THE UNIVERSITY OF MELBOURNE

Melbourne Energy Institute

Public lecture: Offshore HVDC grids – A European perspective

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Research Expert, KU Leuven

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Offshore HVDC Grids - A European Perspective

Hakan Ergun

KU Leuven / EnergyVille

Agenda

- Brief introduction of KU Leuven & EnergyVille
- Why do we need HVDC grids and what are the grand challenges?
- How do we contribute to solving these challenges?
    - Overview of the research at KU Leuven / EnergyVille
    - Deep-dive in optimisation based models for planning and operation of future HVDC grids
- The future of HVDC grids

KU Leuven (Katholieke Universiteit Leuven)

 # 1 declared Most Innovative University of Europe by Reuters four years in a row

 # 42 in the Times Higher Education World University Ranking (2022)

 # 76 in the QS World University Ranking(2023)

- 15 faculties
  - academic staff: ± 8200
  - total staff: ± 13400
  - students: ± 63 000
- Research budget: ± M€ 580

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ELECTA - Electrical Energy Technologies & Applications

www.esat.kuleuven.be/electa

Electa in numbers:

- 5 + 3 professors
- + 10 associated & visiting professors
- 7 senior researchers
- 14 post-docs
- > 50 PhD researchers
- + 25 affiliated researchers
- 17 techn./admin. staff

Research topics:

- Power system planning, operation and control
- HVDC grids
- Smart grids and cities
- Power electronics and their control
- Robust, distributed control systems
- Multi-scale, multi-physics modelling of electromagnetic power systems
- Connection of distributed energy resources
- Industrial applications (high voltage and machine testing)
- (Light) electric vehicles
- Photovoltaic systems

Department of electrical Engineering - ESAT

- MSc students: ± 300
- PhD students: >500

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EnergyVille - Mission

- EnergyVille is a top energy research cooperation between the Flemish universities and research centres KU Leuven, VITO, imec and UHasselt

- Almost 500 people involved
- Over 400 researchers (about 50% international)
- 8 research topics

252 Belgian colleagues | 78 European colleagues | 128 International colleagues

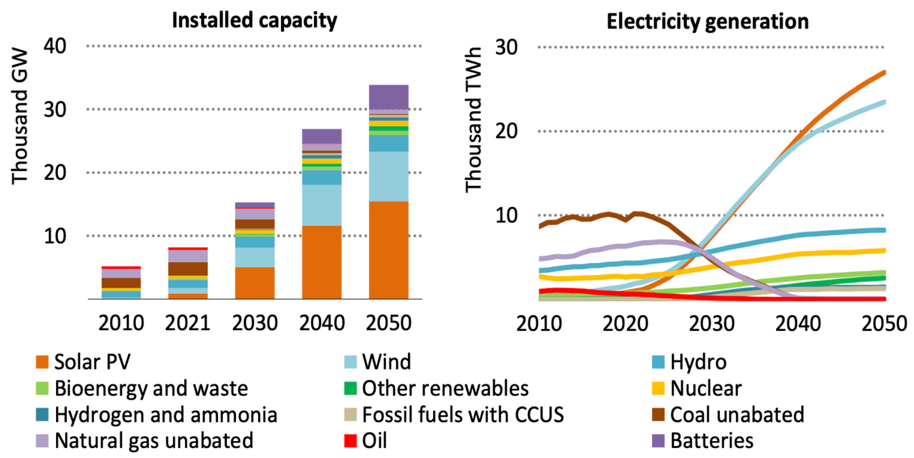
Battery storage | Electrical networks | Energy for buildings and districts | Energy strategies and markets | Power electronics | Power-to-Molecules | Solar energy | Thermal systems

Why HVDC grids?

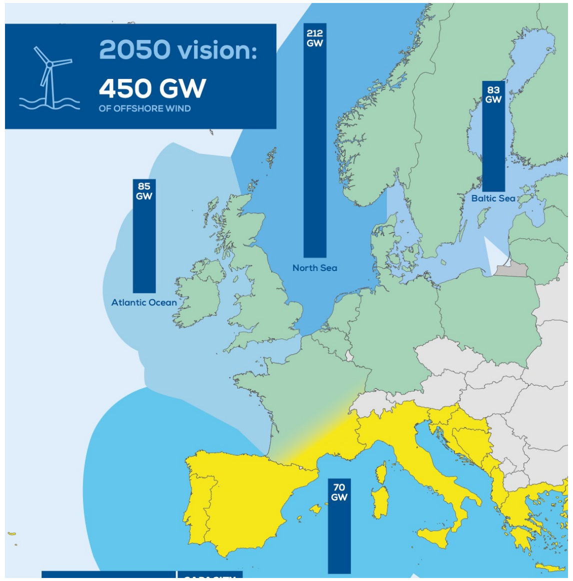
And what are the grand challenges?

Global trends

Figure 3.10 ▷ Total installed capacity and electricity generation by source in the NZE Scenario, 2010-2050



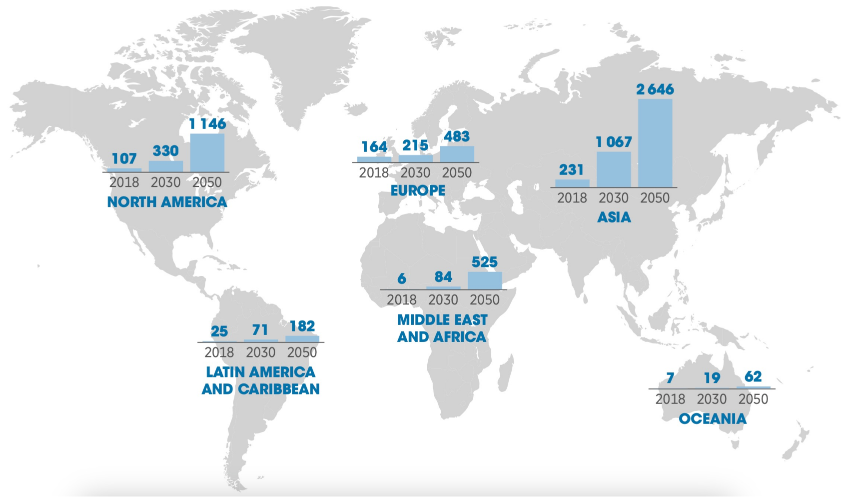
Source: IEA, World Energy Outlook 2022



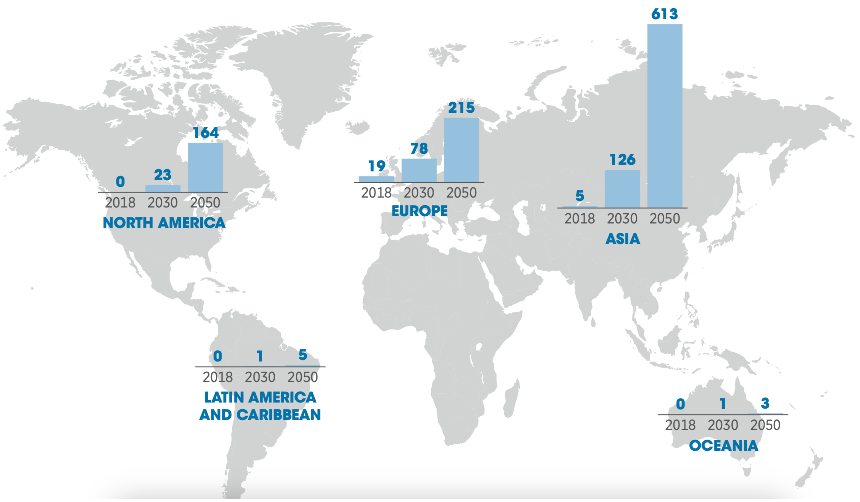
Source: Wind Europe, Our energy, our future 2019

Source: IRENA, Future of Wind, 2019

Onshore wind installed capacities (GW)



Offshore wind installed capacities (GW)



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In the transition towards a sustainable energy future…

- Electrical networks are the key enabling technology for the energy transition
- Electrification is the most efficient route to net-zero, resulting in expected increase in electrical consumption (EV, HP, industry,…)
  - EV + HP in NW European families means consumption X3
  - 1 million EV in Flanders by 2030 (or earlier)
  - PV to become standard on each rooftop
- Electrical networks connect cheap RES sources at the local level and abundant RES at remote sites with each other, consumers and different enabling technologies (e.g. storage)
- (All) components will be interfaced through power electronics
- Energy Efficiency is key:
  - Best possible technology
  - Optimal use within the limits of the system
- ***No grids, no party!***

By 2030: 375-425 BEUR investments in distribution systems are needed (Eurelectric and E.DSO)

