ETH
Eidgenössische Technische Hochschule Zürich
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HVDC Line Placement for Maximizing Social Welfare – An Analytical Approach

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Motivation

- Transmission expansion planning is a complex problem
- Take advantage of the power system properties, in order to derive simple rules which can be generally applied

- Use these results either directly, or within optimization procedures in order to bound the search-space
- Focus is on placement of HVDC lines

OUTLINE

1. **Overview of the Method**
2. Case Study: AC-OPF on a 10-bus network
3. Description of the Algorithm
4. Case Study: European Network
5. Conclusions

Main Results

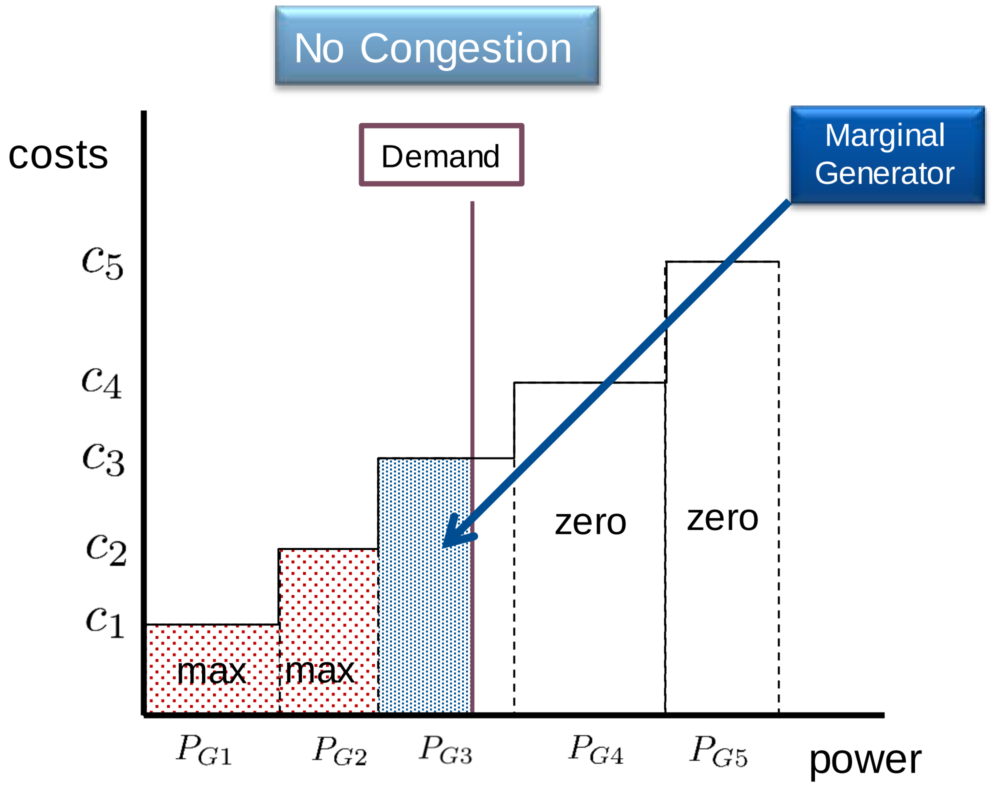
- In order to maximize social welfare the HVDC lines should connect a high-cost with a low-cost marginal* generator

- **Marginal* is the generator which is dispatched *neither at its maximum nor at its minimum limit*

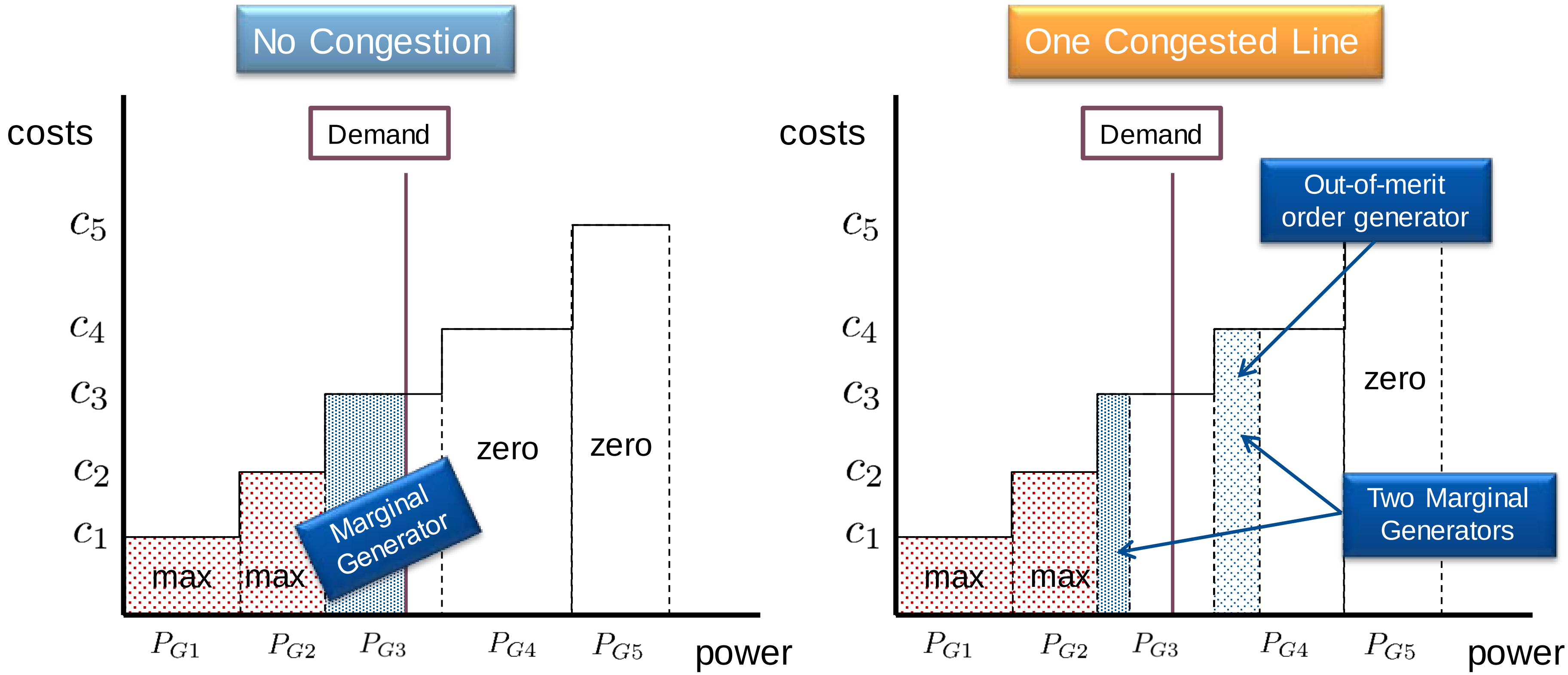
- *Upper bound*: any line with installation costs higher than the line connecting two marginal generators should be discarded

