etch
Energy Transmission Competence Hub

Decision support for transparent cost benefit analysis of HVDC investments

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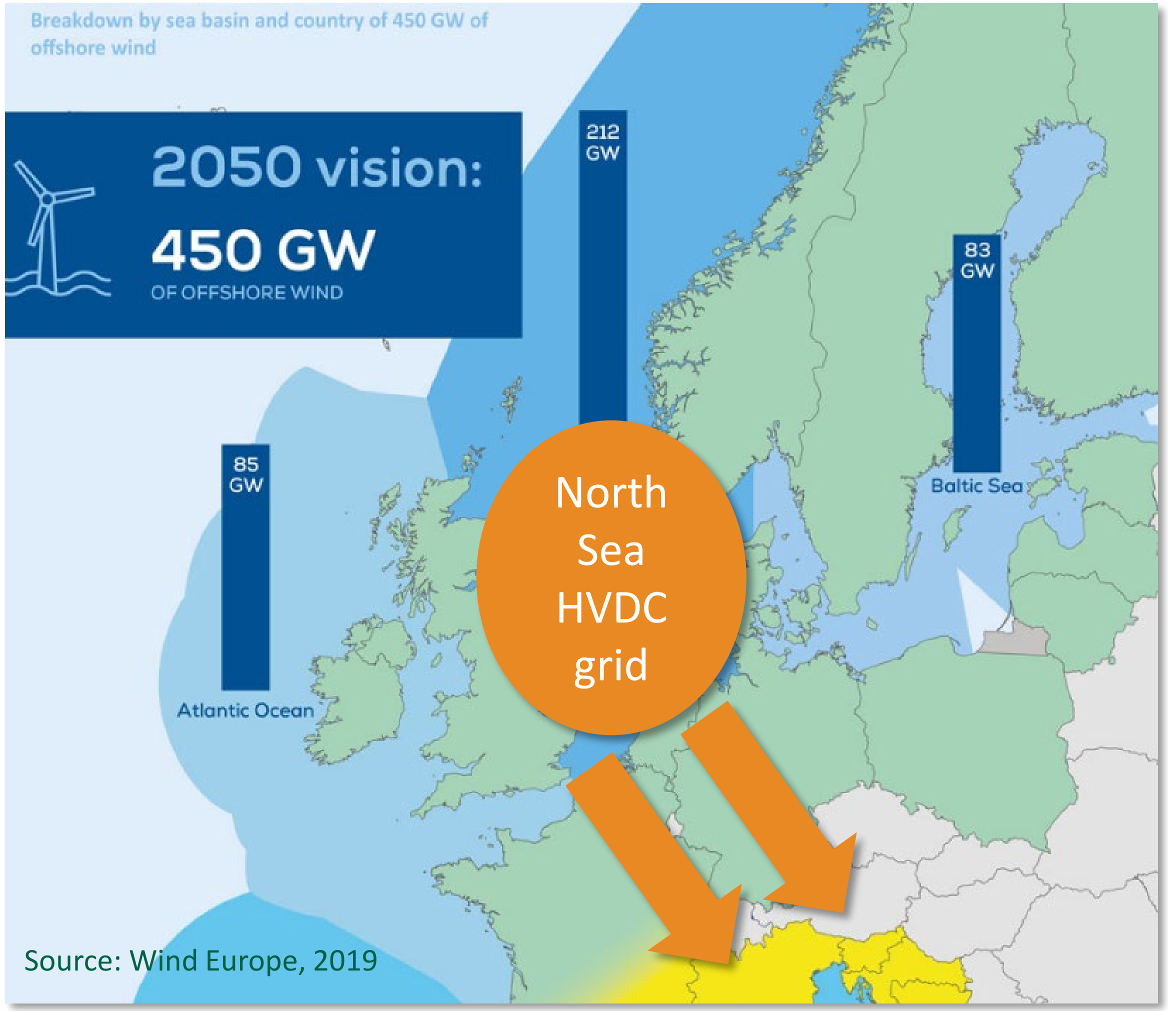
The role of HVDC in Europe's energy transition



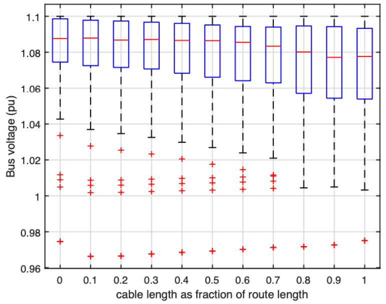
- The share of ***electricity*** in total energy ***consumption*** is projected to rise from ***20% today to over 50%*** by 2050 -> ***electricity demand x 2.5***
- The EU targets at ***least 450 GW offshore wind*** by 2050.
- HVDC grids the ***most viable*** way of connecting such quantities.
- Challenge: The components in the ***future grid*** will be interfaced through ***power electronics***. This requires new planning procedures and operational coordination concepts for secure grid operation.

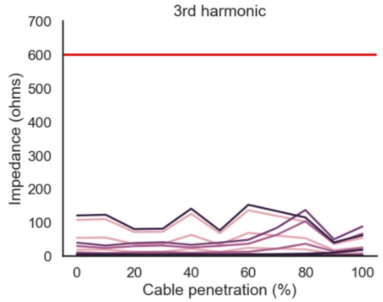
Challenges for system planning and operation

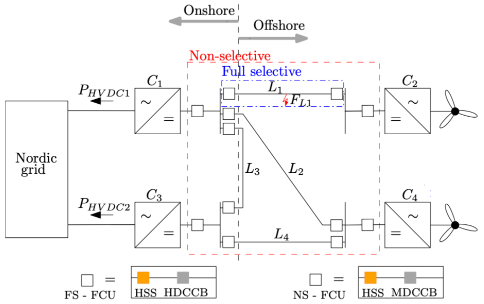
Change in system characteristics and limitations

