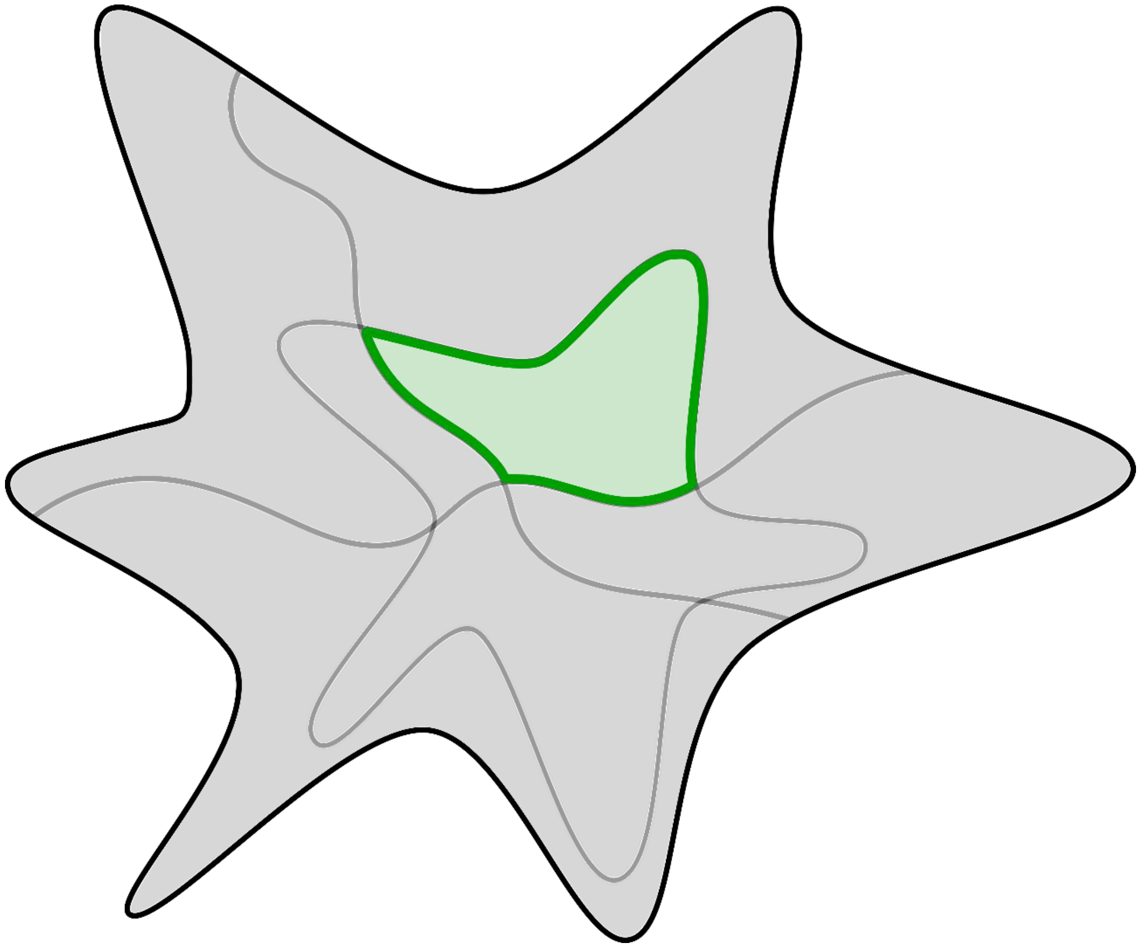

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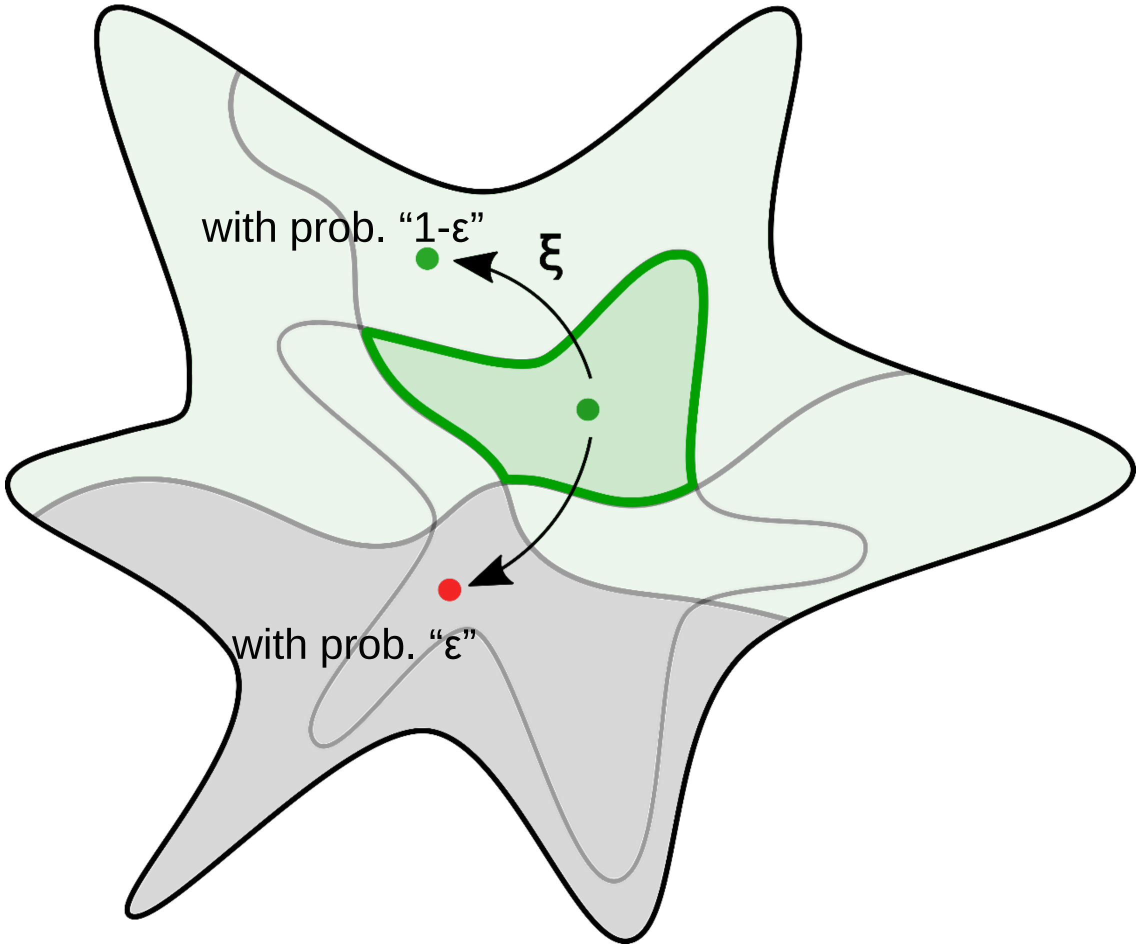