- Algorithm to identify optimal HVDC placement and estimate cost savings

Merit-order curves with and without congestion



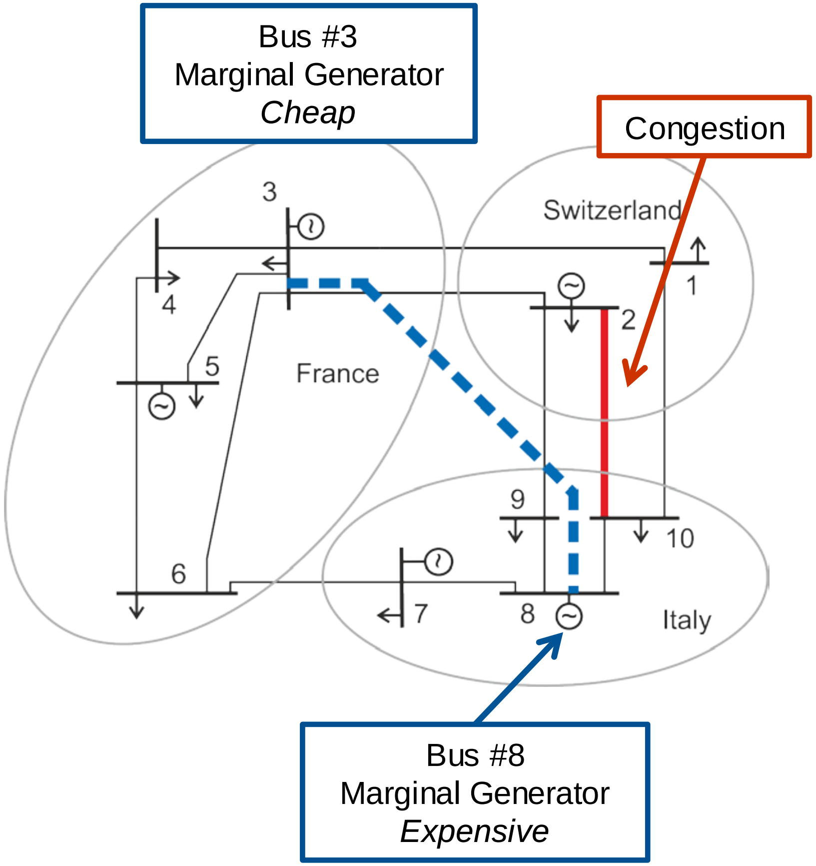
Merit-order curves with and without congestion