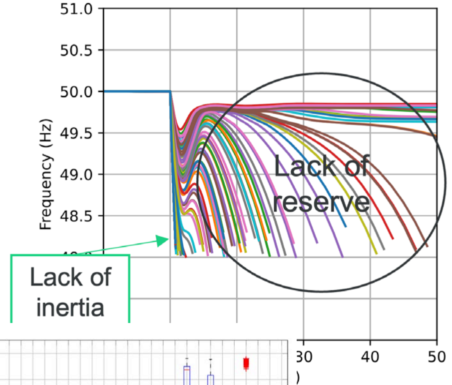
Planning and operational uncertainties

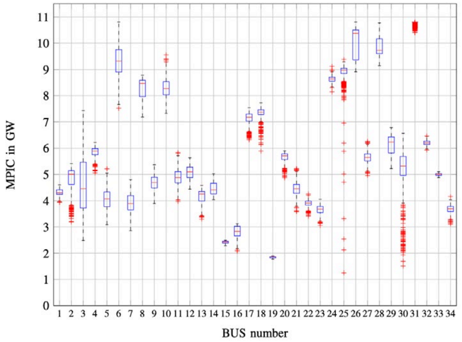
Regulatory and market rules / interactions











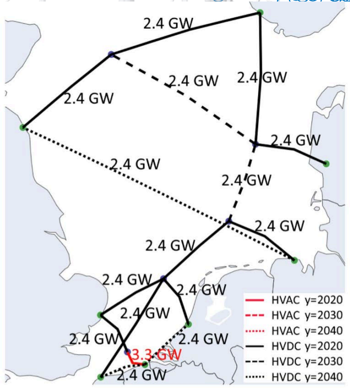


Fig. 4. nOBZ $\mathcal{G}$ topology.

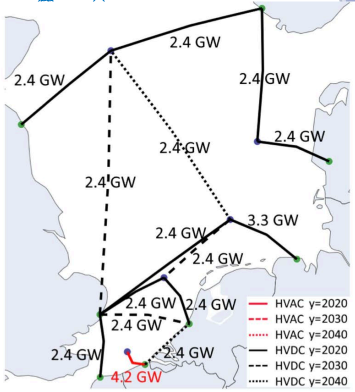


Fig. 5. HMD $\mathcal{G}$ topology.

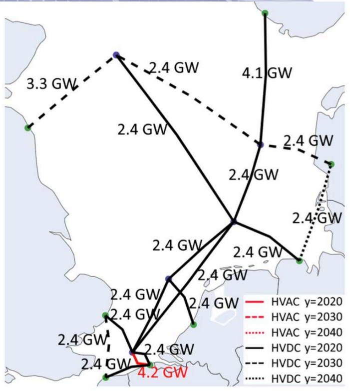
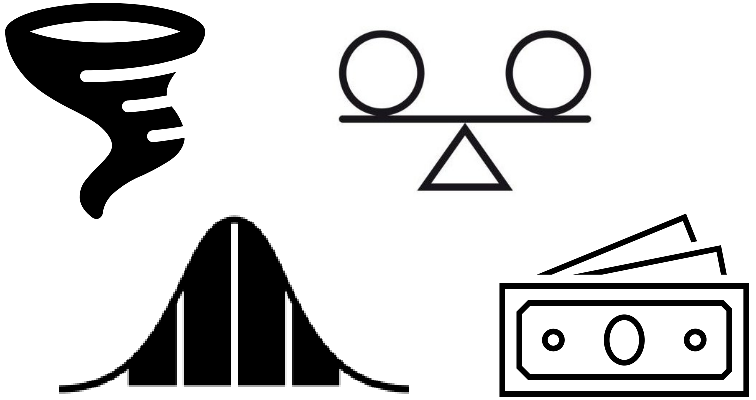


Fig. 6. zOBZ $\mathcal{G}$ topology.

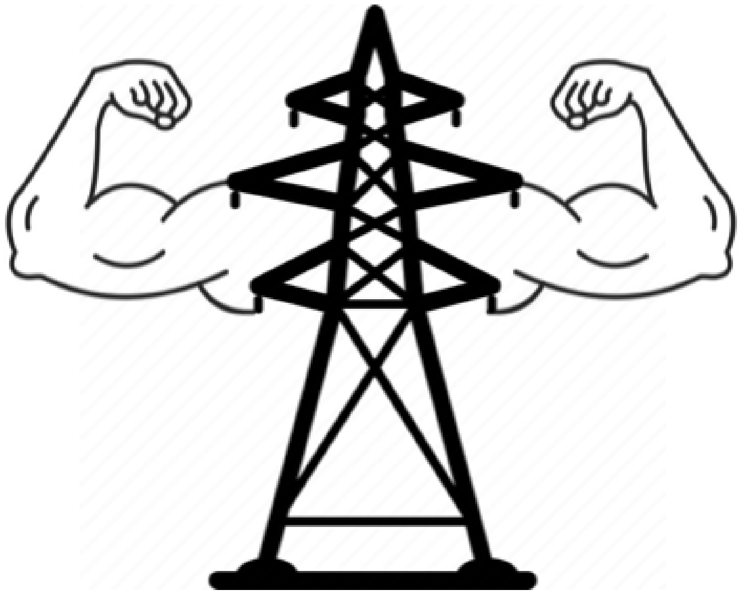
[1] V. Bhardwaj, R. Lundholm, S. Nagels, D. Van Hertem, W. Leterme, H. Ergun, Assessing the cable hosting capacity of extra high voltage AC networks, 2020
[2] Antoine, O., Papangelis, L., Tielens, P., Karoui, K., Ergun, H., Bastianel, G., Agbemuko, A., Beerten, J., Leterme, W., Van Hertem, D. (2023). AC/DC hybrid grid modelling enabling a high share of renewables. European Commission. doi: 10.2833/627100
[3] Dave, J., Van Hertem, D. (sup.), Ergun, H. (cosup.) (2022). *DC Grid Protection Aware Planning of Offshore HVDC Grids.*
[4] Ergun, H., Rawn, B., Belmans, R., Van Hertem, D. (2016). Stepwise Investment Plan Optimization for Large Scale and Multi-Zonal Transmission System Expansion. IEEE Transactions on Power Systems, 31 (4), 2726-2739. doi: 10.1109/TPWRS.2015.2480751
[5] Van Acker, T., Geth, F., Koirala, A., Ergun, H. (2022). General polynomial chaos in the current–voltage formulation of the optimal power flow problem. Electric Power Systems Research, 211, Art.No. 108472. doi: 10.1016/j.epsr.2022.108472
[6] Hardy, S.D W., Van Hertem, D. (sup.), Ergun, H. (cosup.) (2023). Cost Effective Expansion Planning: Mathematical Optimization Models to support Large Scale Offshore Wind Deployment.
[7] Hardy, S., Themelis, A., Yamamoto, K., Ergun, H., Van Hertem, D. (2023). Optimal Grid Layouts for Hybrid Offshore Assets in the North Sea under Different Market Designs. IEEE Transactions on Energy Markets, Policy and Regulation, 1-12. doi: 10.1109/TEMPR.2023.3289582