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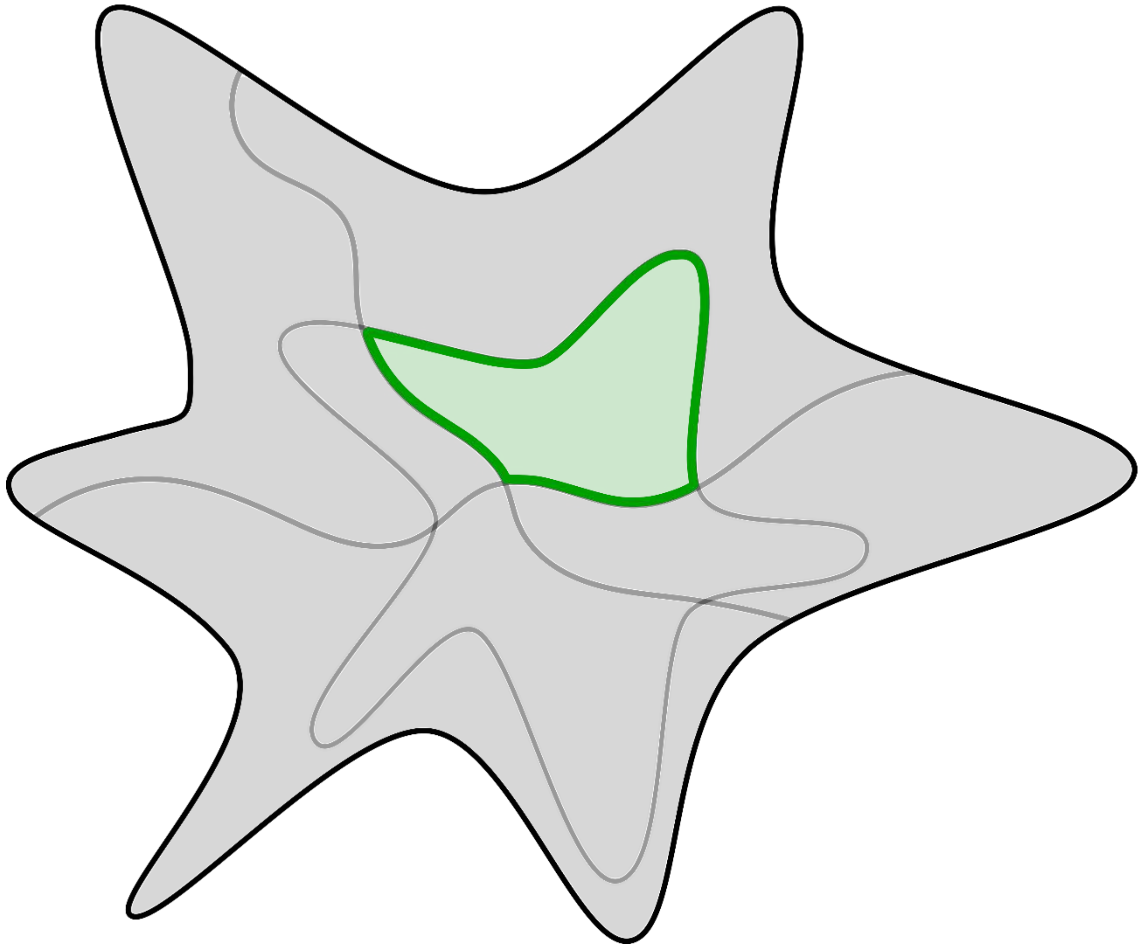
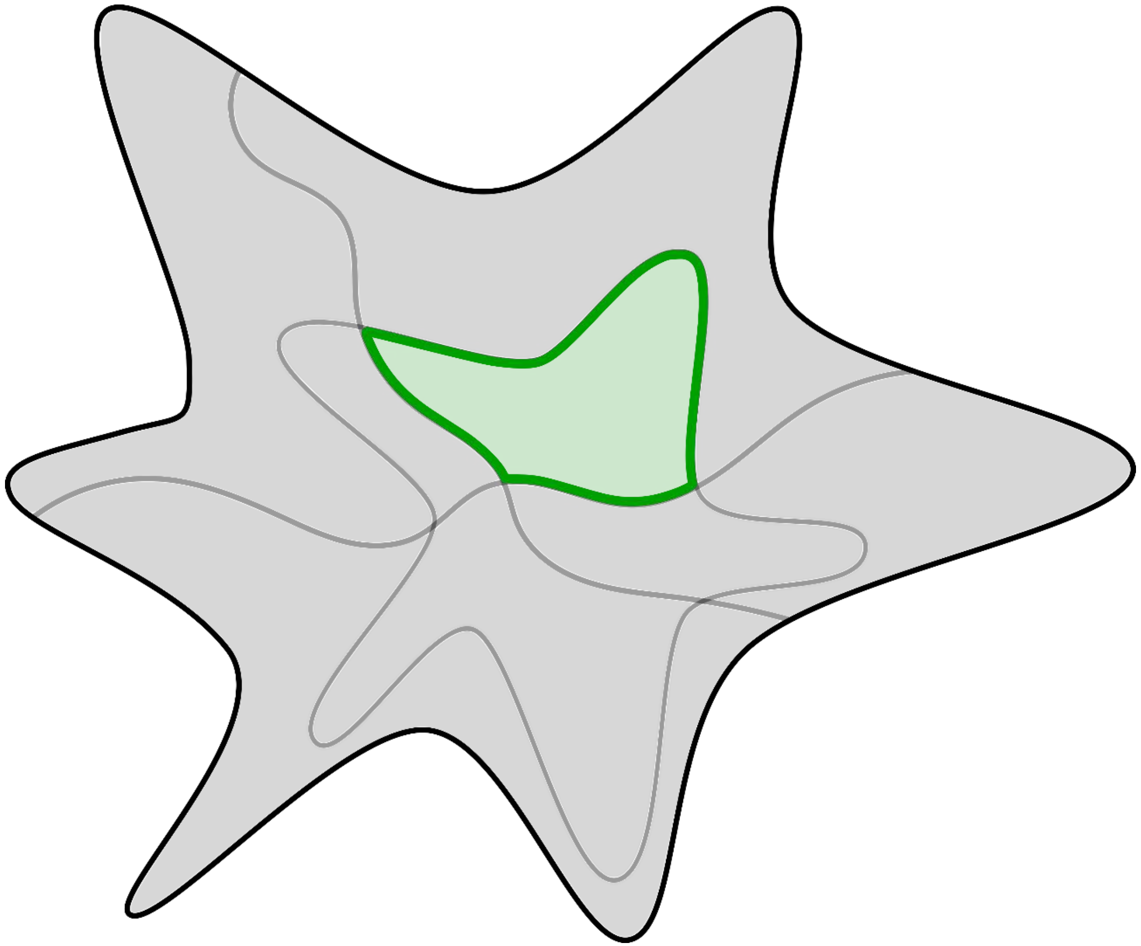
Operational Challenges



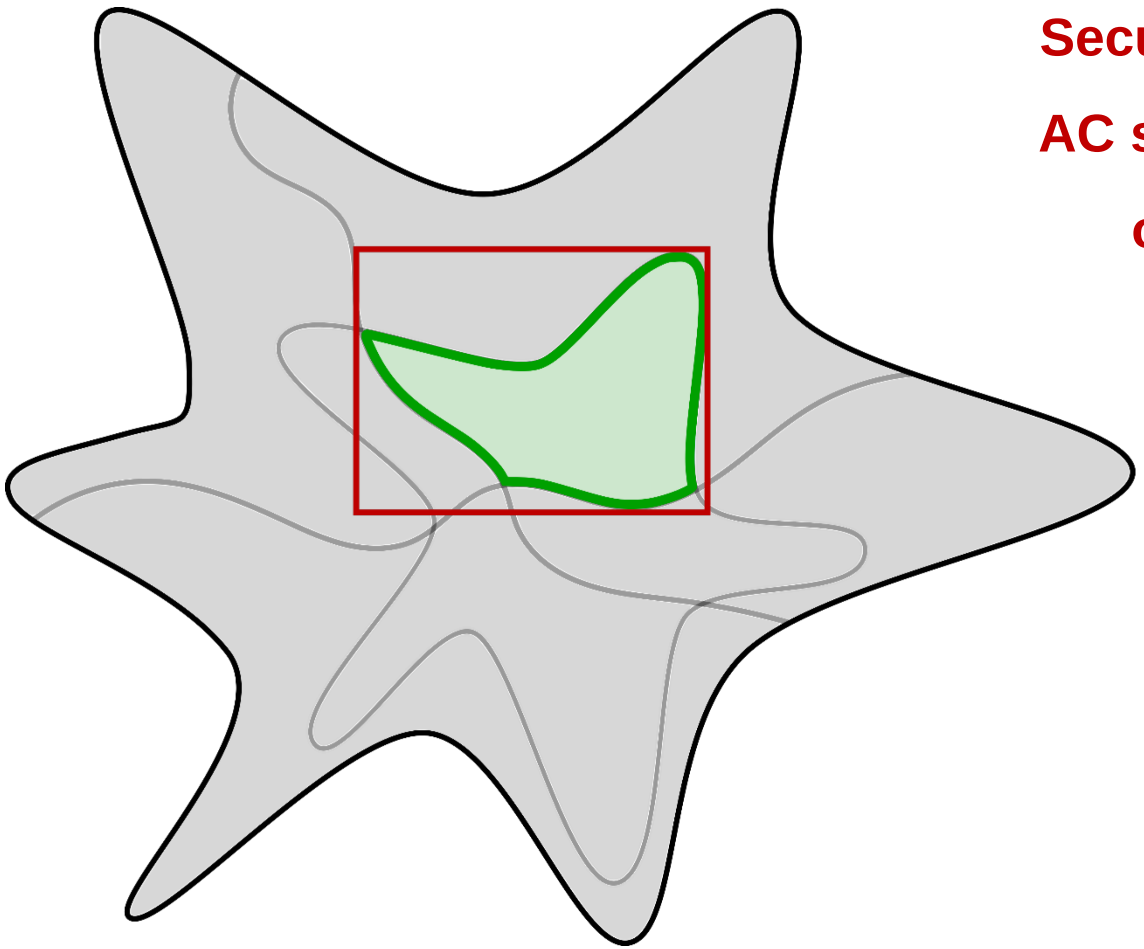
- Identifying the boundary of the feasible operating region
- Incorporating the boundary in an optimization framework
- Finding the true optimal solution & maintaining computational efficiency

How to encode the feasible operating region for electricity markets?