Offshore energy objectives require 800 BEUR of investments by 2050, of which 2/3 for grid infrastructure (EC)

Investing 1.3 bn€/year between 2025 and 2030 translates into a decrease of generation costs of 4 bn€/year, while investing 3.4 bn€/year between 2025 and 2040 decreases generation costs by 10 bn€/year. (source: ENTSO-E TYNDP)

90 % of buildings needs to be renovated by 2050: opportunity for behind the meter grids and building <-> grid interactions

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Grand challenges HVDC

Massive investment needs

- 300-> 450 GW of offshore wind by 2050
  - +/- 35 GW of wind offshore installed to date (2/3 in Europe)
  - ±100 GW by 2030
  - North Sea: 200 GW by 2050
  - Solar will see similar developments
- Offshore requires massive investments (EC: 2/3rd of 800 Billion EUR by 2050)
- Meshed HVDC grids are the only realistic option:
  - Connections are increasingly further from shore
  - Needs to be integrated in the existing system (hybrid AC/DC)
  - Towards new backbone grid
  - 100 % power electronics

We need to connect 200 GW from the north sea
➔ Assume 5 GW links

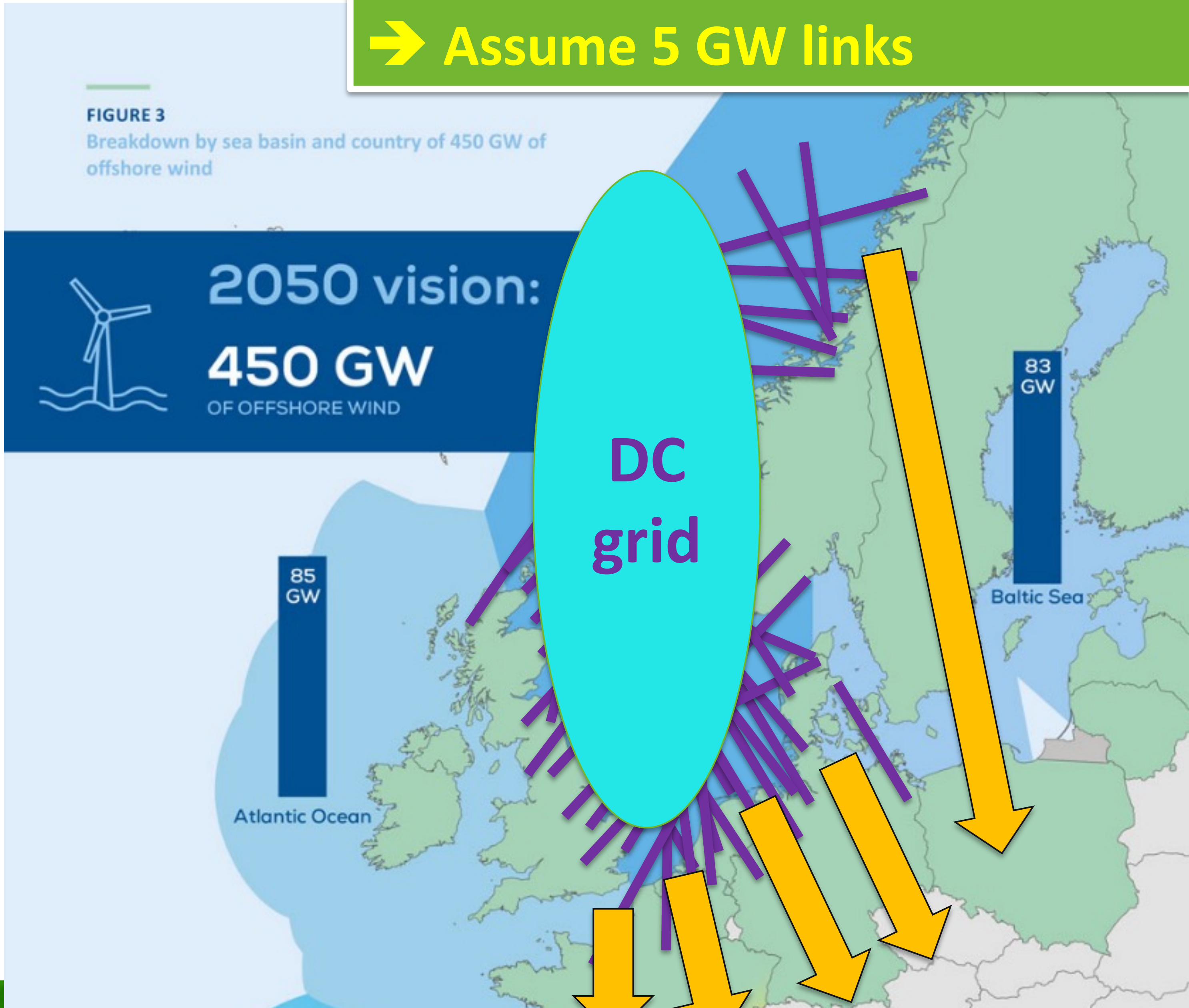

Figure: WindEurope

AC/DC hybrid grid, a vision?

- 58 HVDC connections in Europe to date (including back-to-back links)
- According to TYNDP 2022, 51 out of 141 transmission projects are using HVDC
- Solar developments are equally fast:
  - South to North flows
- Offshore grid development plan*
  - "… ENTSO-E, with the involvement of the relevant TSOs, the national regulatory authorities, the Member States and the Commission, must develop the first sea-basin (SB) related offshore network development plans (SB-ONDPs) by 24/01/2024, based on the goals developed by the Member States' governments…"
  - The second ENTSO-E deliverable is expected by 24/06/2025; namely "the results of the application of the cost-benefit and cost-sharing to the priority offshore grid corridors"

Subset of HVDC connections in TYNDP 2020 of ENTSO-E

*https://eepublicdownloads.blob.core.windows.net/public-cdn-container/tyndp-documents/ONDP2024/220906_ENTSO-E_Guidance_ENER_ENTSO-E_clean.pdf

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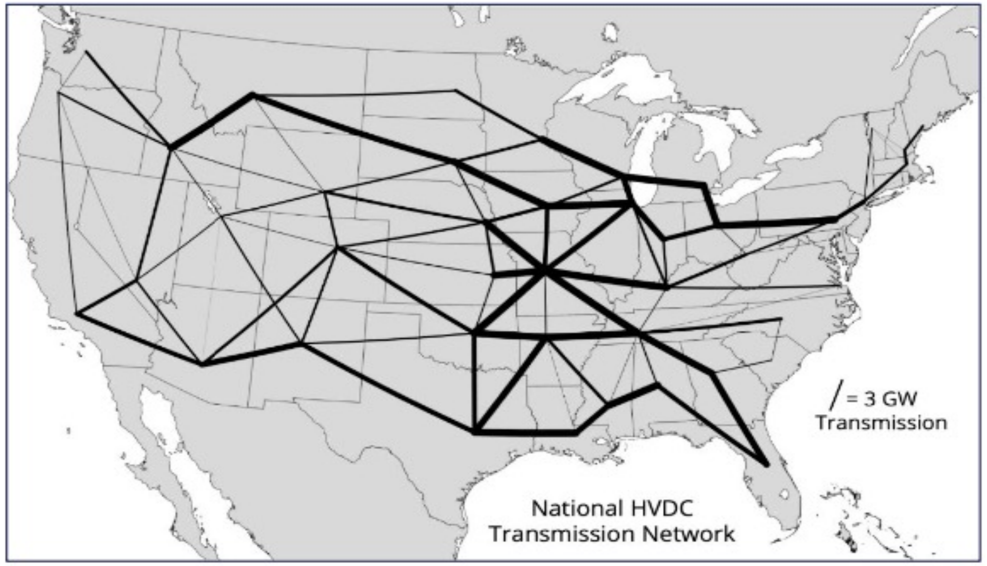
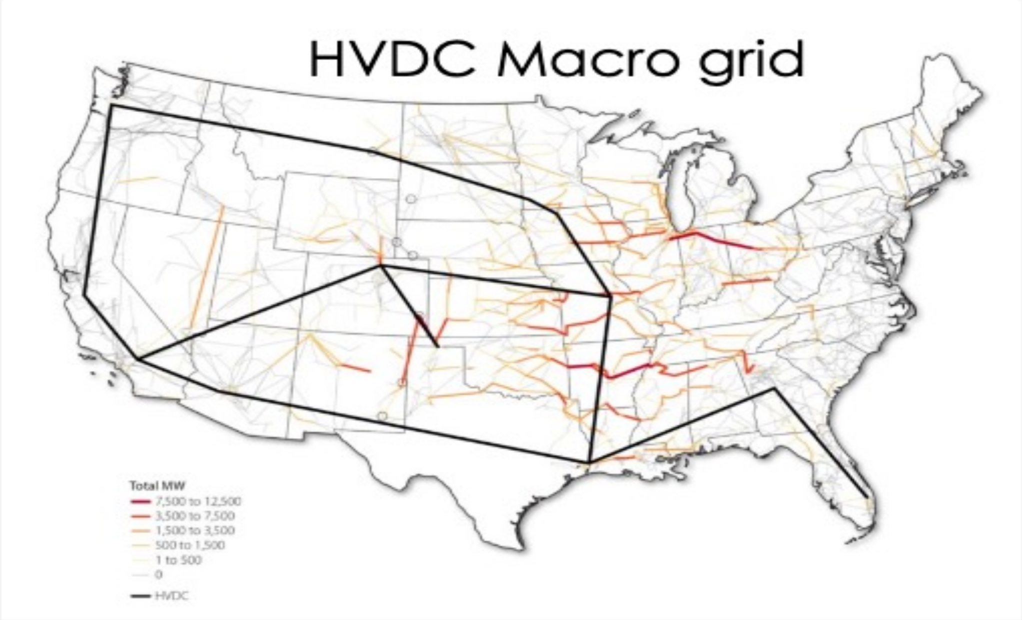
The role of interconnection and HVDC, not only in Europe…