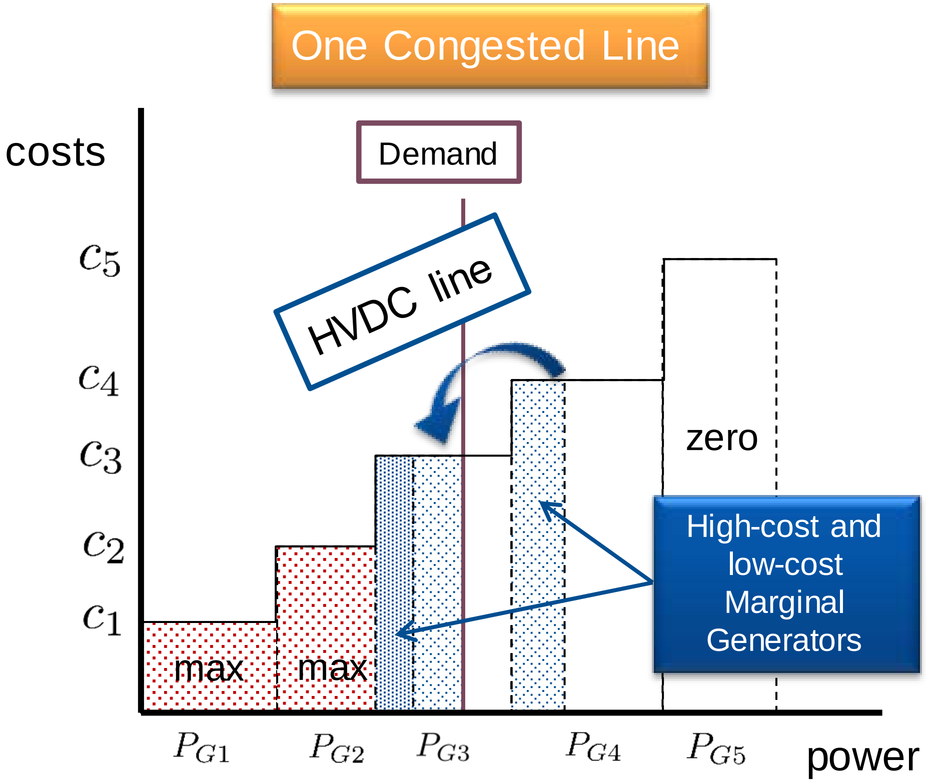


- No congestion = 1 marginal generator
- 1 congested line = 2 marginal generators

HVDC placement and marginal generators

- "Shifting" power from the high-cost to the low-cost marginal generator





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Derivation of the results – Outline

- Congestion relief is equivalent to maximization of the social welfare

↓

- Eliminating the dispatch of the high-cost marginal generator is equivalent to congestion relief (analytically shown)

→ shift power from expensive to cheap marginal generators

↓

- In general, for N congestions there exist N+1 marginal generators (analytically shown) → #marg.gens bounded

↓

- Method applicable to both AC and HVDC lines. Due to HVDC controllability, HVDC capacity can be determined independent of network topology.

$$min \sum_{i=1}^{N_{P_G}} c_i P_{G,i},$$

DC-OPF Formulation based on PTDFs

$$\sum^{N_{P_G}} \ldots = 0,$$

$$\mathbf{PT} \ldots \mathbf{G} - \mathbf{P_L})| \leq \mathbf{F_L},$$

$$\mathbf{0} \leq \mathbf{P_G} \leq \mathbf{P_{G,max}}.$$

$$\mathcal{L}(P_G, \nu, \lambda, \mu) = \sum_{i=1}^{N_{P_G}} c_i P_{G,i} + \nu \cdot \left(\sum_{i=1}^{N_{P_G}} P_{G,i} - \sum^{N_{P_L}} P_{L,i} \right)$$

$$+ \sum^{N_L} \lambda^+ \ldots F_{L,i}]$$

$$\ldots \cdot (\mathbf{P_G} - \mathbf{P_L}) - F_{L,i}]$$

$$+ \sum_{i=1}^{N_{P_G}} (\mu_i^+ \cdot (P_{G,i} - P_{G,i,max})) + \sum_{i=1}^{N_{P_G}} (\mu_i^- \cdot (-P_{G,i})).$$

Lagrangian Function of the Problem

due to KKT conditions

$$\frac{\partial \mathcal{L}}{\partial P_G} = 0$$

$$c_m + \ldots$$

$$c_n + \ldots F_{k,n} = 0$$

Linear Algebra manipulations of the equations resulting from the KKT optimality conditions

LM of equality constraint

LM of congested line

Assumptions

- DC-OPF context
- Linear generator costs

Main Findings

- For N congestions there exist N+1 marginal generators
- For a given network topology, lagrangian multiplier of the the line (Line LM) dependent only on the costs of marginal generators
  - Line LM is a “marginal” measure of how a congestion relief can affect social welfare

OUTLINE

1. Derivation of the Method
2. **Case Study: AC-OPF on a 10-bus network**
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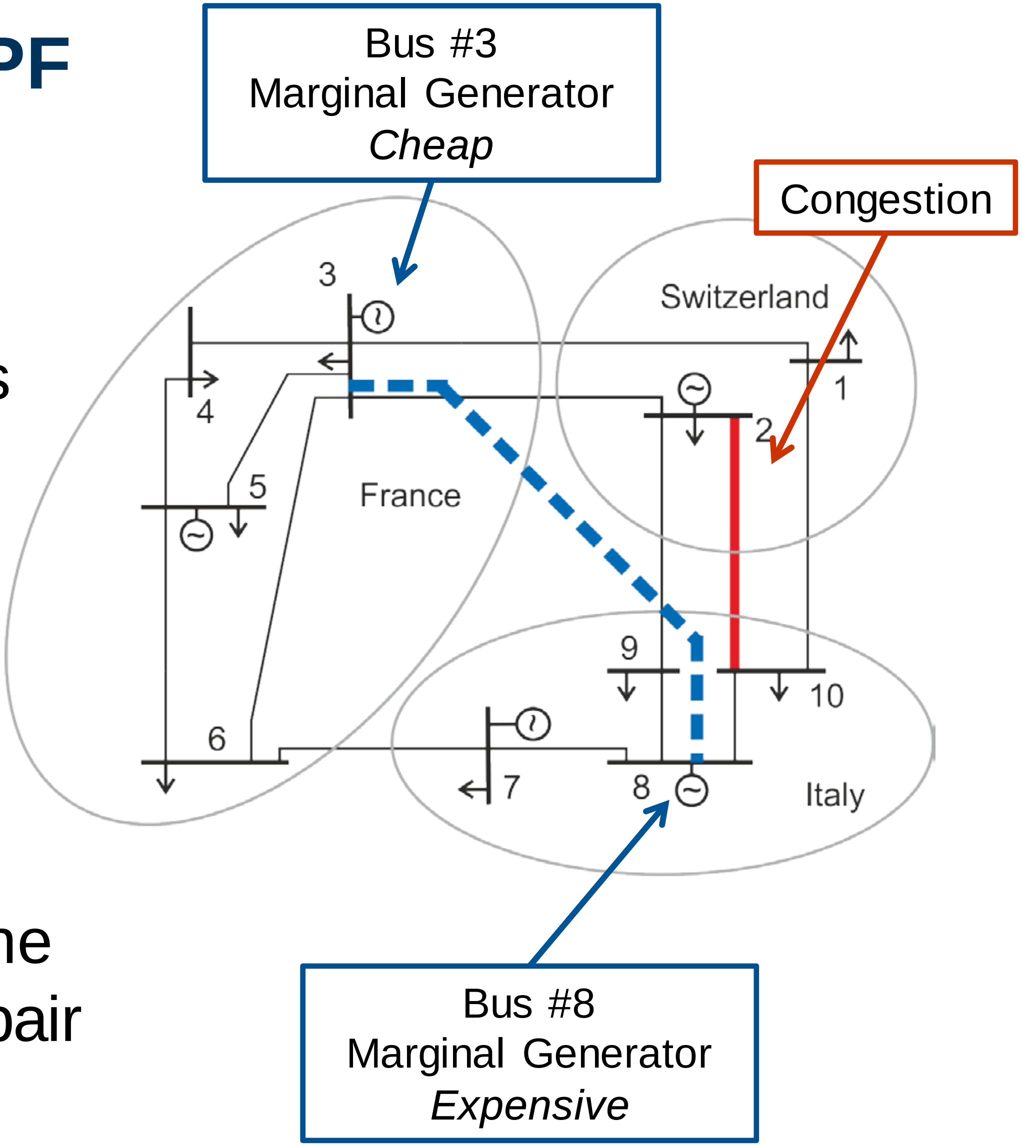
Case Study #1: AC-OPF