Security considerations live in AC space, but market is based on DC approximations!

How to encode feasible operating region for electricity markets?

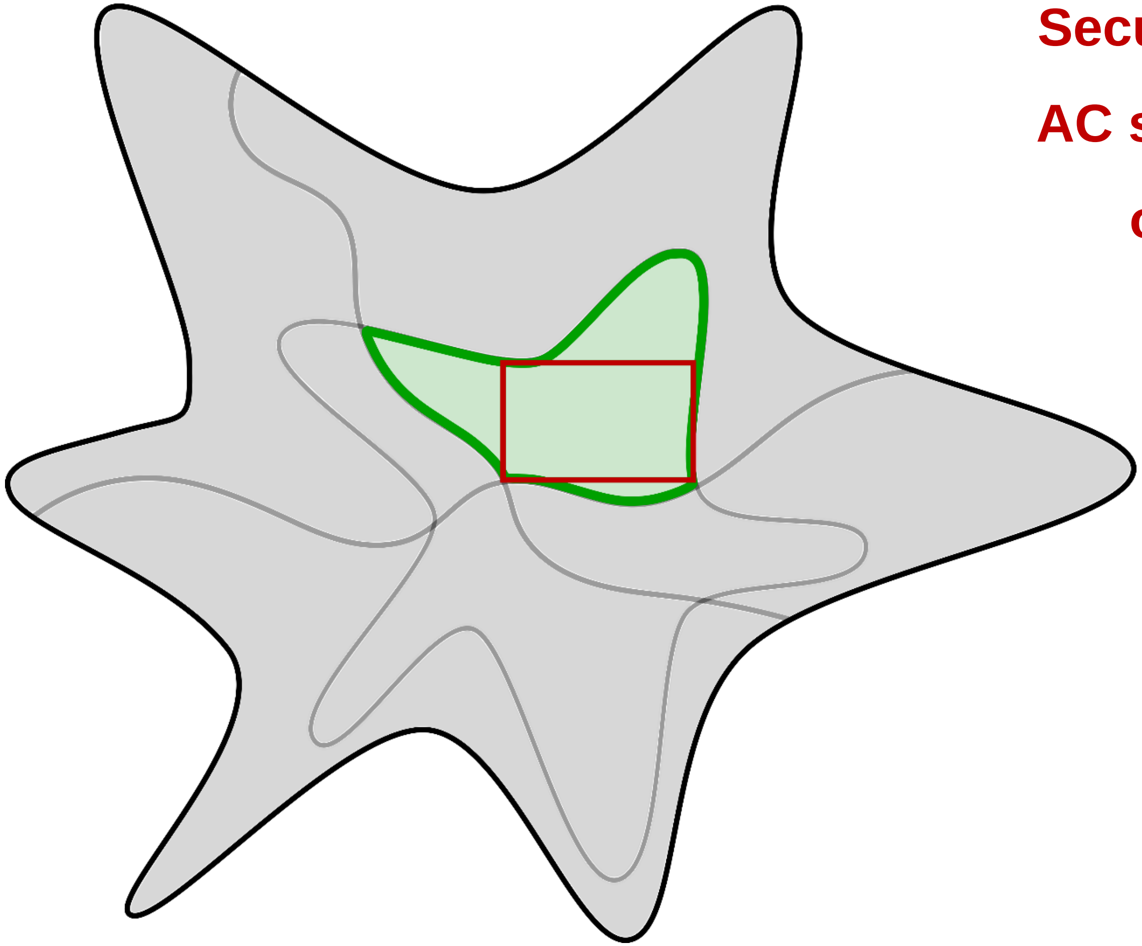


Security considerations live in AC space, but market is based on DC approximations!

Traditionally, TSOs define

Net-Transfer Capacities

How to encode feasible operating region for electricity markets?



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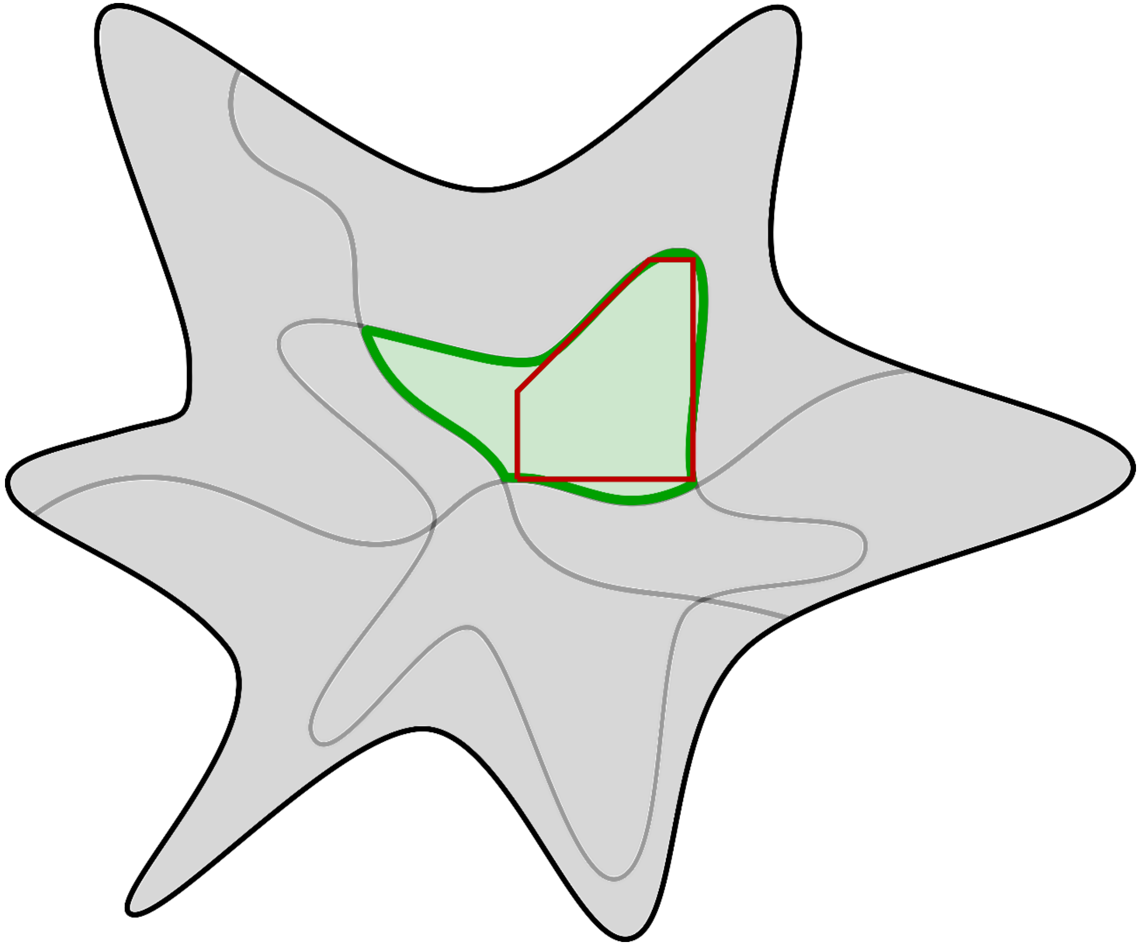
Better but reality of power system operations is nonconvex!