Vibrant Clean Energy ZeroByFifty



Transmission expansion costs $350B for 100% clean energy and $1T more to get to 100% without macro grid

NREL Interconnection Seams Study



Cost benefit ratio of HVDC grid 2.5 – 2.9

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[1] F.Acevedo, et al, *Design and Valuation of High-Capacity HVDC Macrogrid Transmission for the Continental US*, IEEE Transactions on Power Systems, Vol 36, no 4, 2021
[2] Lew, et al, *Transmission Planning for 100% Clean Electricity,* IEEE PES Magazine, Nov/Dec 2021

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Significant investment challenge

- Assume 400 GW offshore via HVDC
- 2 GW wind farms
    - ➔ about 400 converters needed (200 on- and 200 offshore converters, 220 MEUR for onshore, 500 MEUR for offshore)
    - 200 * 220 + 200 * 500 = 144 BEUR
- Assume 150-200 km of average cable length offshore, 2 GW cable (2 MEUR/GW/km)
    - 150 * 200 * 2 * 2 = 120 BEUR (to 160 BEUR)
- 264-304 BEUR

- 14.8 GW/year
- 2 GW wind farms
    - About 15 converter stations per year
- About 2222 km subsea cable per year
    - X 2 (two poles) = **4444** km /year
    - Global submarine EHV cable production **~5000** km /year
- **9.7-11.3 BEUR**/year
- North Sea TSOs: **19 BEUR /year** turnover (2022)

What do we see as the future?

TODAY	IN FUTURE
From point-to-point connections …	… to multi-terminal and meshed grids
Protection From conventional AC system protection …	… to fast-acting DC &AC system protection
Control From one manufacturer per link …	… to multi-vendor interoperability
Operation From HVDC as “assistance” for AC grid …	… to AC & HVDC grid as parts of same grid
Planning From HVDC as addon element…	… to HVDC (grids) directly included as potential grid element for grid expansion integrating all available “features”
Grid code From complying with AC system/TSO requirements …	… to complying with both AC and DC grid requirements in a multi-stakeholder environment

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Roadmap for HVDC grids

Now-2030:

Multi-terminal hybrid connections

(no mesh)

2030-2035:

Offshore energy hubs

2035-2045:

Meshed offshore grids

First deep inland reinforcement

2045-:

EU-wide interconnection

Now-2030:

Underground cable at EHV when needed

2030-2040:

Underground cable at EHV when possible

2040-:

Only undergrounding

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SET Plan for HVDC
HVDC grid ambition levels

EUROPEAN COMMISSION
DG RTD, Directorate C - Clean Planet
DG ENER, Directorate B - Just transition, Consumers, Energy Efficiency and Innovation
JRC, Directorate C - Energy, Transport and Climate
SET Plan Secretariat

- Short term (- 2027)
  - An operable multi-terminal, multivendor HVDC system in Europe (e.g. hybrid interconnector)
  - Top-down orchestration of HVDC grid planning, enabling an efficient step-wise organic development of future HVDC grid system pieces
- Medium term (2030 - 2035)
  - Multi-terminal, multivendor HVDC system is cost-effective solution for large offshore projects
  - Multi-terminal multivendor HVDC system for onshore ready
- Long term (2050)
  - Backbone grid (integrating smaller systems)
  - HVDC available for deep sea applications

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Main challenges in planning and operation of offshore HVDC grids

- The choice of proper market design
  - Depending on the market design, future costs and revenues will be distibuted differently among the actors, influencing investmet decisions

- Operational coordination of offshore grids
  - Moving from point-to-point conenctions to a multi-national HVDC grid will require regional control

- Ensuring safe and stabile operation
  - Fast and efficient algorithms for DC fault detection, advancements in DC breaker technology,, stable operation of low inertia systems

- Ensuring the interoperability of the system
  - Making sure that converters and protection devices of different manufacturers can operate wihtout any problems, avoiding control interactions and instability

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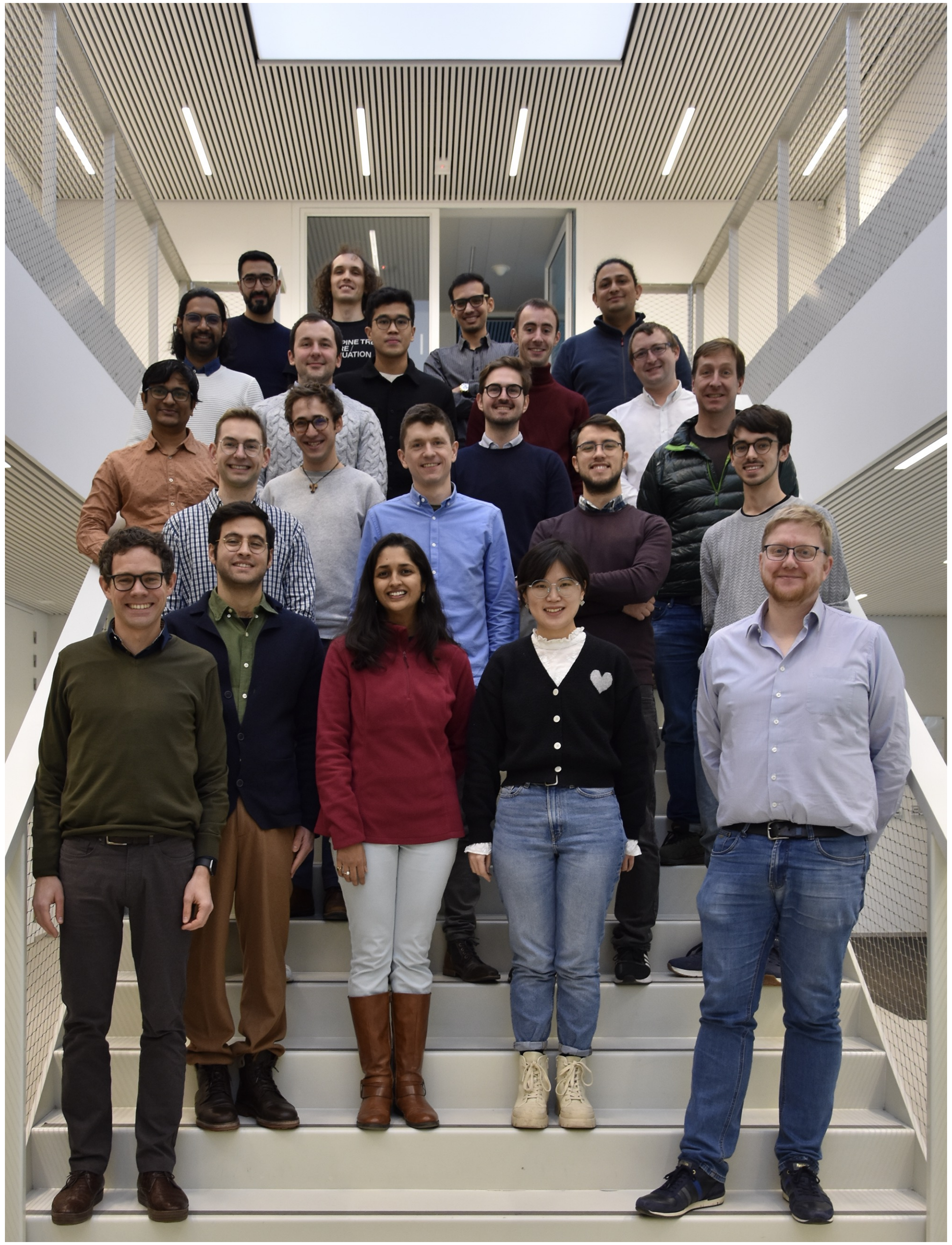
HVDC research at KU Leuven / EnergyVille

How do we contribute to solving these challenges?