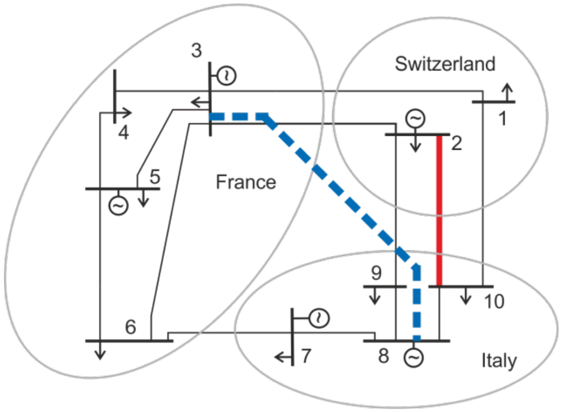
- One congested line
- Two marginal generators

	Pg (MW)	costs (€/MWh)
Bus 3	6'130	24.3
Bus 8	1'530	50.0

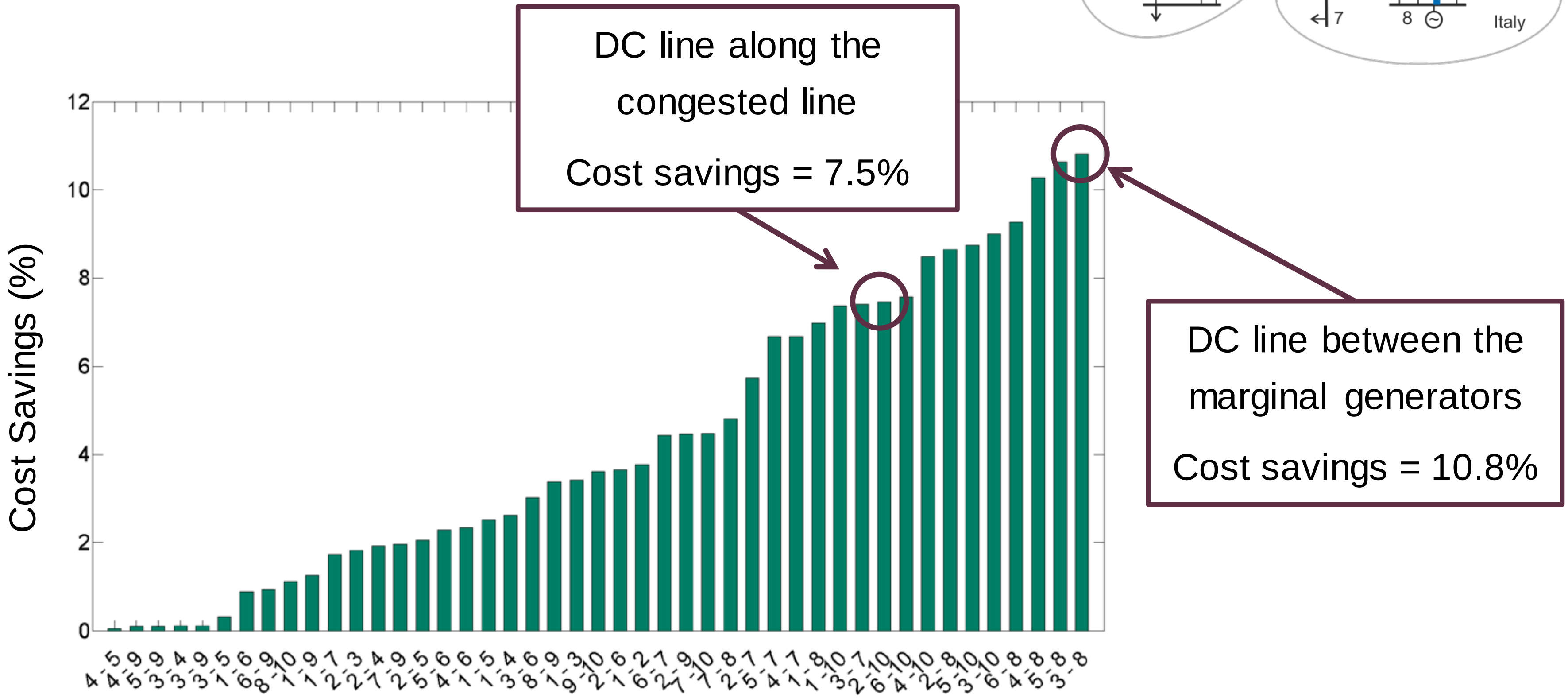
- One 2'000 MW HVDC line between each possible pair of nodes