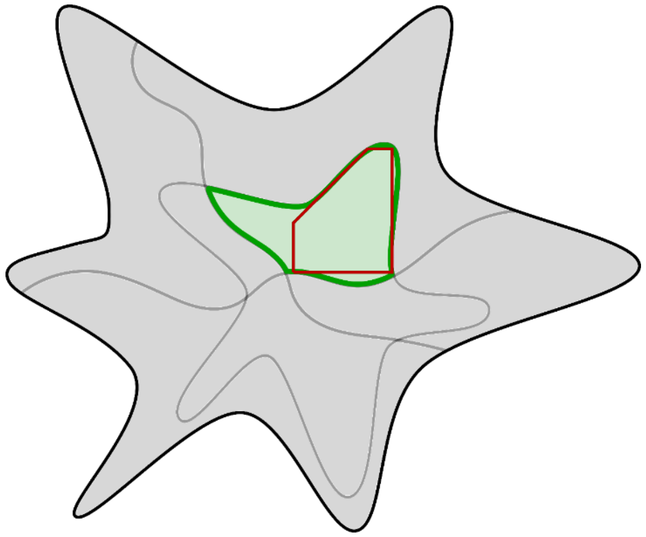


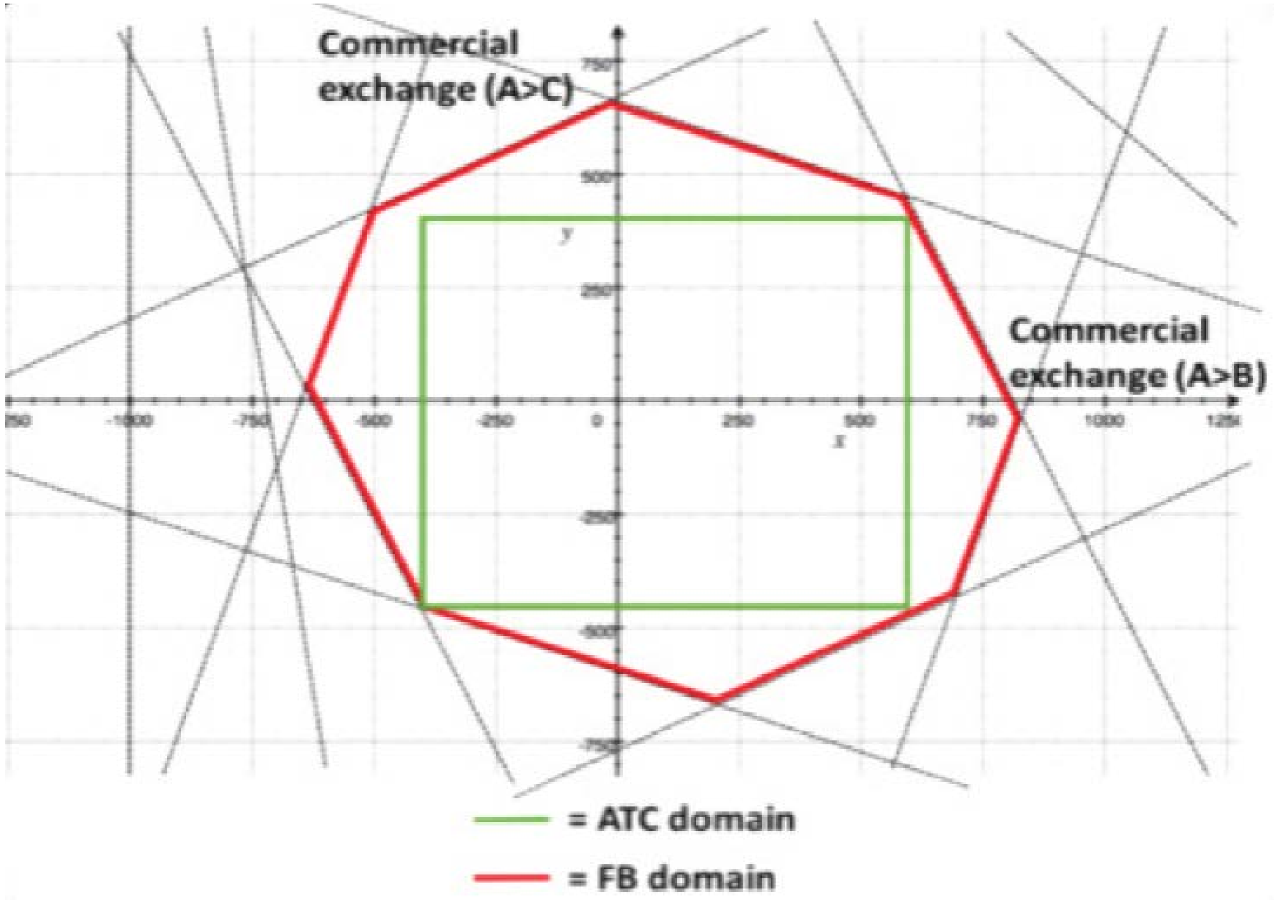
Improvements with Flow-Based

Market Coupling,

but still a **single** convex region!

Better but reality of power system operations is nonconvex!





Improvements with Flow-Based

Market Coupling,

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Figure from: KU Leuven Energy Institute, "EI Fact Sheet: Cross-border Electrcity Trading: Towards Flow-based Market Coupling," 2015. [Online].Available: http://set.kuleuven.be/ei/factsheets

Our proposal

- **Pass the data! (not the line limits)**

- **TSOs have large amounts of data** related to their daily contingency analysis calculations (RSCIs also collect and coordinate these analyses in a regional level)

- Instead of deciding on the interconnection flow limits to form a single convex region, **let the market operator decide** based on the “secure/insecure” status of an operating point

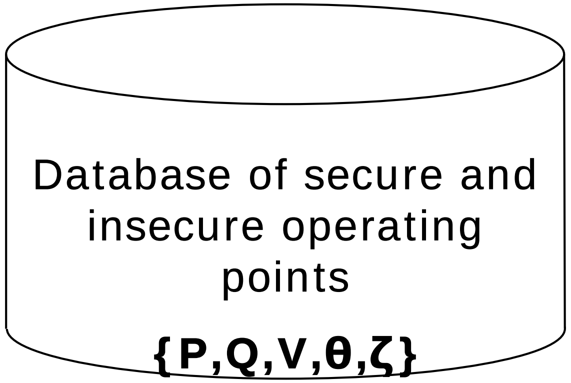
Benefits

- Market players have the **true, larger** (and non-convex) **feasible area** at their disposal → possibility to determine a better (true) global optimum

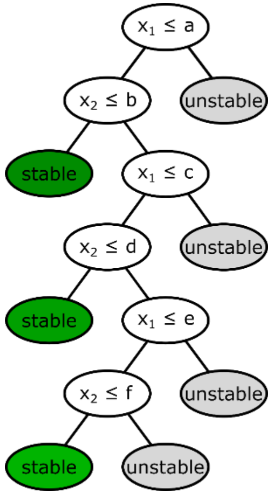
- Uncertainty and security constraints incorporated in the data → **extremely scalable** optimization (MILP)

- Map AC limits to DC-OPF → eliminate redispatching
- Can apply to **both zonal and nodal** markets

How does it work?



Operating points provided by the TSOs through simulated and real data

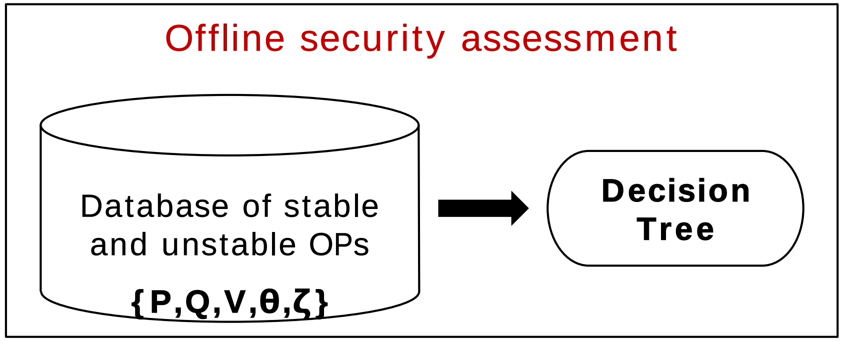


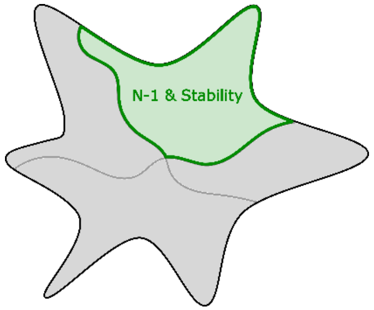
Train a decision tree to classify secure and insecure regions