Towards HVDC Grids

Activity description

- Models and tools for analyzing and improving control interactions with and within HVDC grids and links
- Algorithms, models and equipment for HVDC grids protection
- Models and tools for grid planning and operation including HVDC, while accounting for uncertainty, reliability and flexibility



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Dynamic stability and control interactions

- Solar PV and wind are interfaced via power electronic devices called inverters and are called Inverter Based Resources (IBR) or Power Electronics Interfaced Power Sources (PEIPS)

- The operation of the power system will then be governed by the controls of the power electronic inverters, rather than the natural response of traditional generators

- However, current simulation / optimisation models and sofware tools are not able to capture the high frequency dynamics, transients and harmonics in an accurate way

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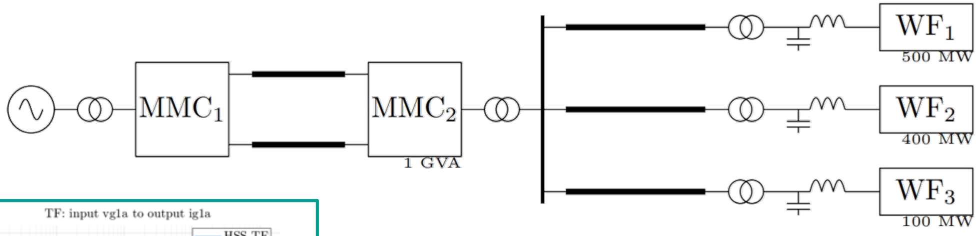
Dynamic stability and control interactions

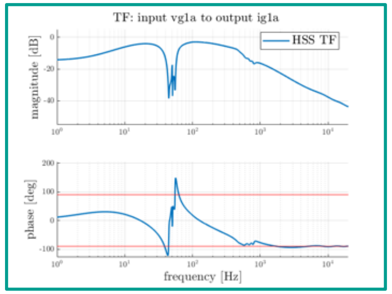
Fundamental research and softwware tools

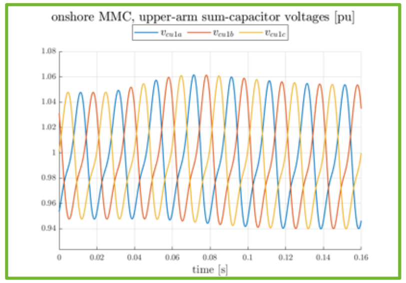
- Fundamental research
  - Impedance-based modelling & stability analysis
  - State-space modelling & stability analysis
  - Frequency-lifted methods
  - Passivity

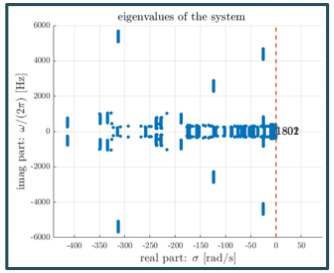
- In house tools
  - MATLAB: State-space models & eigenvalue-based stability analysis
  - Julia: Impedance-based stability analysis tool
  - PSCAD: Benchmark models & harmonic impedance scanning tool

HVDC
MMC
harmonics
nonlinearity
periodicity
delays
stability





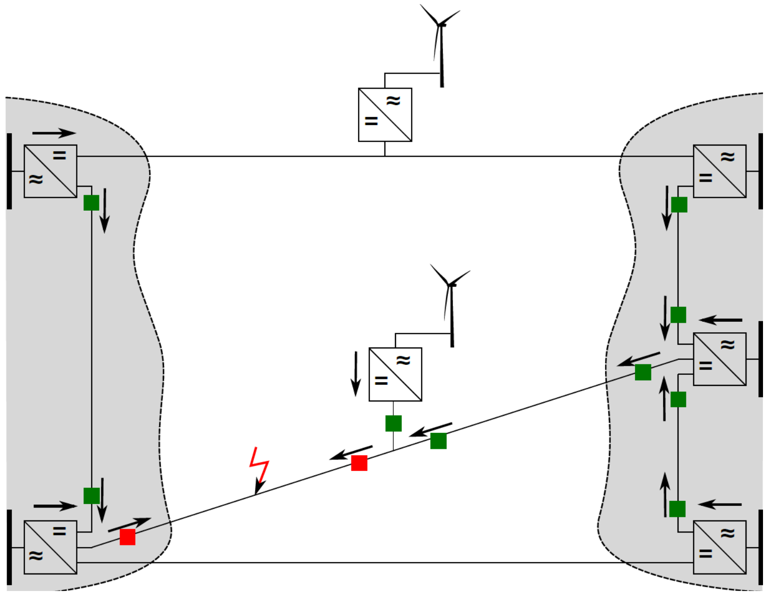




For more information -> prof. Jef Beerten lead of the HVDC control group

Integration of cable-based HVDC grids requires fundamental changes to the way we look at protection

- HVDC systems introduce challenges for both AC and DC grid protection
  - In ac systems, fault current characteristics change as converters have different response compared with conventional power plants
  - In dc systems, fundamentally new protection algorithms are needed due to difference in time scales and waveforms
- HVDC protection may face different trade-offs compared to AC side protection; what are the costs and consequences of clearing faults?
- HVDC cables are characterized by a lower number of faults compared to overhead lines, but outage times may be longer



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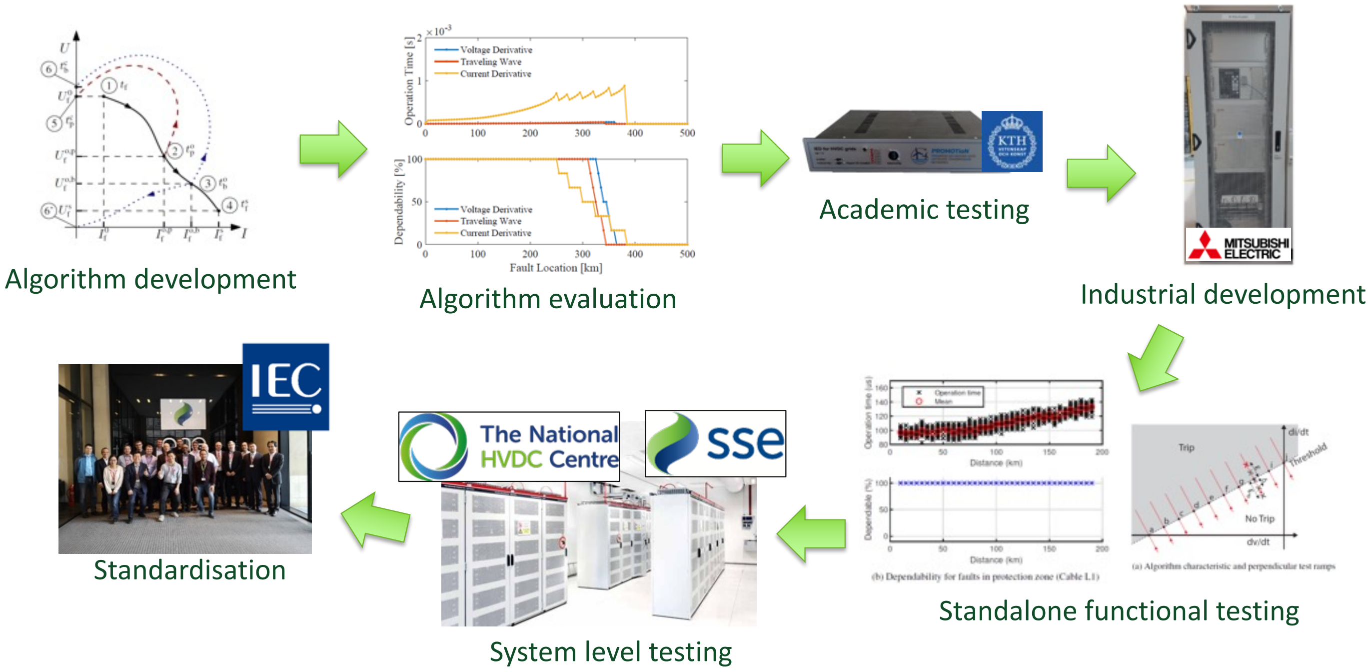
The HVDC grid protection team tackles following questions

- **1. Effective protection algorithms for HVDC grid protection**
  - How to design and test HVDC grid protection algorithms
    (online/fault localization)
  - How to model for HVDC grid protection studies
- **2. Design of HVDC grid protection**
  - Which strategies are effective for HVDC grid protection?
  - How to design HVDC grid protection components
  - What is the impact at the AC- and DC-side?
- **3. How to integrate HVDC grids into existing AC systems**
  - What are the impacts of HVDC grids on the surrounding AC systems?
  - How to adapt control/protection for effective AC protection?