Case Study #1: AC-OPF



- Run 45 instances of OPF for all possible placements

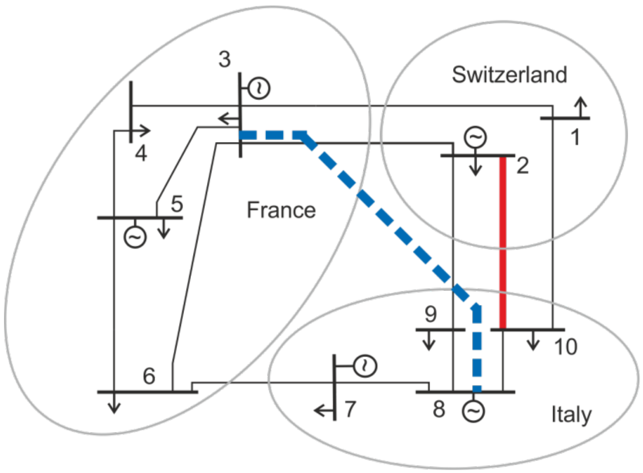


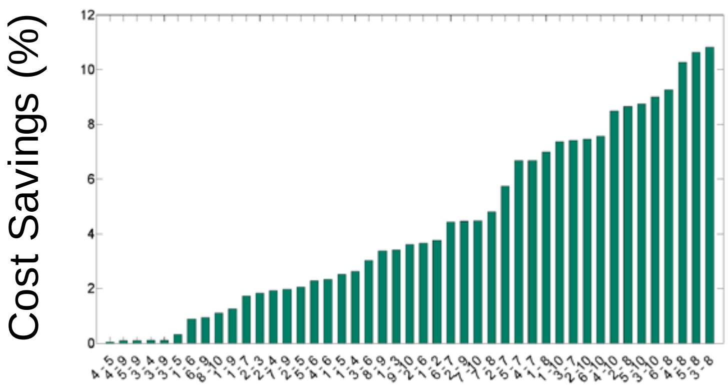
Case Study #1: AC-OPF Conclusions

- DC line between marginal generators results to highest cost savings

- Placing a DC line in parallel with the congested line is not necessarily optimal

- Placement method can also hold in more realistic system representations





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Algorithm – Main Idea

- Maximize Cost Savings

Generated power "shifted" from high-cost to low-cost by the HVDC

$$\mathrm{CS} = (c_{\mathrm{HC}} - c_{\mathrm{LC}}) \cdot \Delta P$$

marginal costs of the *high-cost* marginal generator

marginal costs of the *low-cost* marginal generator

Algorithm

1. Run DC-OPF and find marginal generators
2. Select HVDC capacity C_{DC}
3. Find the *high-cost* marginal generator

$$G_{\mathrm{HC}}: \quad \max_i \{ \quad c_{Gi} \cdot \min\{C_{DC}, P_{Gi}\} \quad \}$$

power currently produced

4. Find the *low-cost* marginal generator

remaining unused capacity

$$G_{\mathrm{LC}}: \quad \min_i \{ \quad c_{Gi} \cdot \min\{C_{DC}, (P_{Gi,max} - P_{Gi})\} \quad \}$$

5. Connect the two generator nodes with an HVDC line
6. Calculate an estimate for the cost savings

$$\mathrm{CS} \geq (c_{\mathrm{HC}} - c_{\mathrm{LC}}) \cdot \min\{C_{DC}, P_{G,\mathrm{HC}}, (P_{G,\mathrm{LC},max} - P_{G,\mathrm{LC}})\}$$

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IRENE-40 European Project

- **I**nfrastructure **R**oadmap for the **E**nergy **N**etworks in **E**urope for the next **40** years