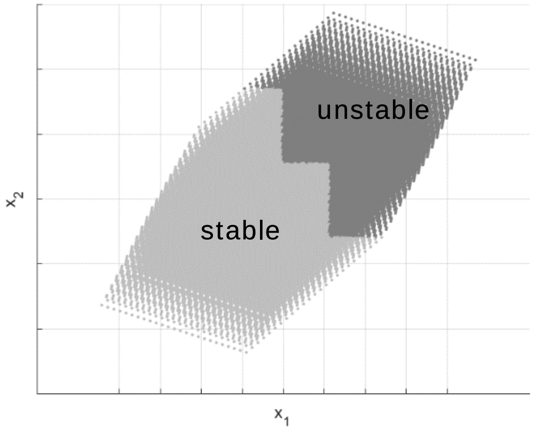
$$\mathrm{PTDF}\cdot\left(\mathrm{P_G}-\mathrm{P_D}\right) \le \mathrm{F}^{\mathrm{max}}_{\mathrm{L,p}}\, y_p + \mathrm{F}^{\mathrm{max}}_{\mathrm{L}}(1-y_p)$$
$$\mathrm{PTDF}\cdot\left(\mathrm{P_G}-\mathrm{P_D}\right) \ge \mathrm{F}^{\mathrm{min}}_{\mathrm{L,p}}\, y_p - \mathrm{F}^{\mathrm{max}}_{\mathrm{L}}(1-y_p)$$

Exact reformulation to MILP

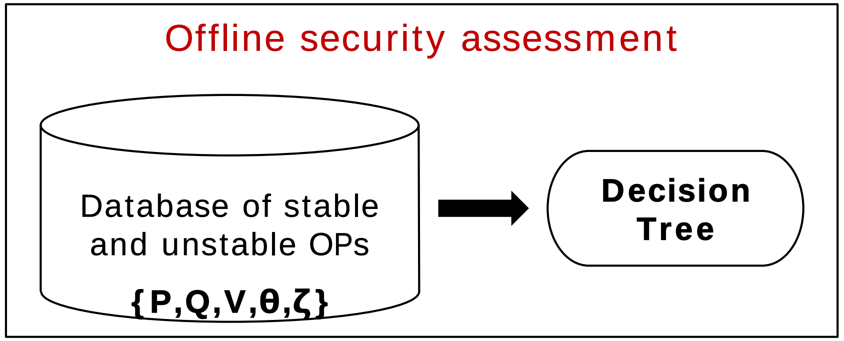
Data-driven security-constrained OPF

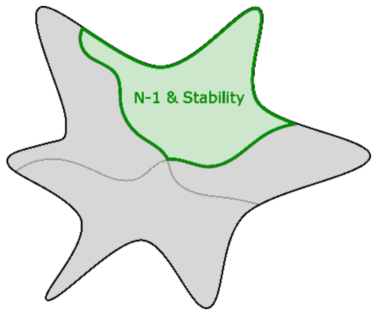




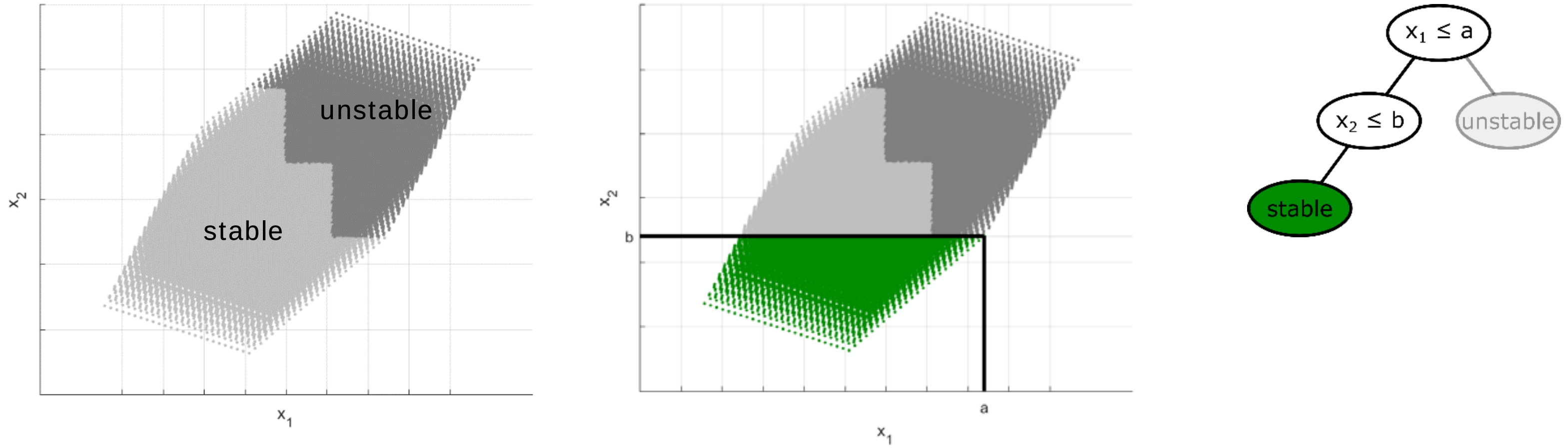


Data-driven security-constrained OPF

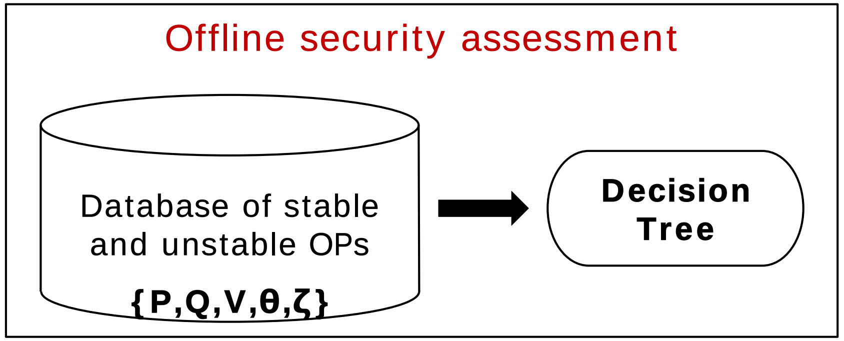


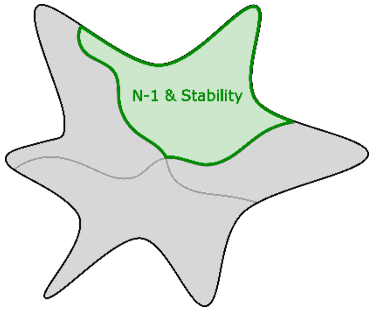


Partitioning the secure operating region



Data-driven security-constrained OPF





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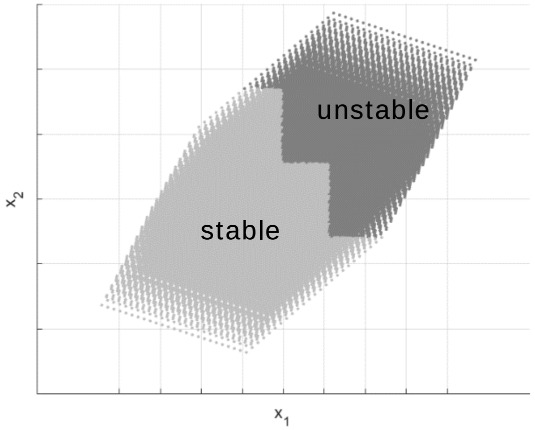
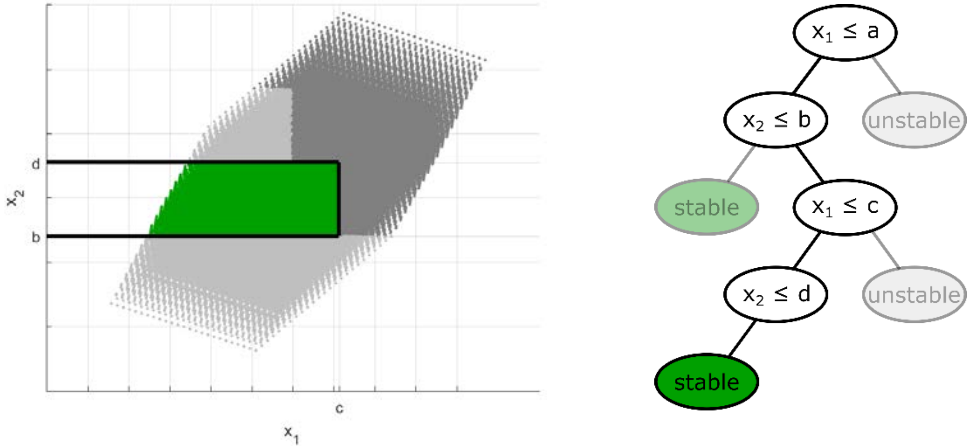
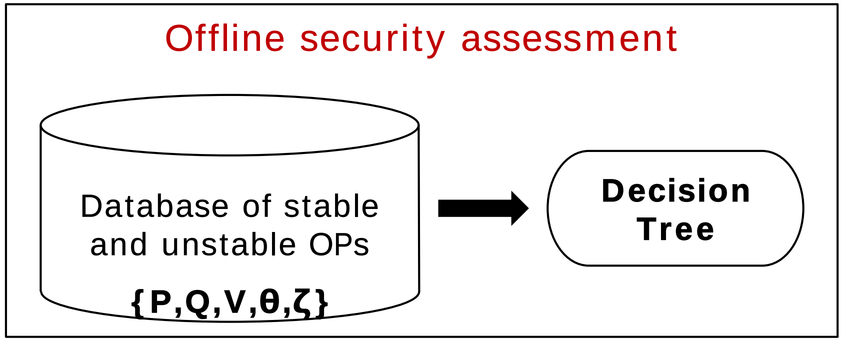
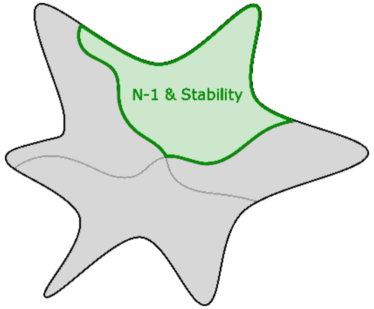