For more information -> prof. Dirk Van Hertem (lead electrical networks), dr. Willem Leterme (lead HVDC protection), dr. Geraint Chaffey (lead digital grid emulation)

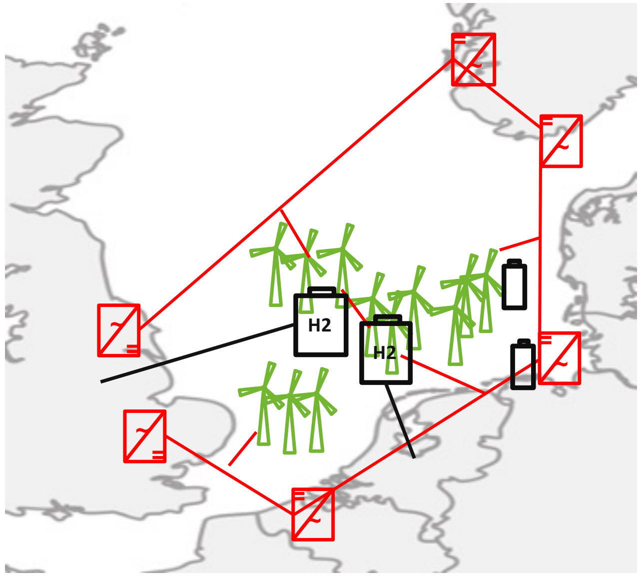
Optimisation models for planning and operation of HVDC grids

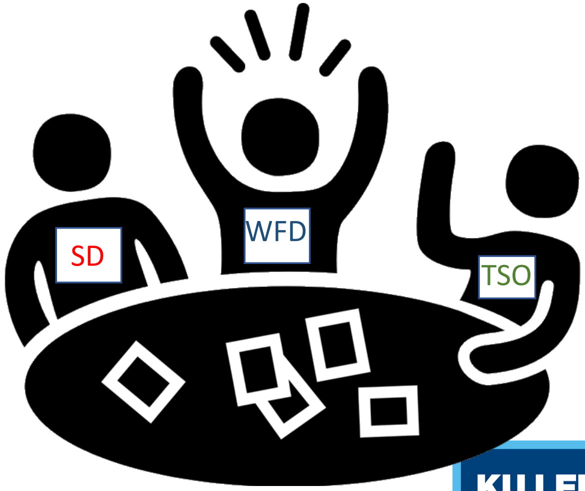
CORDOBA - Coordinated planning of hybrid offshore assets

- Different stakeholders with different objectives
  - Wind Farm Developer (WFD)
  - Storage Developer (SD)
  - Transmission Service Operator (TSO)
  - Consumers/Conventional generators

- All stakeholders maximize their utility for their objective
  - WFD: When, where and how big should the wind farm be, considering possible future earnings?
  - SD: When, where and how big should the storage system be, considering possible future earnings?
  - TSO: When, where and what capacity of interconnectors be constructed, considering the system needs and potential revenues?

- **Challenges: Modelling of all stakeholder interactions, market rules and uncertainties.**





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Optimisation of the grid layout under different market designs

- Expansion planning is analyzed for three market designs:
  - The nodal OBZ (nOBZ): Each node is its own market zone (local marginal pricing)
  - The zonal OBZ (zOBZ): All OWPPs form a common offshore market zone
  - The home market design (HMD): Each OWPP is part of its home market zone
- A multi-step model to analyze the market designs in a common framework

Optimize interzonal grid layout
- Stochastic, multi-period MILP problem maximizing social welfare
- Determines optimal size of wind farms, storage assets and interconnection need and between different market zones

Optimize intrazonal grid layout
- Apply same optimisation model as in step 1 to optimize layout of intrazonal grid
- The interzonal flows are considered as fixed

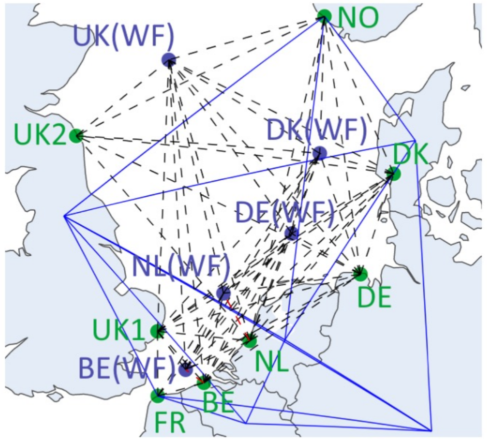
Solve operational problem
- Determine market prices of the grid design considering the investments to be fixed

Correct nodal imbalance
- Determine possible imbalances in zonal models and perform redispatch optimisation

Hardy, Stephen, Andreas Themelis, Kaoru Yamamoto, Hakan Ergun, and Dirk Van Hertem. "Optimal Grid Layouts for Hybrid Offshore Assets in the North Sea under Different Market Designs." ***arXiv preprint arXiv:2301.00931*** **(2023).**

Case study – North Sea offshore grid

Existing and cadidate grid and offshore wind hubs



Optimal grid layouts under different market designs

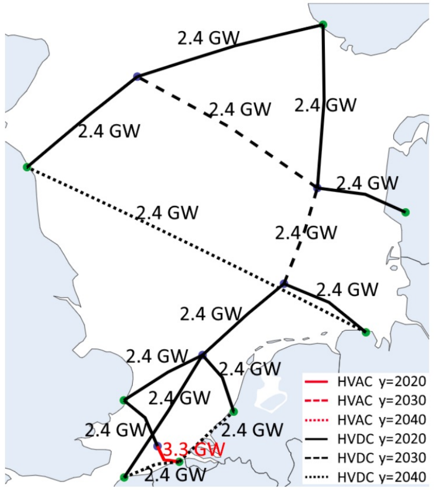


Figure 4: nOBZ $\mathcal{G}$ topology.

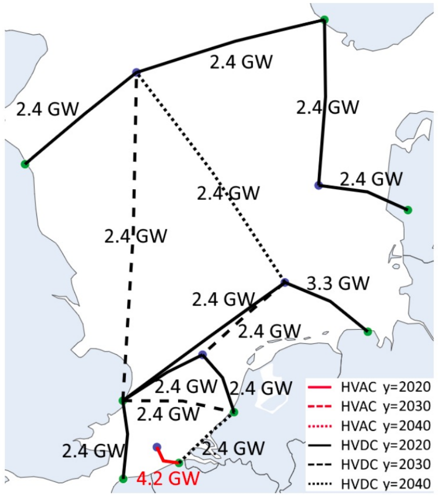


Figure 5: HMD $\mathcal{G}$ topology.

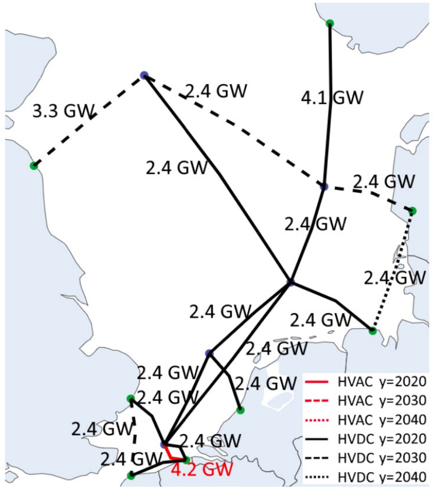


Figure 6: zOBZ $\mathcal{G}$ topology.

Cost and benefit distribution

	Transmission		OWPP		Storage	
	Cost	Benefits	Cost	Benefits	Cost	Benefits
nOBZ	21.754	64.147	42.000	134.135	0.059	0.058
HMD*	22.380	64.722	42.000	133.700	0.059	0.058
zOBZ*	22.984	70.453	41.885	125.568	0.059	0.057
zOBZ	22.984	57.703	41.885	135.241	0.059	0.056
nOBZ**	21.754	53.452	42.000	139.866	0.059	0.057
nOBZ*	21.754	49.015	42.000	143.459	0.059	0.047
HMD	22.380	48.526	42.000	144.152	0.059	0.046

HMD*: The HMD topology operating in an nOBZ market.
zOBZ*: The zOBZ topology operating in an nOBZ market.
nOBZ*: The nOBZ topology operating in an HMD market.
nOBZ**: The nOBZ topology operating in a zOBZ market.