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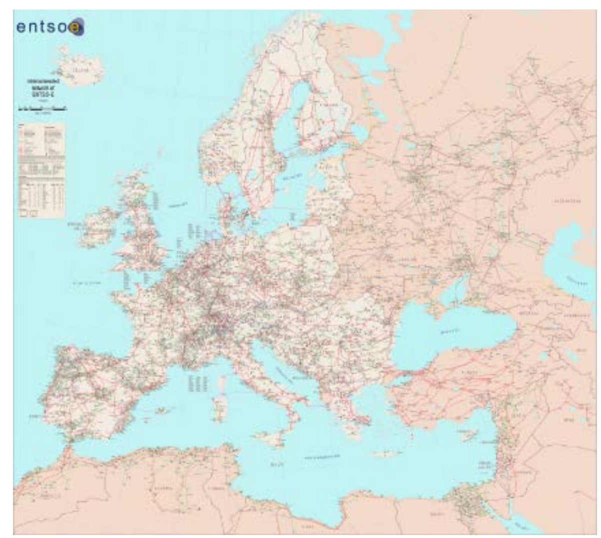
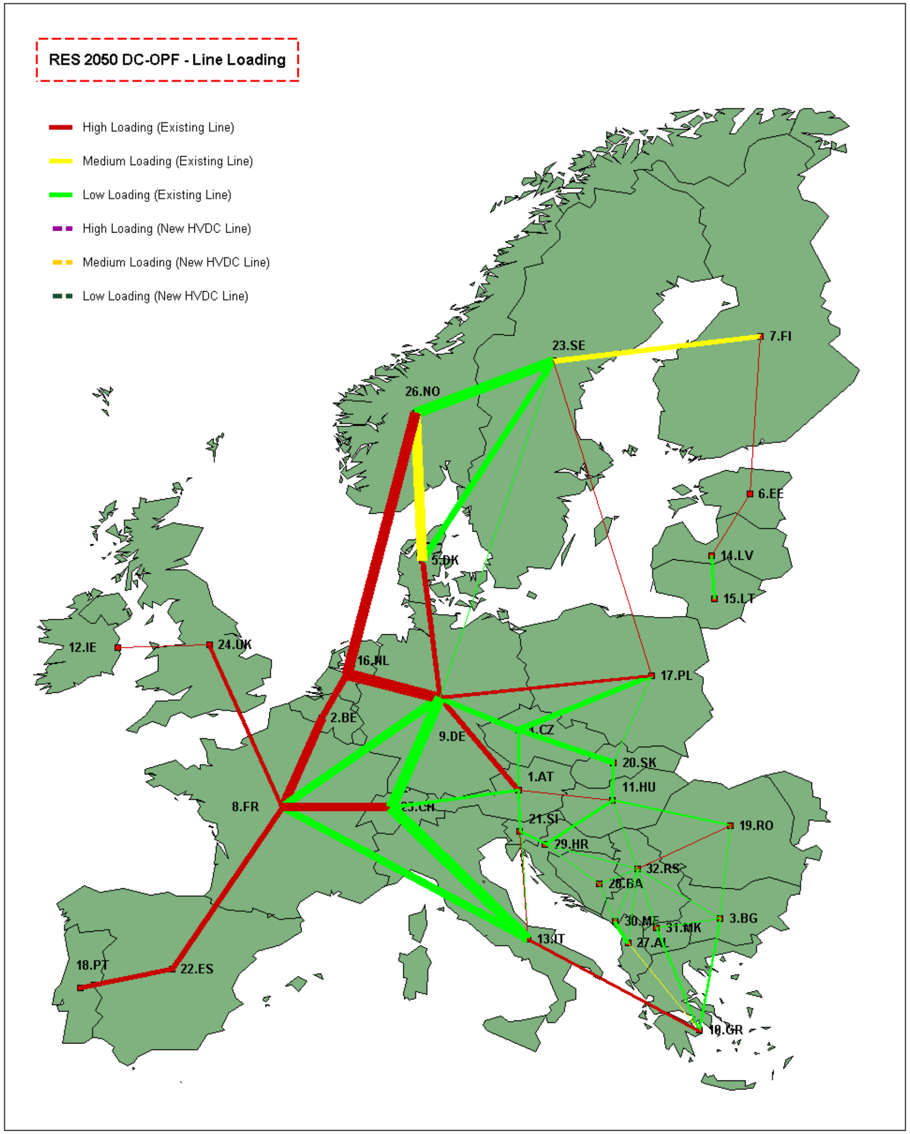
- Identify expansion measures with respect to:
  - Sustainability → more RES
  - Security
  - Competitiveness → efficient market operation



Case Study #2: European Network

- Single-node per country; real network data (UCTE)
- Generation Scenario: 80% RES by 2050
- ~70 gens: RES, conventional, nuclear
- Placement of 3 HVDC connections



OPF Results – Marginal Generators

	Pg (MW)	Pg,max (MW)	Costs (€/MWh)
...	...	...	...
Ireland	7'230	10'730	0.01
Portugal	16'210	30'640	0.01
Romania	9'040	10'840	0.01
Norway	33'720	44'060	0.01
France	52'940	54'280	0.54
Sweden	1'530	11'450	0.55
...	...	...	...
Hungary	830	9'300	129.05
Poland	20'830	52'760	142.51
Spain	20'660	42'410	151.00
Greece	4'630	9'340	151.07