Designing a resilient AC/DC grid

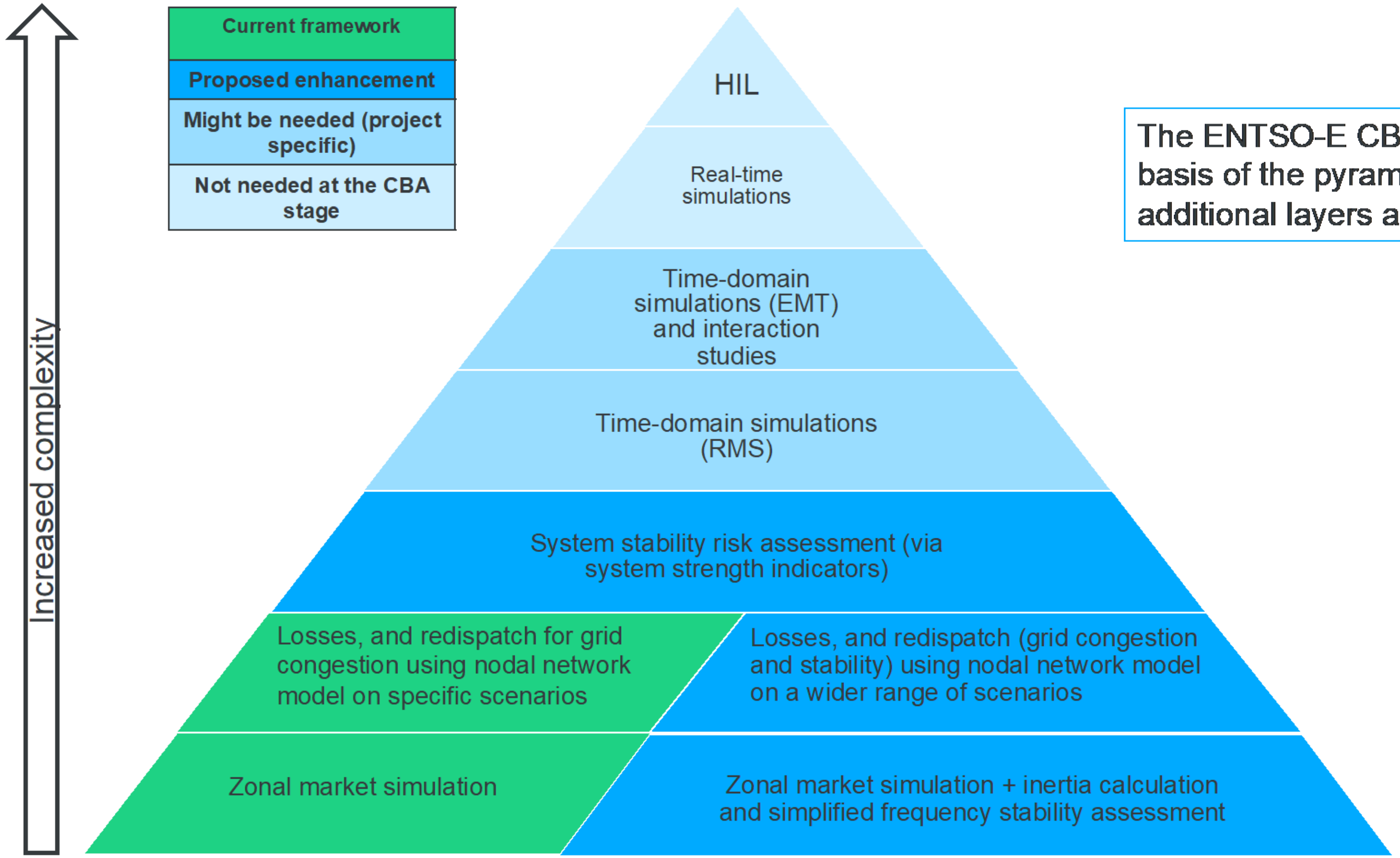
- Weather events, physical and cyber threats are getting more severe putting infrastructure under risk
- System inertia is decreasing due to power electronics replacing classical synchronous generation jeopardizing system stability
- **Using a worst-case design approach is very costly, especially with latest price increase of HVDC technology!**



- How can we leverage the benefits brought by ***HVDC*** transmission to increase ***the system resilience***?
- How can we quantify the techno-economic efficiency for HVDC systems in a ***risk-based but transparent way***?