- Nodal market structure results in highest social welfare
- Market structure has a higher impact on the welfare than grid topology

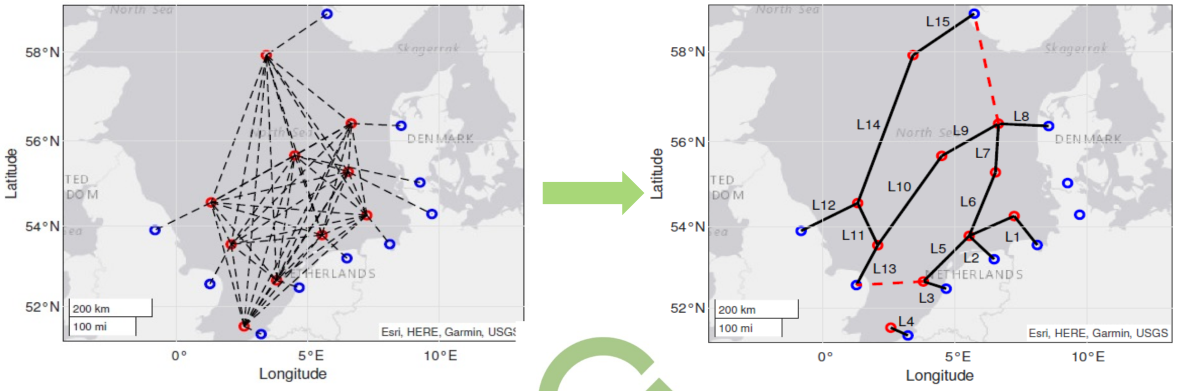
Hardy, Stephen, Andreas Themelis, Kaoru Yamamoto, Hakan Ergun, and Dirk Van Hertem. "Optimal Grid Layouts for Hybrid Offshore Assets in the North Sea under Different Market Designs." ***arXiv preprint arXiv:2301.00931*** **(2023).**

Planning of offshore HVDC grids considering protection strategies and stability

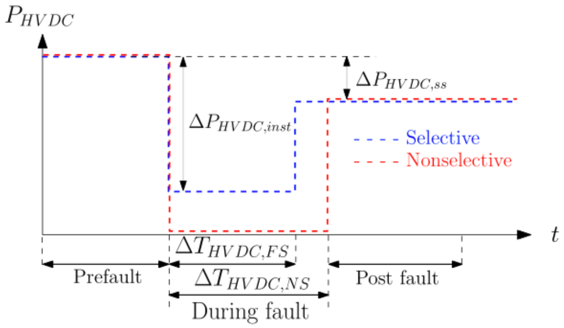
- What are the effects of the DC grid topology and the protection system design on the necessary reserves?
  - With faster DC protection, we can obtain higher reliability, and lower reserve requirements
- How can we find the optimal system design including protection, reserves and loss of load expectation?
  - Incorporating frequency deviation constraints and reserve response in the planning process
- What is our dimensioning incident?
  - DC grid failure vs pole failure
  - 5 GW DC grid: where to connect?
  - For DC grids with fast protection, a permanent loss based dimensioning incident is too conservative!

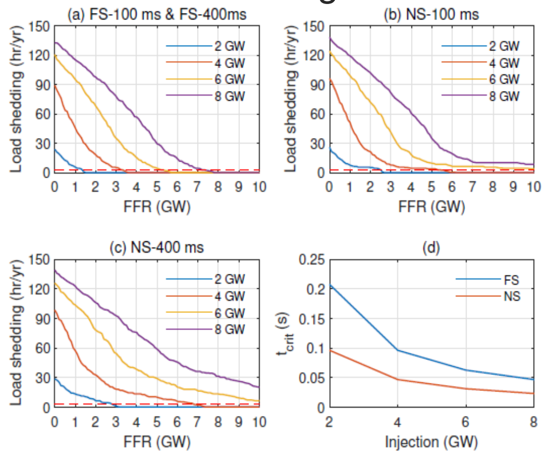
Input candidates

Expansion plan



Stability assessment and reserve dimensioning





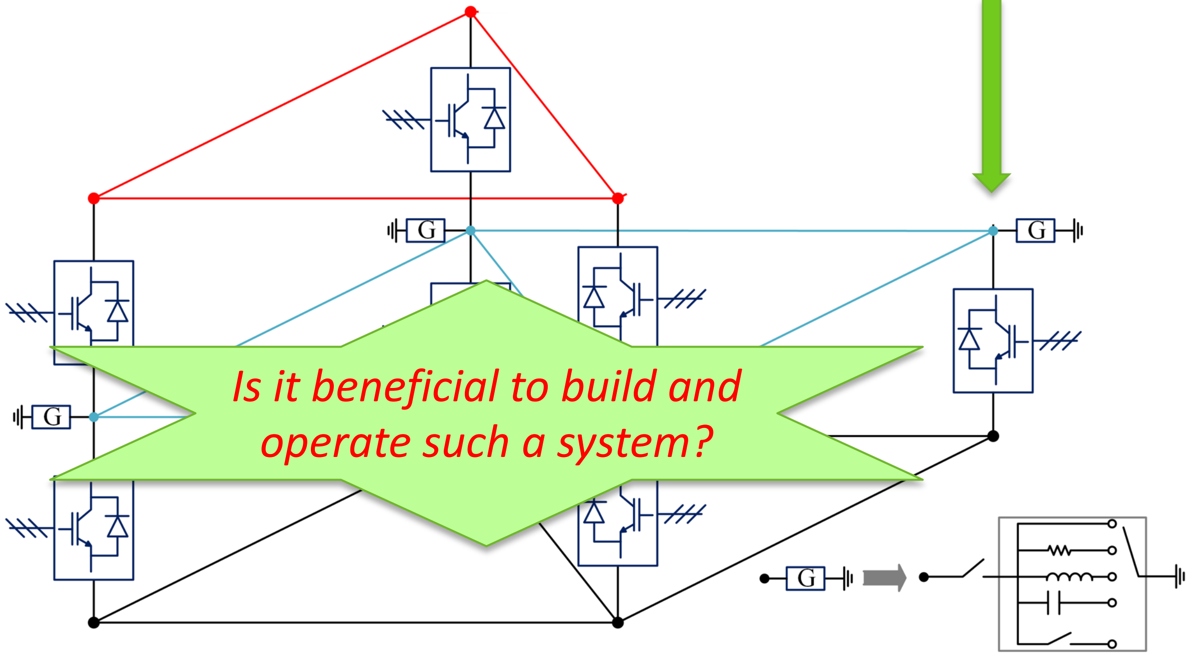
[1] Dave, J., Van Hertem, D. (sup.), Ergun, H. (cosup.) (2022). *DC Grid Protection Aware Planning of Offshore HVDC Grids*.

[2] Dave, J., Ergun, H., Van Hertem, D. (2020). Incorporating dc grid protection, frequency stability and reliability into offshore dc grid planning. *IEEE Transactions On Power Delivery*, *35* (6), 2772-2781. doi: 10.1109/TPWRD.2020.3011897 Open Access

[3] Dave, J., Ergun, H., Van Hertem, D. (2021). Relaxations and approximations of HVdc grid TNEP problem. *Electric Power Systems Research*, *192*, Art.No. 106683. doi: 10.1016/j.epsr.2020.106683 Open Access

Unbalanced operation of HVDC grids

- As of now DC side is always considered to be balanced (symmetric) ➔ *same in future?*
- Single pole outage?
- Monopolar tapping on a bipolar backbone: Offshore wind
- Operating mixed configurations causes unbalances in the DC grid