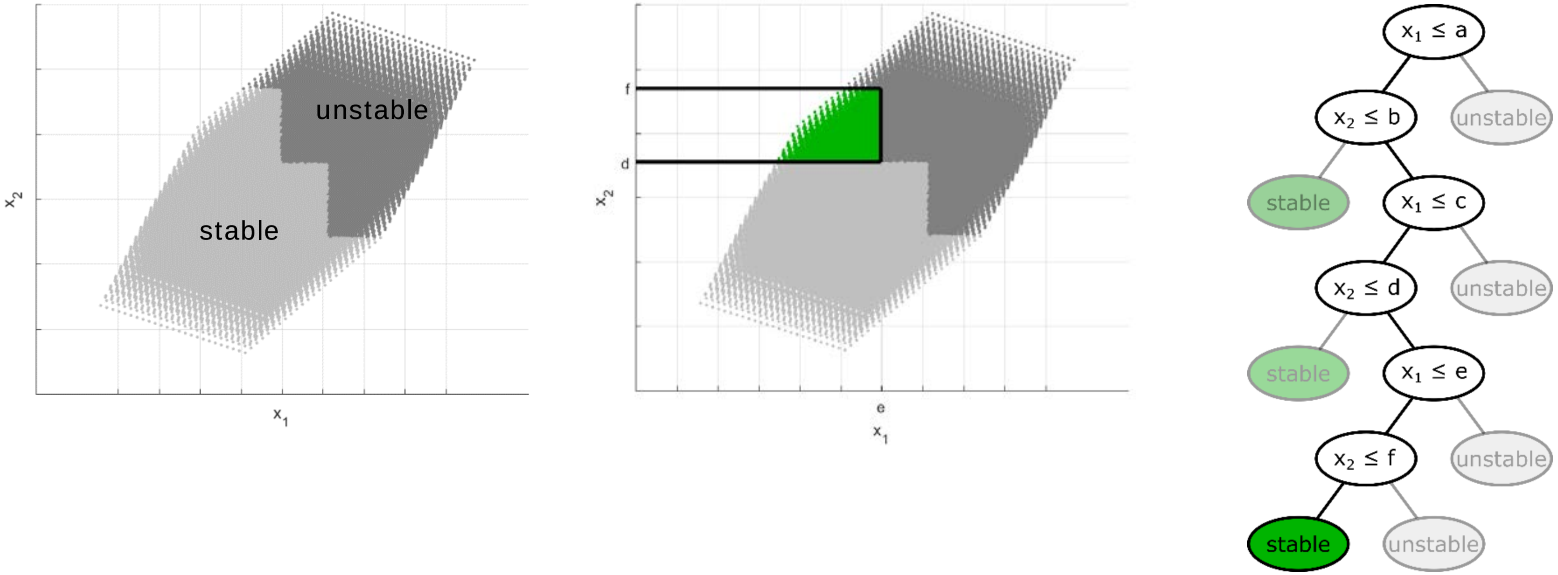


Data-driven security-constrained OPF





Partitioning the secure operating region



Data-driven security-constrained OPF

Offline security assessment

Database of stable and unstable OPs

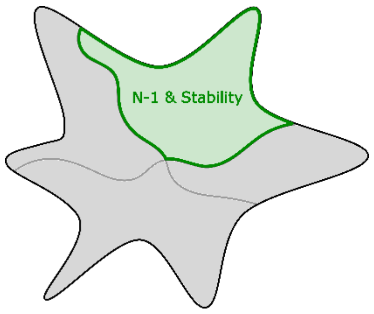
{P,Q,V,θ,ζ}

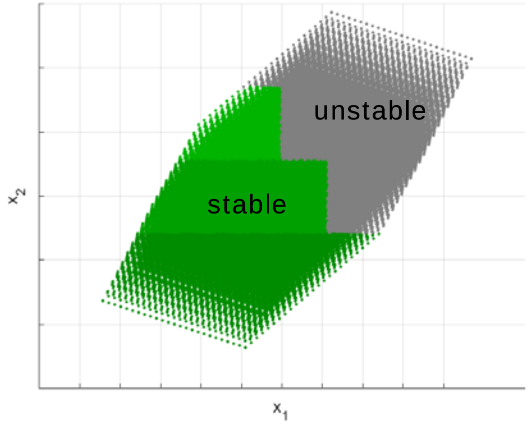
→ **Decision Tree**

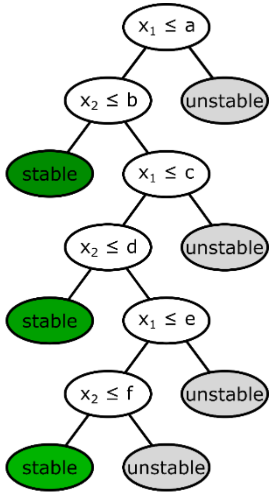
Optimization

Integer Programming to incorporate partitions (DT)

- DC-OPF (MILP)
- AC-OPF (MINLP)
- Relaxation (MIQCP, MISOCP)