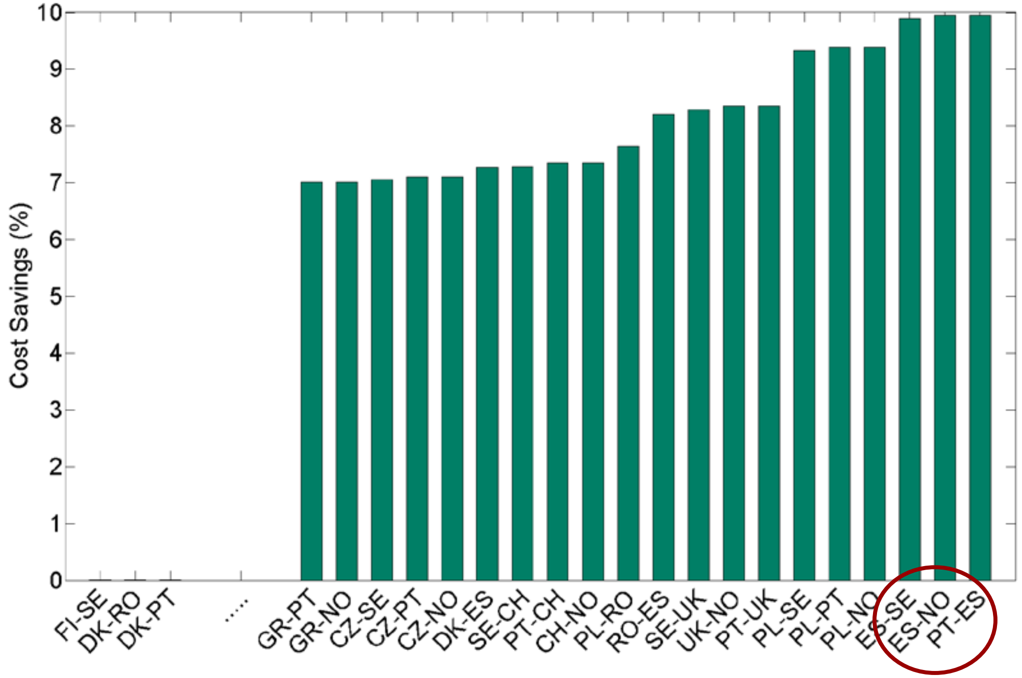
- Placement of 10'000 MW HVDC

$$\min\{\ c_{\mathrm{LC}} \cdot \Delta P\ \}$$

Placement of 1st Line

$$\max\{\ c_{\mathrm{HC}} \cdot \Delta P\ \}$$

Verification through OPF runs



- Run 496 instances of OPF for each possible placement between the 32 nodes
- Lines PT-ES and NO-ES resulted in the highest cost savings: 9.95%

OPF Results – Marginal Generators
Placement of 2nd and 3rd HVDC connection

	Pg (MW)	Pg,max (MW)	Costs (€/MWh)
...	...	...	...
Ireland	7'230	10'730	0.01
Portugal	26'210	30'640	0.01
Romania	9'040	10'840	0.01
Norway	33'720	44'060	0.01
France	52'940	54'280	0.54
Sweden	1'530	11'450	0.55
...	...	...	...
Hungary	830	9'300	129.05
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Spain	10'660	42'410	151.00
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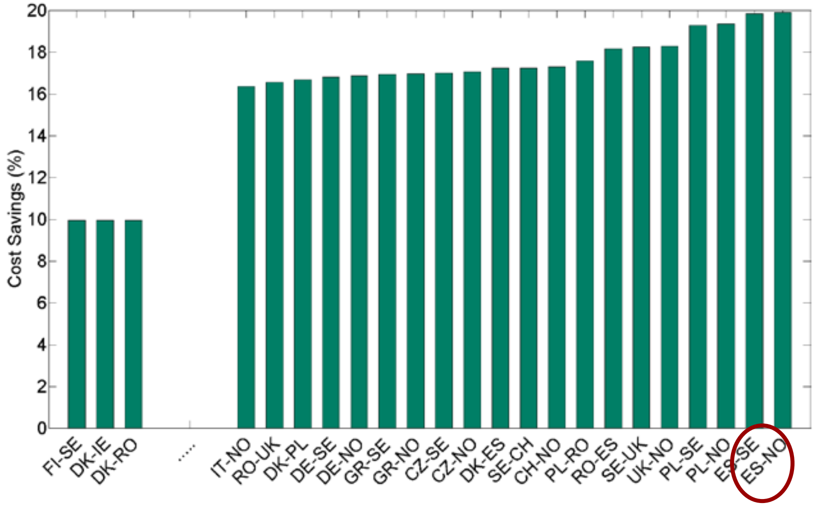
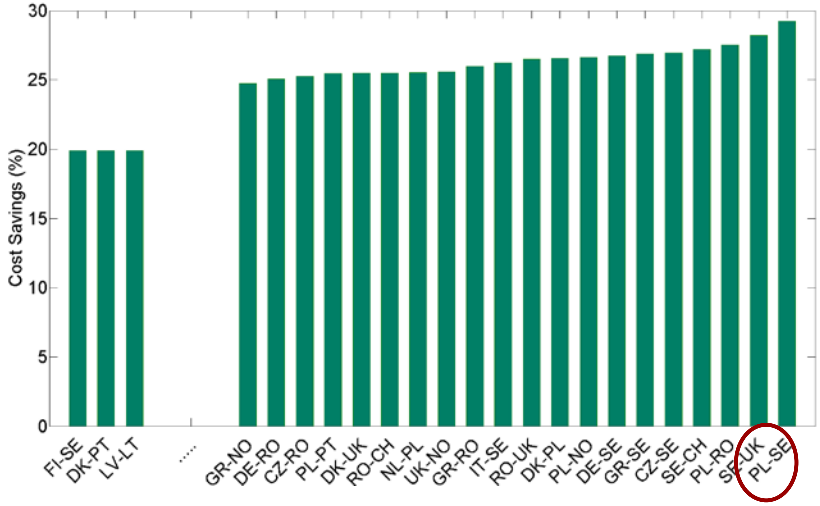
- Placement of 10'000 MW HVDC