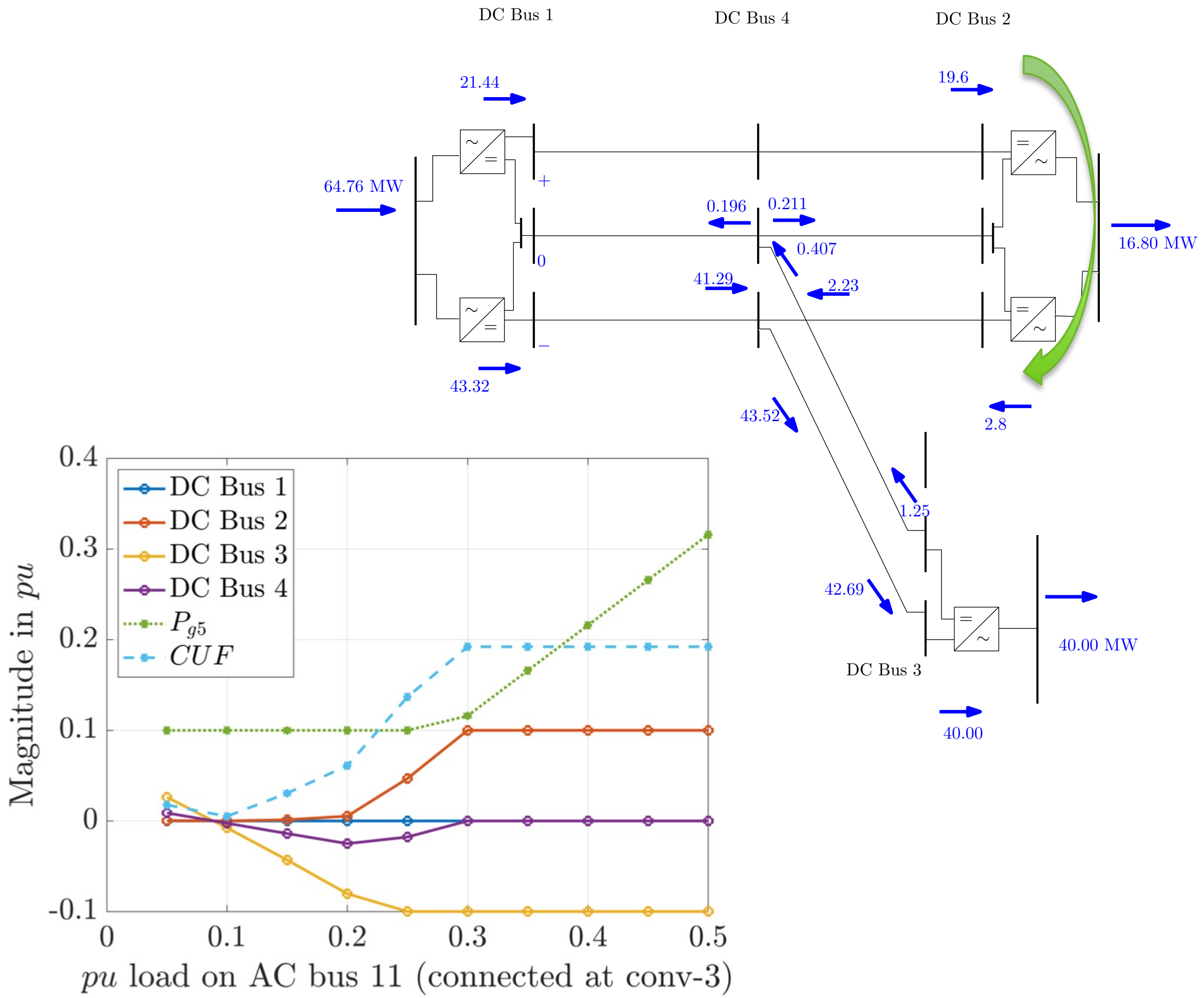
Takeaways from the unbalanced DC grid model

Key features of the model:

- Explicit modelling of metallic return conductor
- Current-Voltage (I-V) model is implemented for HVDC side: because the common Power-Voltage (P-V) models suffers from numerical instability.

Key observations:

- Power flow through the two poles of a bipolar converter can differ not only in magnitude but also in sign (direction) i.e. “converter loop flows” in extreme cases
- Grounding and metallic return resistance have significant effect on the power flow due to voltage increase in single poles with high unbalance

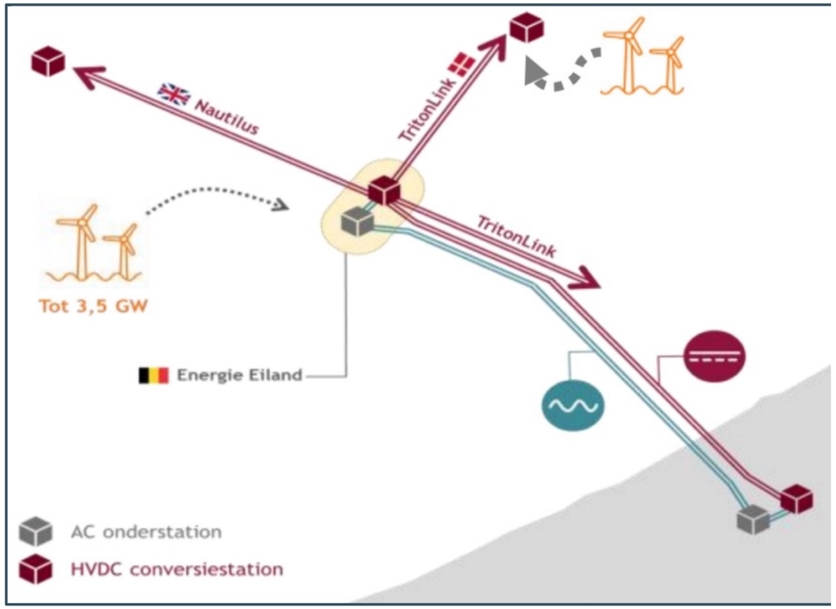


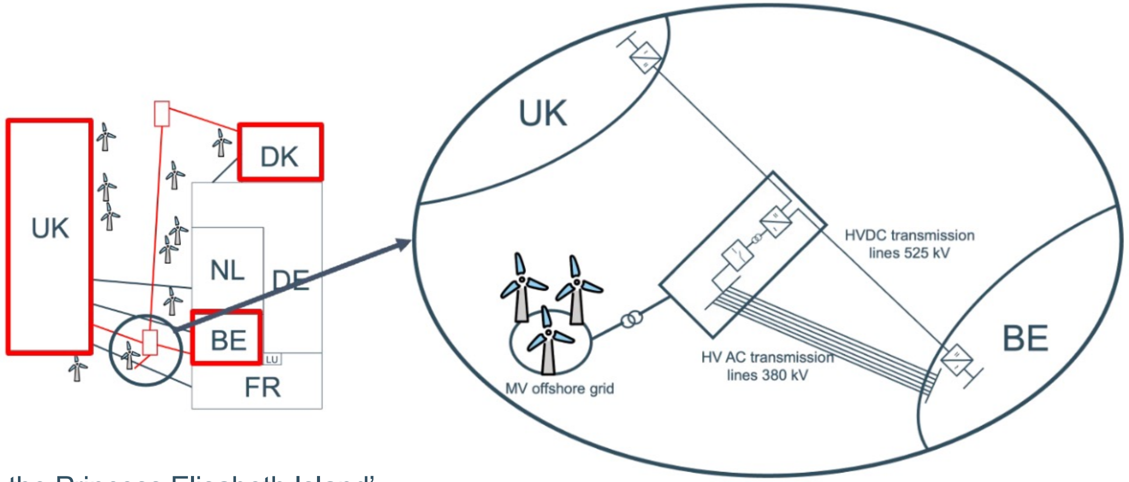
Chandra Kant Jat, Jay Dave, Dirk Van Hertem, Hakan Ergun, Unbalanced OPF Modelling for Mixed Monopolar and Bipolar HVDC Grid Configurations, arXiv preprint arXiv:2211.06283

Operational concepts for enegy islands

- How to operate AC/DC energy islands with meshed offshore HVDC grids, considering topological actions, operational uncertainty and (unbalanced) contingencies?

- How does a TSO select the optimal substation topology of an energy island (in both its AC and DC part)?





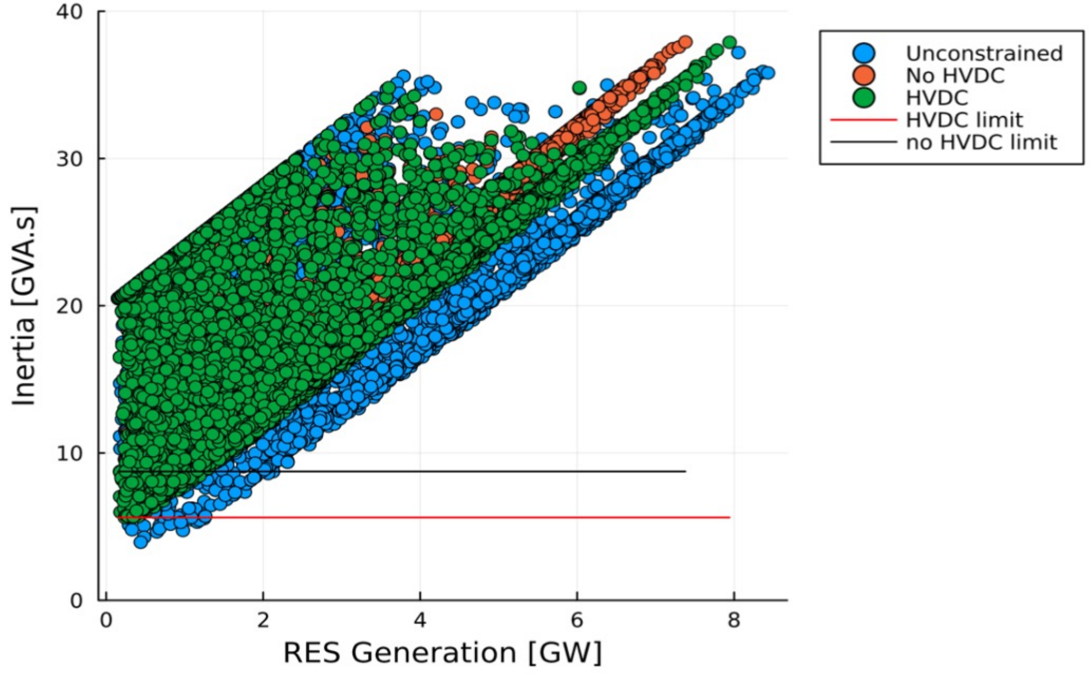
Elia group, 'Elia presents its plans for an energy island, which will be called the Princess Elisabeth Island', https://www.elia.be/en/news/press-releases/2022/10/20221003_offshore-energy- island. (accessed 25th Febuary, 2023).