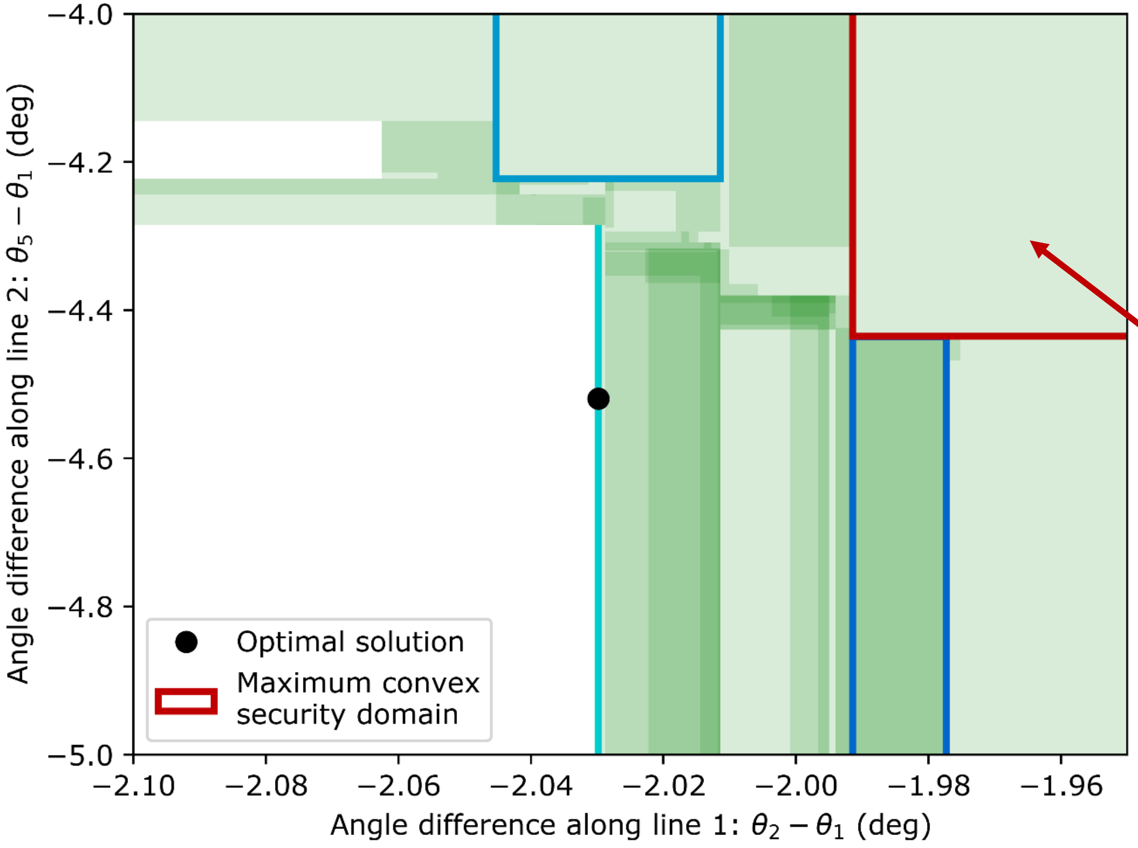


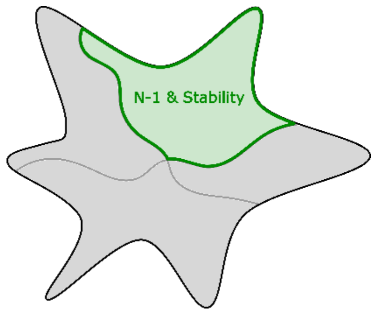




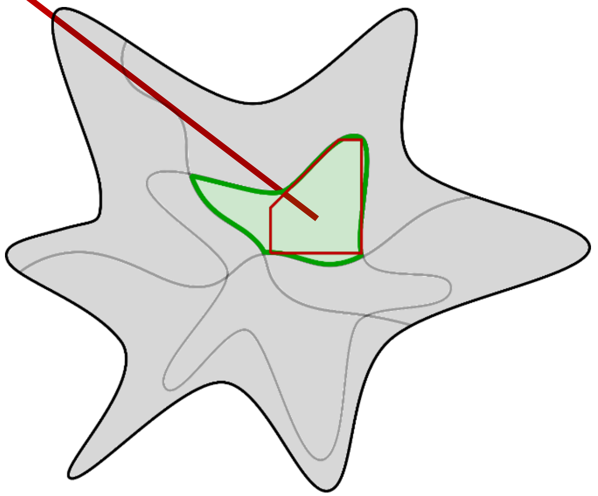
- Each leaf is a convex region
- FBMC corresponds to the leaf that maps the largest convex region
- Here, each convex region includes security constraints (N-1 and other) → we can include N-1 in zonal markets

We gain ~22% of the feasible space using data and Mixed Integer Programming

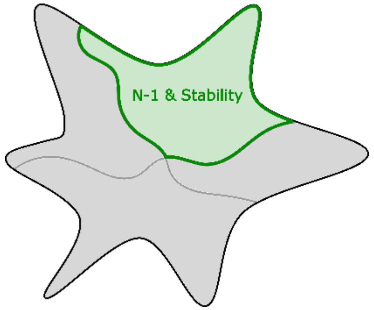


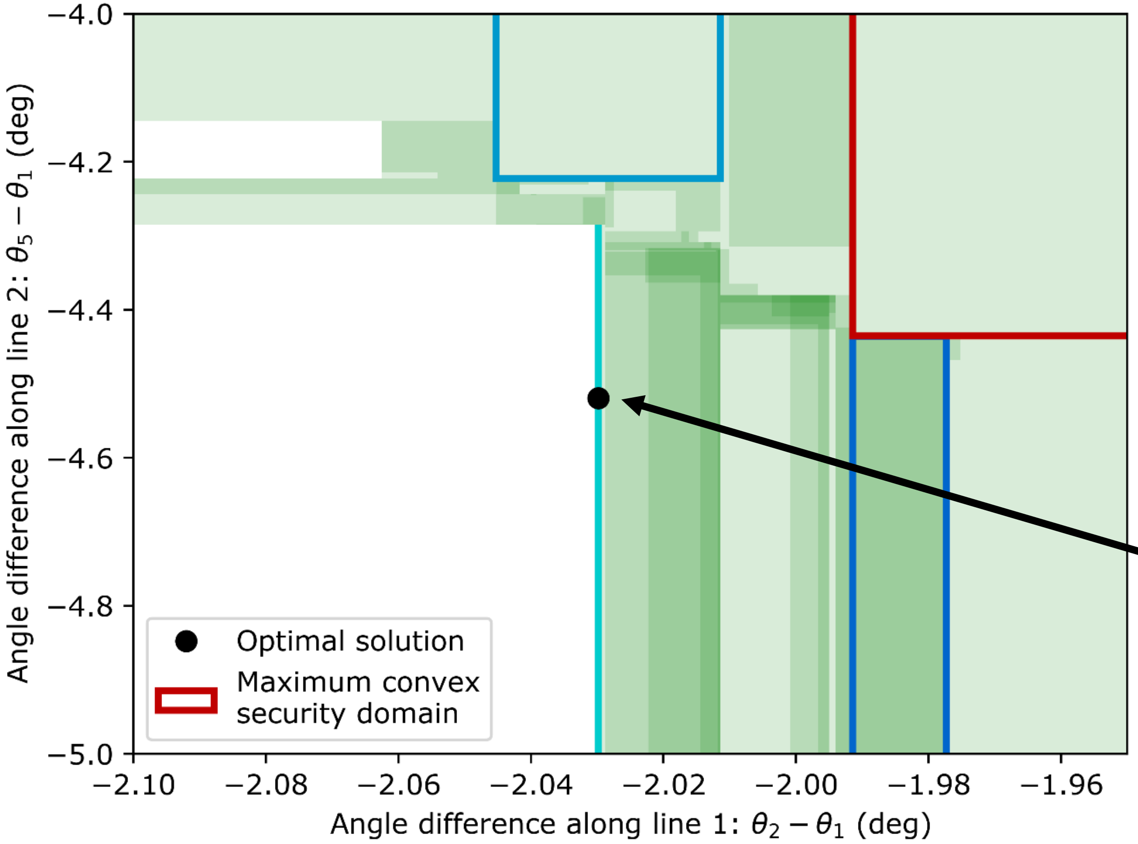


Largest convex region covers ~78%



MIP + convex AC-OPF approximation finds better solutions than nonconvex problem!





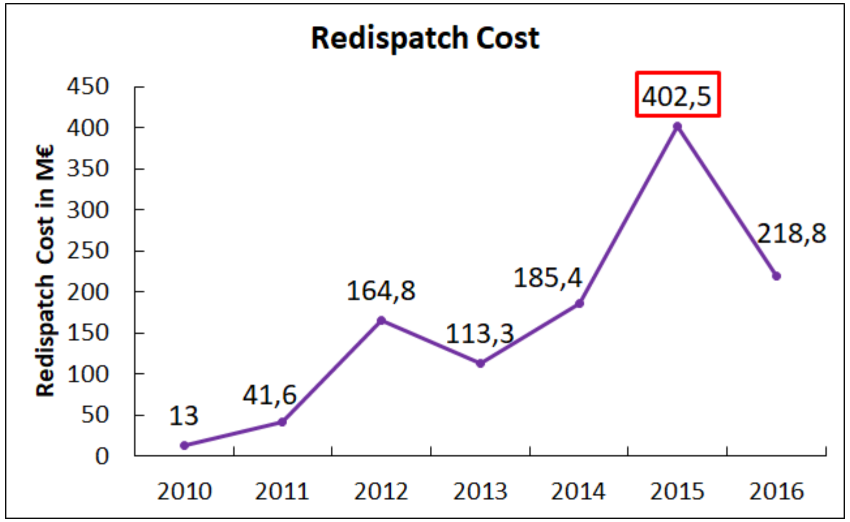
Optimum located at boundary of considered security region

L. Halilbašić, F. Thams, A. Venzke, S. Chatzivasileiadis, and P. Pinson, ”Data-driven security-constrained AC-OPF for operations and markets,” in *2018 Power Systems Computation Conference (PSCC)*, 2018.