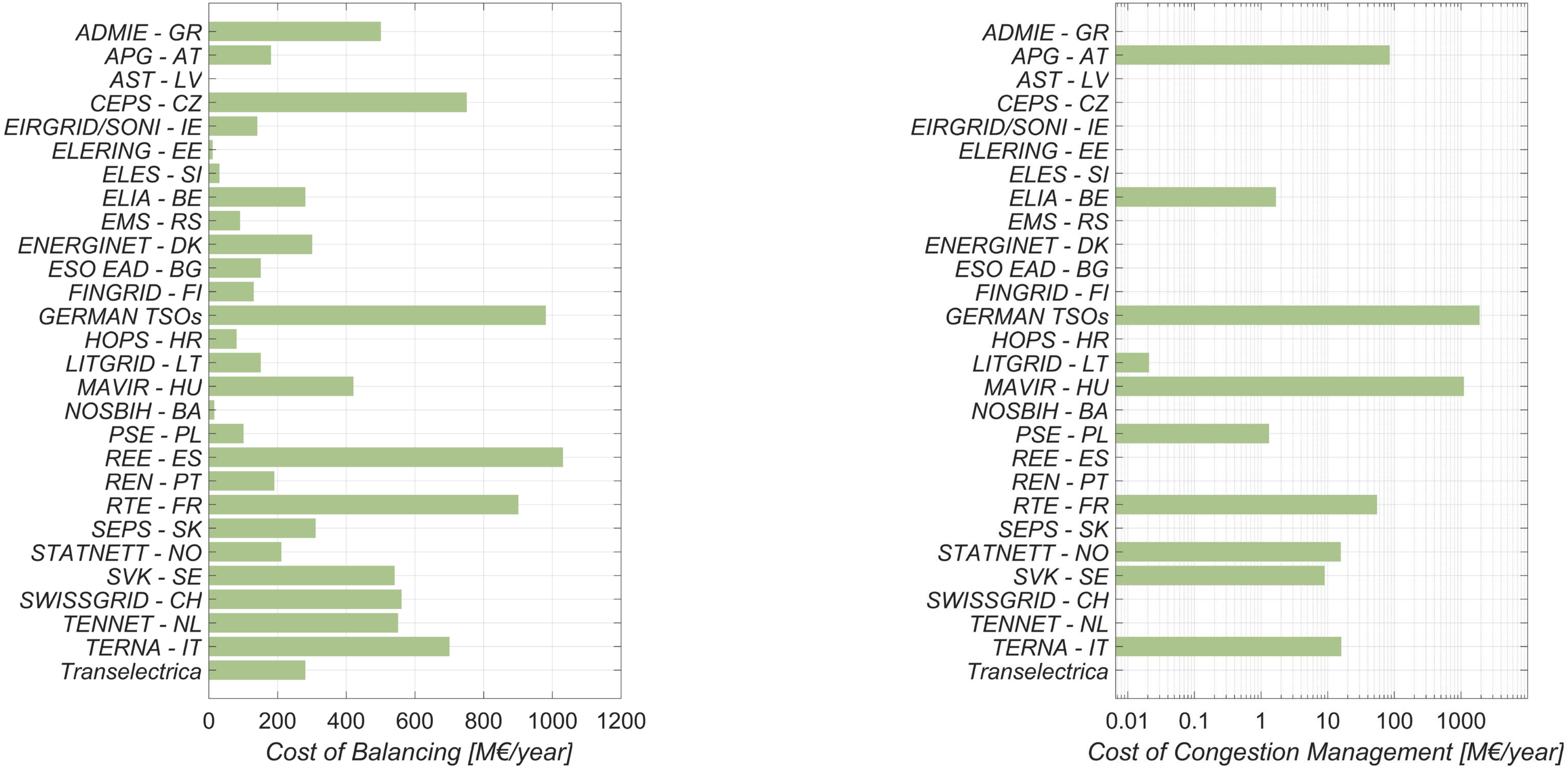
An improved CBA methodology considering system security and stability



The ENTSO-E CBA 3.0 forms the basis of the pyramid on which additional layers are added

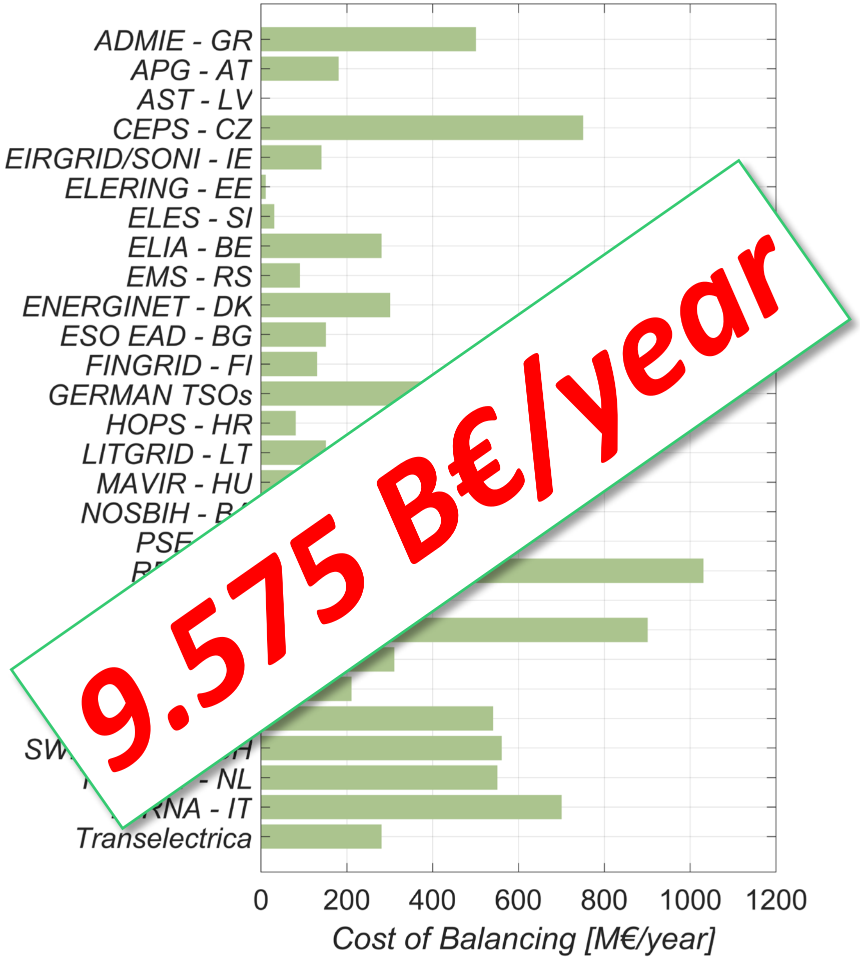
European Commission, Directorate-General for Energy, Antoine O, Papangelis L, Tielens P, Karoui K, Ergun H, Bastianel G, et al. *AC/DC hybrid grid modelling enabling a high share of renewables : final report*. Publications Office of the European Union; 2023. Available from: doi/10.2833/627100