2nd Line: Norway – Spain
3rd Line: Sweden – Poland

Verification through OPF





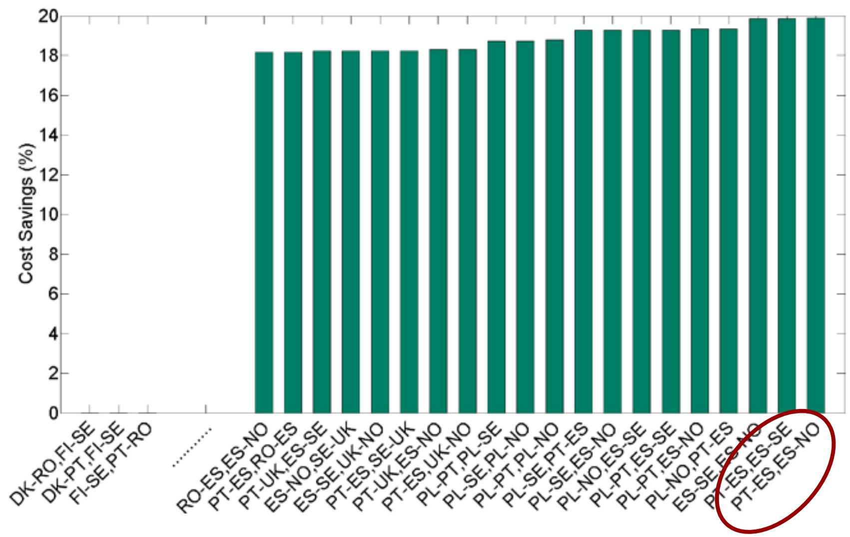
- OPF Results fully confirm the findings through the analytical approach

- 2nd HVDC: Spain-Norway
  Total Savings: 19.90%

- 3rd HVDC: Poland-Sweden
  Total Savings: 29.23%

Simultaneous Placement

- Proposed algorithm followed a sequential approach
- Simultaneous placement: run 122’760 instances of OPF for placing simultaneously two HVDC connections
- Results from simultaneous placement are exactly the same as for sequential placement



Maximum Cost Savings for:
- simultaneous HVDC placement: PT-ES and NO-ES
- Sequential HVDC placement: 1st: PT-ES, 2nd: NO-ES

Conclusions

- Placing an HVDC line between a high-cost and a low-cost marginal generator leads to the maximization of the social welfare

- *Upper bound*: any line with installation costs higher than the line connecting two marginal generators should be discarded

- Algorithm for sequential placement based on the analytical approach

Additional findings

- For N congestions there exist exactly N+1 marginal generators *(assumption: DC-OPF, linear generator costs)*
- Line LMs only dependent on costs of marginal generators
  - Line LMs are an index of how congestion relief affects social welfare
- Lower bound on the expected cost savings

Thank you!

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For N congestions there are N+1 marginal generators

$$min \sum_{i=1}^{N_{P_G}} c_i P_{G,i},$$

$$\sum^{N_{P_G}} \ldots = 0,$$

$$\mathbf{PT}\ldots(\mathbf{P_G} - \mathbf{P_L})| \leq \mathbf{F_L},$$

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DC-OPF Formulation based on PTDFs

$$\mathcal{L}(P_G, \nu, \lambda, \mu) = \sum_{i=1}^{N_{P_G}} c_i P_{G,i} + \nu \cdot \left(\sum_{i=1}^{N_{P_G}} P_{G,i} - \sum^{N_{P_L}} P_{L,i} \right)$$

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Lagrangian Function of the Problem

due to KKT conditions

$$\frac{\partial \mathcal{L}}{\partial P_G} = 0$$

for one congested line

Two equations and two unknowns

$$c_m + \nu + \lambda_k^+ \cdot PTDF_{k,m} = 0$$

$$c_n + \nu + \lambda_k^+ \cdot PTDF_{k,n} = 0$$

LM of equality constraint

LM of congested line

What if we had three marginal generators for one congested line?

Three equations for two unknowns

$$\begin{cases} c_m + \nu + \lambda_k^+ \cdot PTDF_{k,m} = 0 \\ c_n + \nu + \lambda_k^+ \cdot PTDF_{k,n} = 0 \\ c_p + \nu + \lambda_k^+ \cdot PTDF_{k,p} = 0 \end{cases}$$

- In order to exist such a solution, the third marginal generator should satisfy a certain relationship between generator costs and PTDF factors (~network topology):

$$c_p = c_m + \frac{c_m - c_n}{PTDF_{k,n} - PTDF_{k,m}} \cdot (PTDF_{k,m} - PTDF_{k,p})$$

Such a "coincidence" is very difficult to occur in real power systems

→

Therefore, in most power systems for N congestions there are N+1 marginal generators

Elimination of Marginal Generators = Congestion Relief

- Congestion relief = set λ_k to zero
- Lagrangian Multipliers λ_k of congested lines are dependent only on the costs of the marginal generators

One congested line:

$$\lambda_k = \xi_k \cdot \frac{c_m - c_n}{PTDF_{k,n} - PTDF_{k,m}}$$

Costs of the two marginal generators (c_m, c_n)

Direction of the flow (ξ_k)

Dependent on network topology ($PTDF_{k,n}$, $PTDF_{k,m}$)

For more congested lines:

$$\begin{bmatrix} 1 & \xi_{k1} \cdot PTDF_{k1,g1} & \xi_{k2} \cdot PTDF_{k2,g1} \\ 1 & \xi_{k1} \cdot PTDF_{k1,g2} & \xi_{k2} \cdot PTDF_{k2,g2} \\ 1 & \xi_{k1} \cdot PTDF_{k1,g3} & \xi_{k2} \cdot PTDF_{k2,g3} \end{bmatrix} \cdot \begin{bmatrix} \nu \\ \lambda_{k1} \\ \lambda_{k2} \end{bmatrix} = -\begin{bmatrix} c_{g1} \\ c_{g2} \\ c_{g3} \end{bmatrix}$$

marginal generators (c_{g1}, c_{g2}, c_{g3})