Works also for DC-OPF (MILP): Market dispatch is N-1 secure and stable

Eliminate redispatching costs

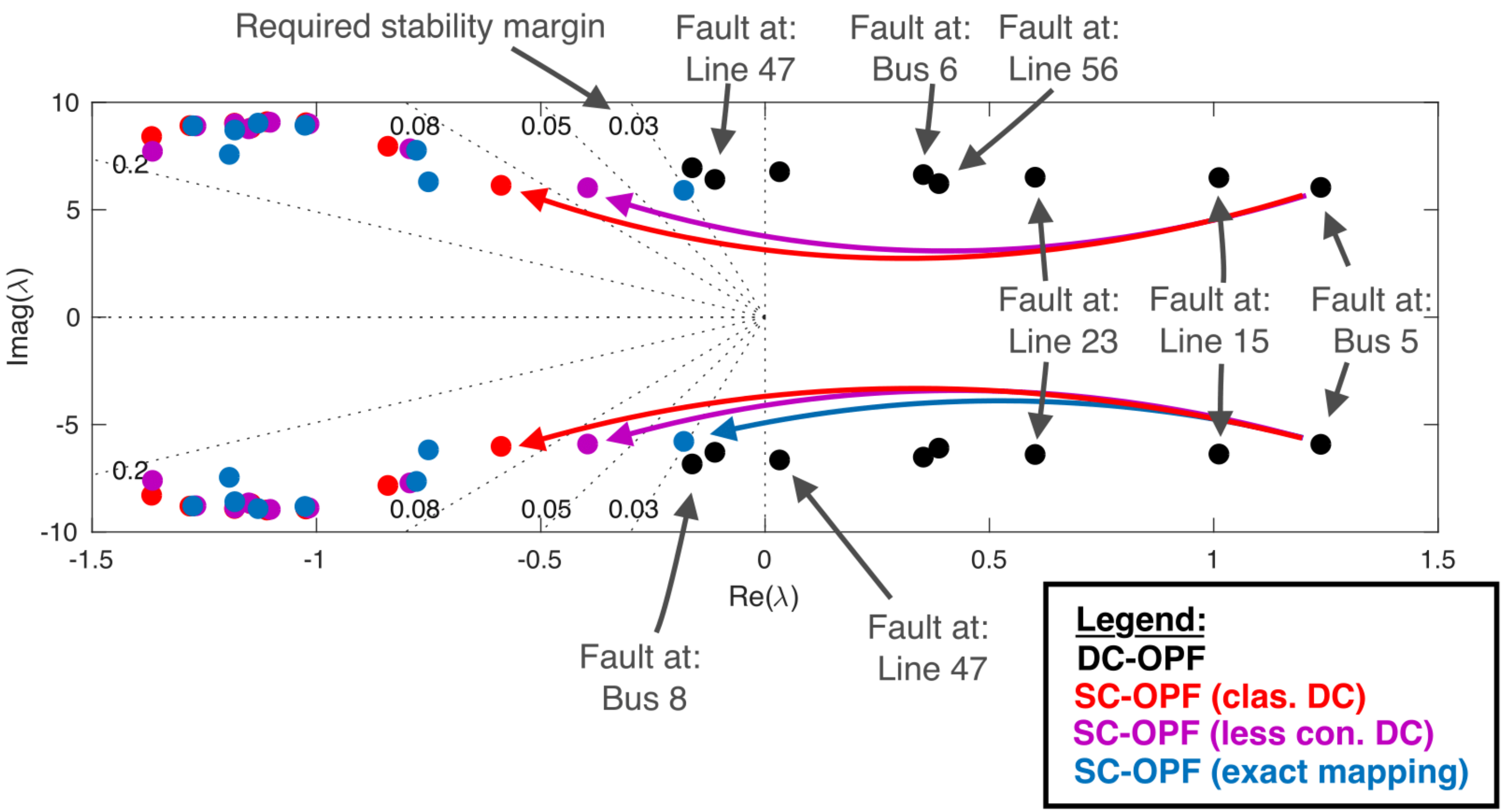
- Data-driven SC-OPF for markets: DC-OPF becomes MILP
  - **But,** MILP is already included in market software (e.g. Euphemia, for block offers, etc.)
  - Efficient MILP solvers already existing



Redispatching costs: over 400 Million Euros in a year, just for Germany

Works also for DC-OPF (MILP): Market dispatch is N-1 secure and stable

➡ all eigenvalues on the left-hand side



Efficient Database Generation

- Modular and highly efficient algorithm

- Can accommodate numerous definitions of power system security (e.g. N-1, N-k, small-signal stability, voltage stability, transient stability, **or a combination** of them)

- **10-20 times faster** than existing state-of-the-art approaches

- Our use case: N-1 security + small-signal stability

- Generated Database for NESTA 162-bus system online available!
  https://github.com/johnnyDEDK/OPs_Nesta162Bus (>500,000 points)

F. Thams, A. Venzke, R. Eriksson, and S. Chatzivasileiadis, ”Efficient database generation for data-driven security assessment of power systems”. Accepted in IEEE Trans. Power Systems, 2019. https://www.arxiv.org/abs/1806.0107.pdf

Results

	Points close to the security boundary (within distance γ)	
	IEEE 14-bus	**NESTA 162-bus**
Brute Force	100% of points in **556.0 min**	*intractable*
Importance Sampling	100% of points in **37.0 min**	**901 points** in 35.7 hours
Proposed Method	100% of points in **3.8 min**	**183’295 points** in 37.1 hours

- Further benefits for the decision tree:
  - Higher accuracy
  - Better classification quality (Matthews correlation coefficient)

Generated Database for NESTA 162-bus system online available!
https://github.com/johnnyDEDK/OPs_Nesta162Bus

Conclusions 1/2

- **Large-scale simulations** on a ~7500 node European grid
  - **Controllable flows** and a **combined AC & DC** upgrade are **necessary** to accommodate increased RES
  - **2030:** nodal price variance increases, multimodal distribution of prices, **very-high-price pockets within one zone** (e.g. France)
  - Work in progress: **how will the nodal prices get affected by the planned grid reinforcements?**

- **HVDC**: offers the necessary power flow flexibility, but **TSOs cannot recover the cost of losses**
  - Introduction of loss factors: for a guaranteed social welfare increase, **loss factors for both AC and DC lines** must be introduced
  - **Alternative: move to a nodal market with a (linearized) AC-OPF** [some US ISOs already run similar algorithms)
  - Work in progress: **how can we have an "LMP" for HVDC flexibility?**

Conclusions 2/2

- Introduced a new **Data-driven Security-Constrained OPF framework**
  - Tractable and scalable
  - Can handle any security criteria
  - Can handle uncertainty
  - Can handle topology changes and controllable flows by HVDC
  - **Pass the data, not the line limits**

- **Currently working on (knowledge gaps)**
  - Locational Price for HVDC flexibility (and possible extensions to other topology changes)
  - Evolution of nodal prices with RES penetration and grid reinforcements
  - Scalable formulations to include security and uncertainty in OPF

Thank you!

www.chatziva.com/publications

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References:

L. Halilbašić, F. Thams, A. Venzke, S. Chatzivasileiadis, and P. Pinson, ”Data-driven security-constrained AC-OPF for operations and markets,” in *2018 Power Systems Computation Conference (PSCC)*, 2018.

F. Thams, L. Halilbašić, P. Pinson, S. Chatzivasileiadis, and R. Eriksson, ”Data-driven security-constrained OPF,” in *10th IREP Symposium – Bulk Power Systems Dynamics and Control*, 2017.

F. Thams, A. Venzke, R. Eriksson, and S. Chatzivasileiadis, ”Efficient database generation for data-driven security assessment of power systems”. *IEEE Trans. Power Systems, 2019*. arXiv: http://arxiv.org/abs/1806.01074.pdf .

A. Tosatto, T. Weckesser, S. Chatzivasileiadis, *Market Integration of HVDC lines*, submitted. https://arxiv.org/abs/1812.00734

L. Halilbašić, P. Pinson, and S. Chatzivasileiadis, ”Convex relaxations and approximations of chance-constrained AC-OPF problems,” *IEEE Transactions on Power Systems*, 2018, (in press).

A. Venzke, *L. Halilbasic, U. Markovic, G. Hug, S. Chatzivasileiadis*., ”Convex relaxations of chance constrained AC optimal power flow,” *IEEE Transactions on Power Systems*, vol. 33, no. 3, pp. 2829-2841, May 2018.

How to model redispatching

- Different alternatives (cooptimization, running series of load flows, AC-OPF)

- Suggestion: **run a linearized AC-OPF**
  - Objective function: minimize *costs * (Predisp-Pinit)*
  - **Linearize power flow equations around the selected operating point**, determined by the zonal (day-ahead) market, and extract linear sensitivities
  - Solve a **convex** optimization problem

  - Several approaches available
  - It has been shown that as long as we are focusing on a solution close to a selected operating point, linear approximations of AC power flow can offer an acceptable accuracy