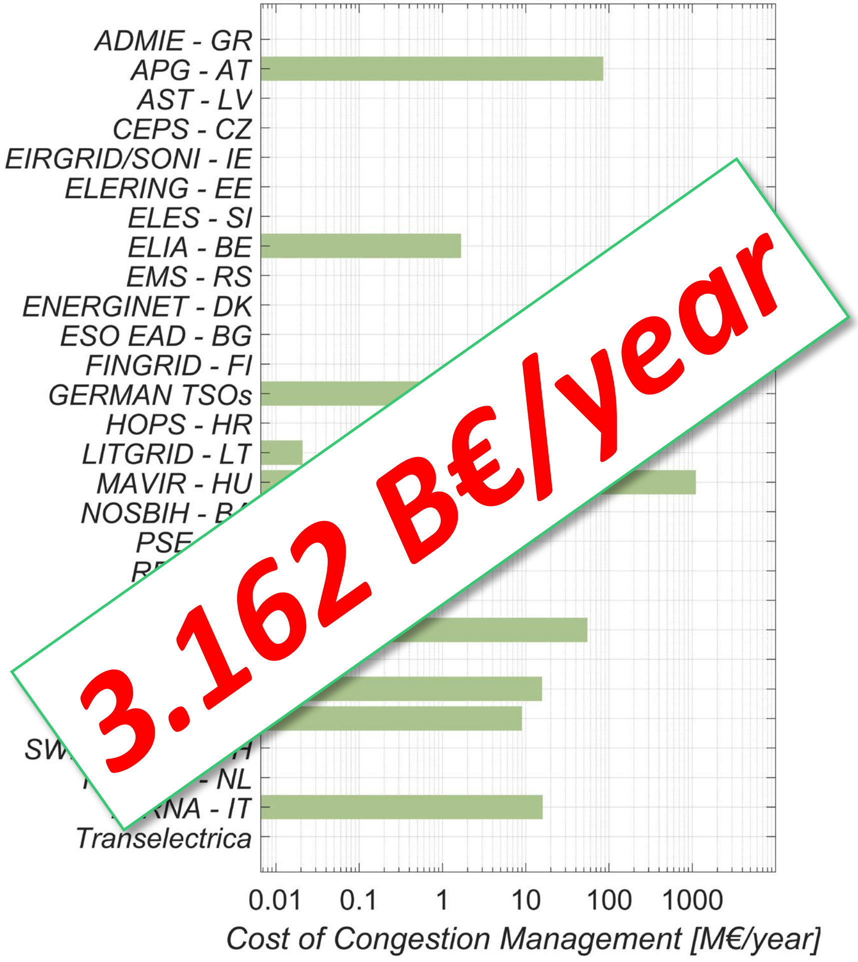
Congestion management and balancing needs



Data Sources: ENTSO-E Balancing Report 2024 and ENTSO-E Transparency Platform

Congestion management and balancing needs





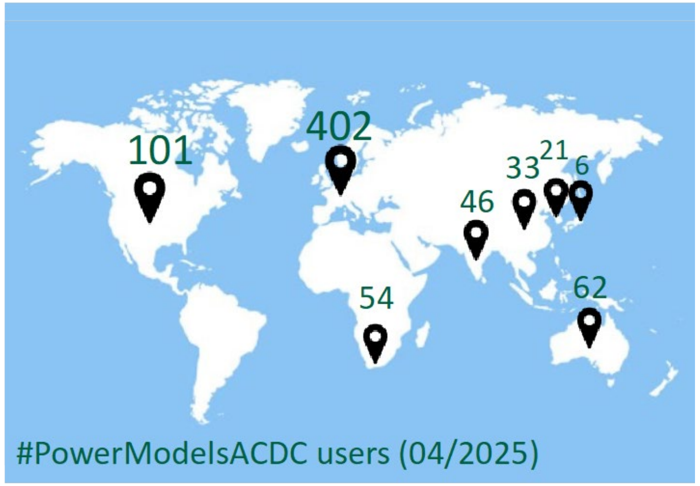
Failing to manage uncertainty effectively leads to ***significant congestion management*** and ***balancing costs***.

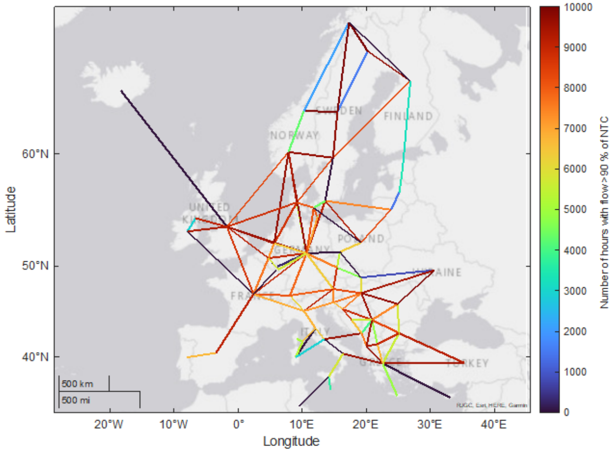
AC/DC grid decision support with PowerModelsACDC

- Allows to conduct cost benefit analysis (CBA) for different types of investments using optimal power flow and unit commitment models

- Includes a variety of power flow formulations for different types of studies
  - Zonal model using network flow for continental scale market and capacity analysis
  - Nodal model for detailed analysis of specific investments

- Includes interfaces and support for using TYNDP data for European grid studies
  - Model disaggregation from zonal to nodal models
  - Nodal European high voltage grid model
  - Isolation of different market zones for faster computation

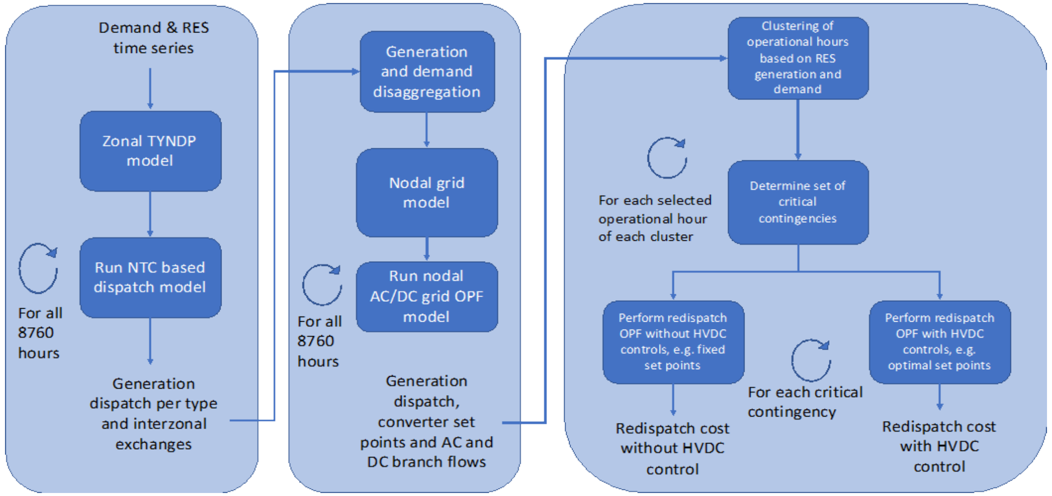


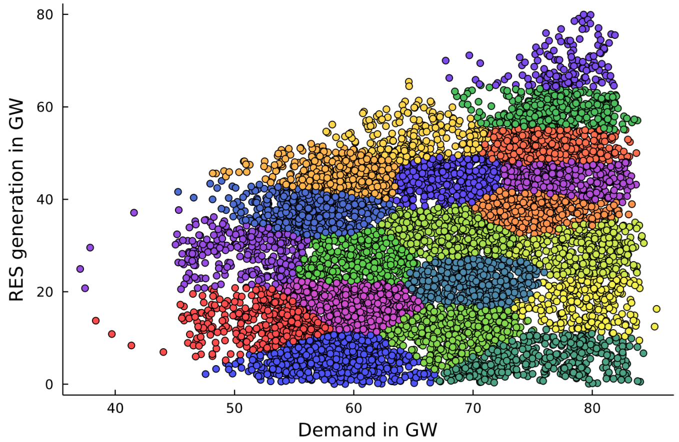


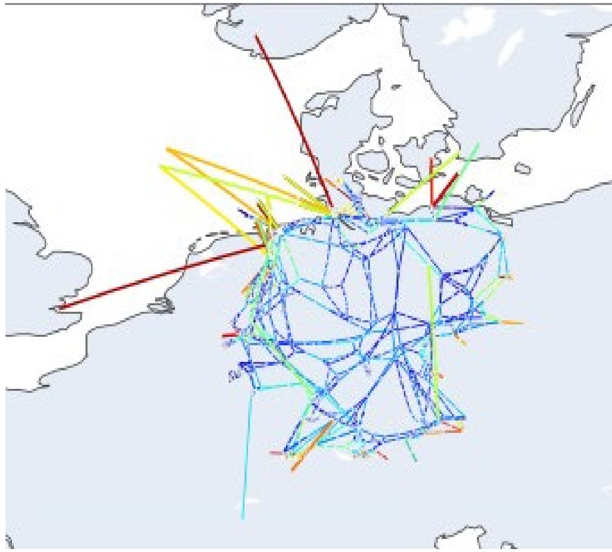
[1] Ergun, H., Dave, J., Van Hertem, D., Geth, F., Optimal Power Flow for AC/DC Grids: Formulation, Convex Relaxation, Linear Approximation and Implementation. IEEE TRANSACTIONS ON POWER SYSTEMS. doi: 10.1109/TPWRS.2019.2897835
[2] Antoine, O., Papangelis, L., Tielens, P., Karoui, K., Ergun, H., Bastianel, G., Agbemuko, A., Beerten, J., Leterme, W., Van Hertem, D. (2023). AC/DC hybrid grid modelling enabling a high share of renewables. European Commission. doi: 10.2833/627100
[3] Bastianel, Giacomo, Hakan Ergun, and Dirk Van Hertem. "A Multi-GW Energy Hub for Southern Europe: the Mediterranean Energy Island Proposal." 2023 AEIT HVDC International Conference (AEIT HVDC). IEEE, 2023.

Use case: Benefits through HVDC power flow control

- Zonal market calculations to establish base case dispatch and interconnector flows
- Generation and demand disaggregation to nodal model
- Hourly OPF calculations to determine nodal dispatch
- Clustering hourly data for selecting representative hours for optimal redispatch calculation
- Contingency filtering
- Performing re-dispatch calculation for all N-1 contingencies



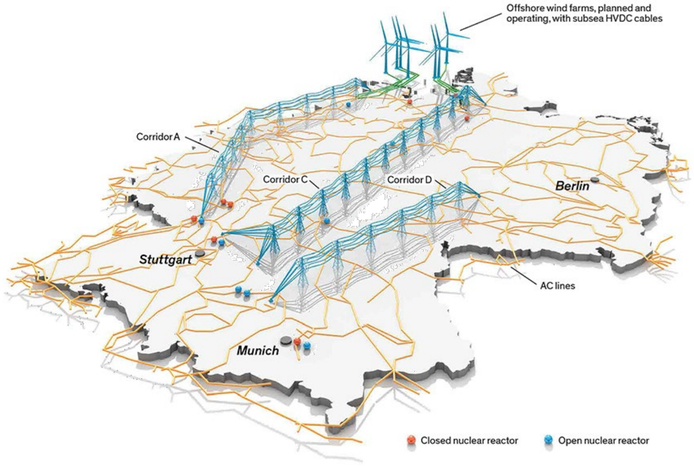


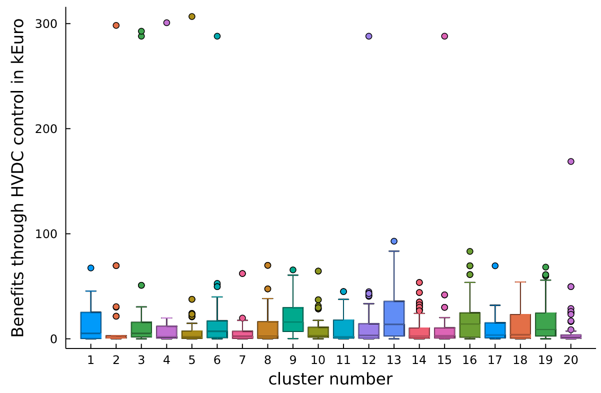


[1] Ergun, H., Bastianel, G., Van Hertem, D. (2023). Quantifying benefits of power flow control through HVDC under network Contingencies. In: Cigre B4 Colloquium 2023, (1-10). Presented at the Cigre B4 Colloquium 2023, Vienna, 11 Nov 2023-16 Nov 2023.

Use case: Benefits through HVDC power flow control

- Detailed model of the 400 kV model for the Entso-e region including generator types, line impedances and line ratings based on [1]
  - Both AC and DC lines
- Analysis of UltraNet, Südlink and Südostlink
- German grid model
  - 1049 AC nodes, 1381 Ac branches, 1540 generators, 43 HVDC links
- All links present significant benefits through HVDC power flow control on average
- Worst case contingencies result in extreme high benefits
  - This can be part of structural congestion which should be alleviated via investments
  - Includes also trivial N-1 contingencies, e.g. possible antennas leading to demand curtailment



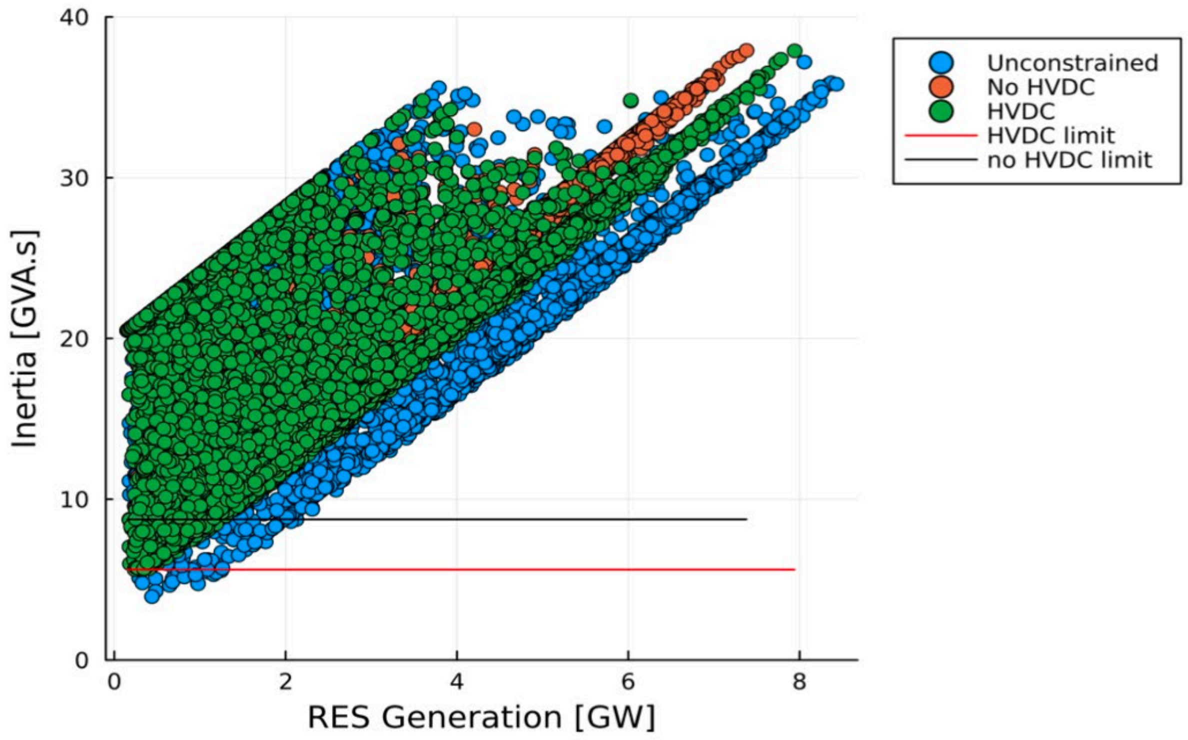


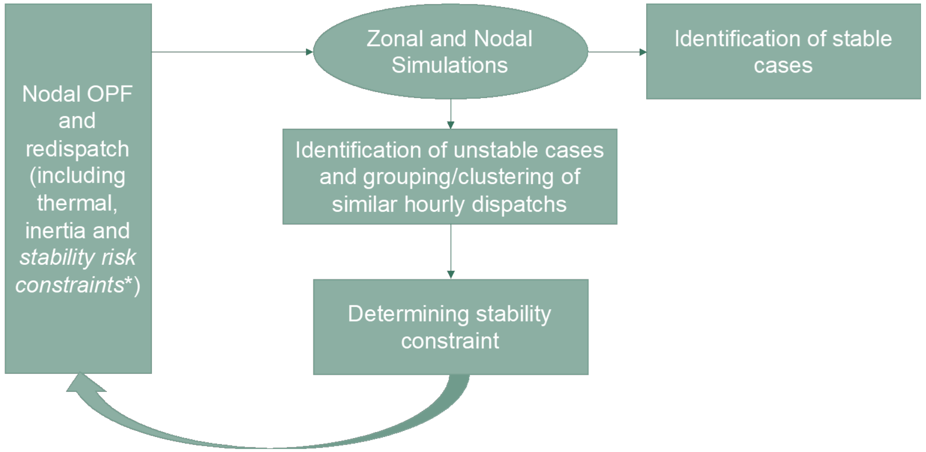
	Average Benefits [M€/year]		Maximum Benefits [M€ /year]	
	GA 2030	GA 2040	GA 2030	GA 2040
Ultranet	28.8	35.4	258	253.5
Südlink	42.6	46.2	365.1	401.8
Südostlink	13.7	11.1	365.2	268.3
All links	58.1	35.3	274.8	287.3

[1] Andrea Tosatto, Xavier Martínez Beseler, Jacob Østergaard, Pierre Pinson, Spyros Chatzivasileiadis, North Sea Energy Islands: Impact on national markets and grids, Energy Policy, Vol. 167, 112907, 2022. https://doi.org/10.1016/j.enpol.2022.112907."
[2] Ergun, H., Bastianel, G., Van Hertem, D. (2023). Quantifying benefits of power flow control through HVDC under network Contingencies. In: Cigre B4 Colloquium 2023, (1-10). Presented at the Cigre B4 Colloquium 2023, Vienna, 11 Nov 2023-16 Nov 2023.

Analysing the value of inertia provision through HVDC – Inertia constrained OPF model

Example of Celtic Interconnector (IE - FR)





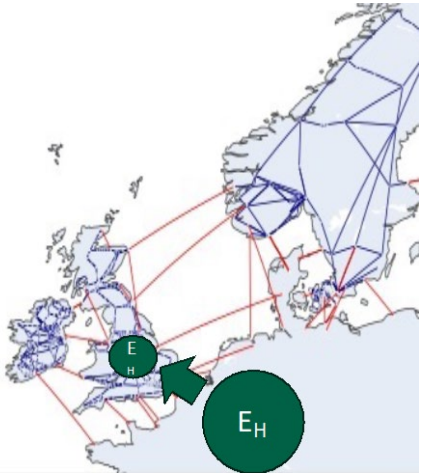
Case	Total cost [bn€]	Difference wrt unconstrained model [M€]
Unconstrained model	170.85	-
Inertia constrained, no HVDC	170.96	113
Inertia constrained, with HVDC	170.91	62

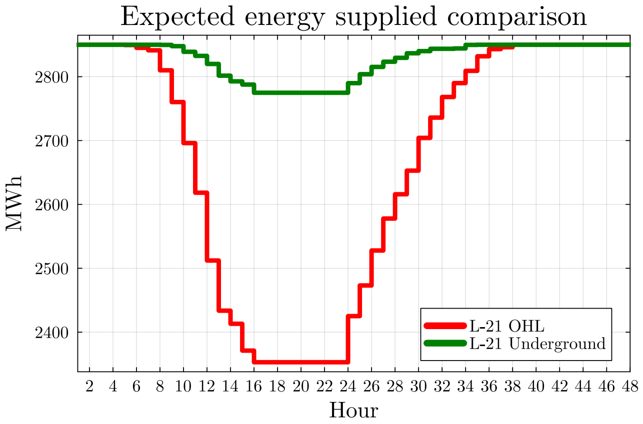
Table 2 – Total cost and comparison to the unconstrained zonal model with investment of the inertia-based OPF model with and without HVDC Celtic interconnector, GA2030, climate year 2007

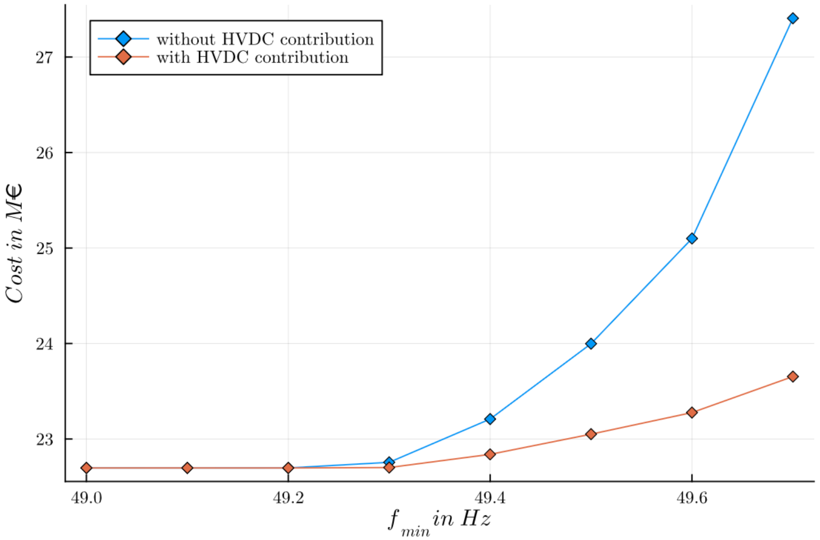
[1] European Commission, Directorate-General for Energy, Antoine O, Papangelis L, Tielens P, Karoui K, Ergun H, Bastianel G, et al. *AC/DC hybrid grid modelling enabling a high share of renewables : final report*. Publications Office of the European Union; 2023. Available from: doi/10.2833/627100

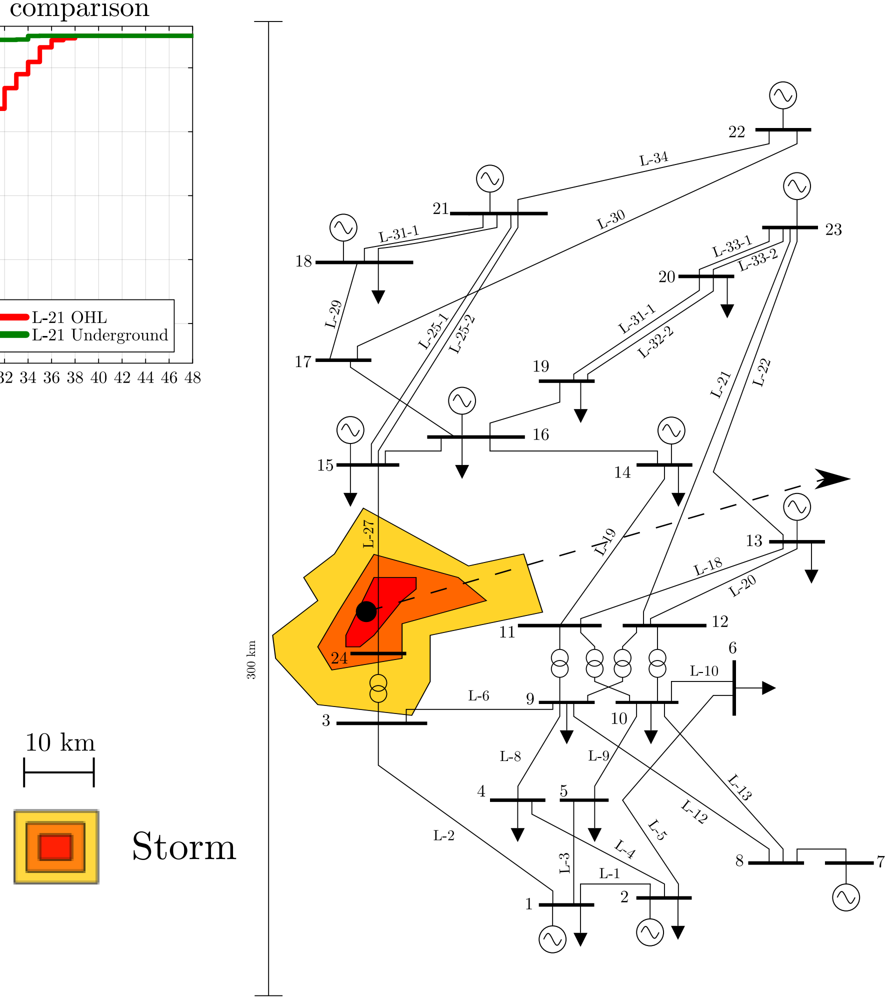
Resilience aware planning of AC/DC grids

- Modelling of low probability high impact events and benefits from HVDC systems
  - Power flow control
  - Fast frequency support
  - Voltage control
  - Undergrounding









[1] H. Ergun, R. Heidari, S. Mhanna, P. Mancarella, "The value of Fast Frequency Reserve provision through HVDC systems", *under preparation*.
[2] O. Damanik, D. Van Hertem, H. Ergun, Mitigating large-scale offshore wind farm shutdowns during a severe storm using an adaptive robust optimization approach, 12th Bulk Power System Dynamics and Control Symposium IREP'2025

Conclusions

- HVDC systems bring multiple benefits in terms ***of congestion management, system security and system stability improvement.***

- ***New type of modelling tools*** are needed to quantify such benefits and provide a ***transparent cost-benefit*** analysis.

- Transparency in models and data of outmost importance for ***regulatory support and public acceptance*** of the investments.

- ***Open-source data sets and models can be the solution:*** Community driven development of model improvements, data quality checks, replicability of studies, ….!

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