Value of inertia provision through HVDC

Example of Celtic Interconnector

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

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

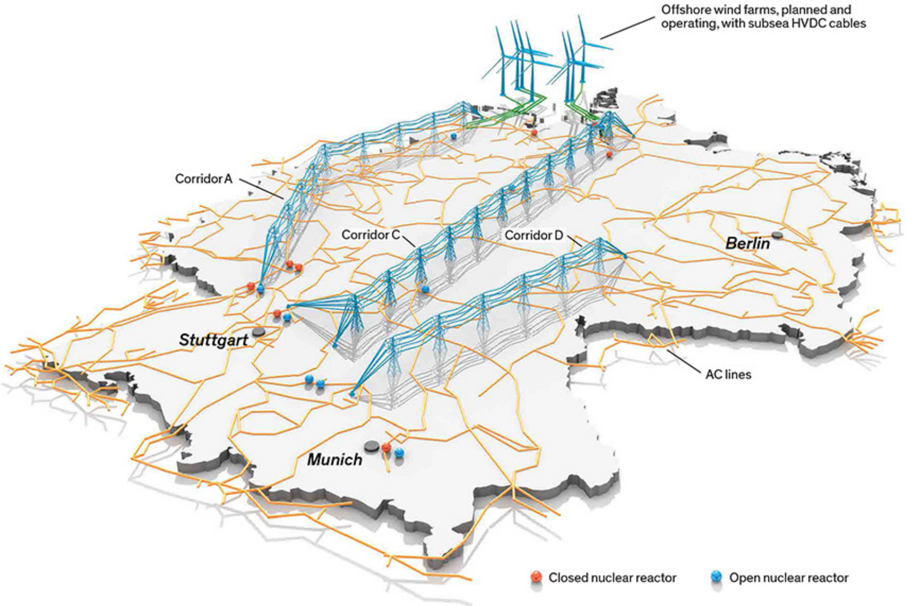


The same concept can also be applied to other options for inertia support, e.g. synchronous condensers, BESS, ….

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

Benefits of power flow control through HVDC

- Using a redispatch optimal power flow model
- Objective is to minimize the up- and downwards redispatch needed, and potential load sheeding during contingencies
- Nodal redispatch optimisation for a selected number of hours and critical contingencies
  - Case 1: Fixed HVDC converter set points w.r.t. “market outcome”
  - Case 2: Optimized HVDC converter set points w.r.t. “market outcome”
  - The difference provides the benefits of power flow control
- Same concept can be applied to different means of power flow control e.g., PSTs….



	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

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Open source toolboxes

PowerModelsACDC.jl

- Optimal power flow model for AC/DC grids
- A number of different formulations (linear, second-order cone, nonlinear, …)
- Different problem types (OPF, TNEP, multi-period OPF, ….)

PowerModelsMCDC.jl

- Optimal power flow model for unbalanced operation of monopolar, bipolar HVDC grids

OptimalTransmissionRouting.jl

- Determining optimal transmission routes using shortest path algorithm
- Allows to assess landscape impact of transmission assets

FlexPlan.jl

- An open-source Julia tool for transmission and distribution expansion planning considering storage and demand flexibility

CBAOPF.jl

- An open-source model for conducting cost-benefit analysis for HVDC interconnectors, considering inertia constraints

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The future of HVDC grids

Towards a more resilient system

- More renewables
  - Longer distance transmission
  - Higher variability in flows
- Vulnerability increases
  - Climate change (floods, fires,…)
  - HVDC system unavailability
  - Large incidents (including storm)
- Reliability management will be risk based
- Fully controllable injections in the system
- ➔ The system will become more interconnected and cross border operation is key

BAU

High security margins
HVDC grid as a constraint

One TSO/ISO

(to rule them all)

Grid-of-Grids

Depending on the state of the system, the coupling between systems can **change** to make **more efficient** use of the system, or **for reliability purposes**

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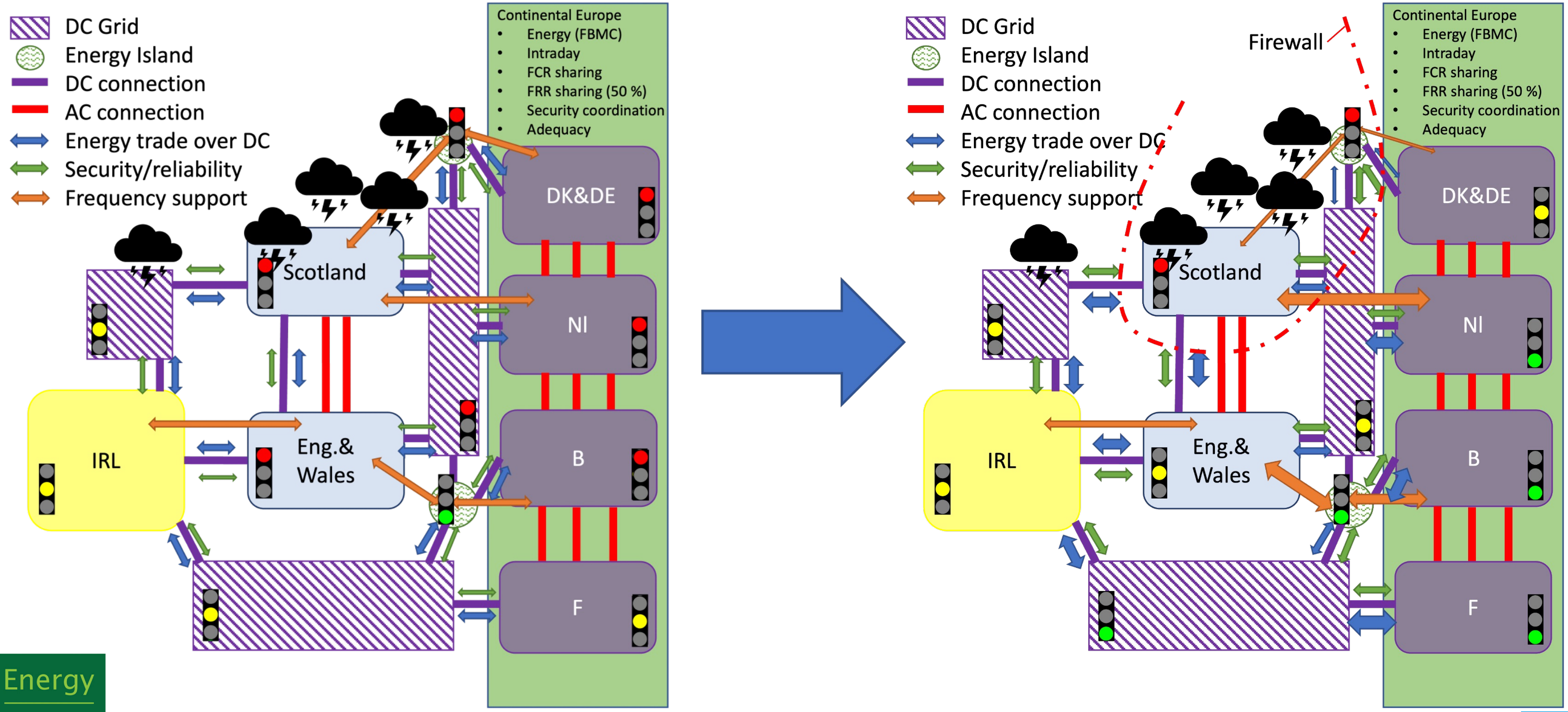
Rearranging system to cope with adverse weather

→ new paradigm, grid-of-grids



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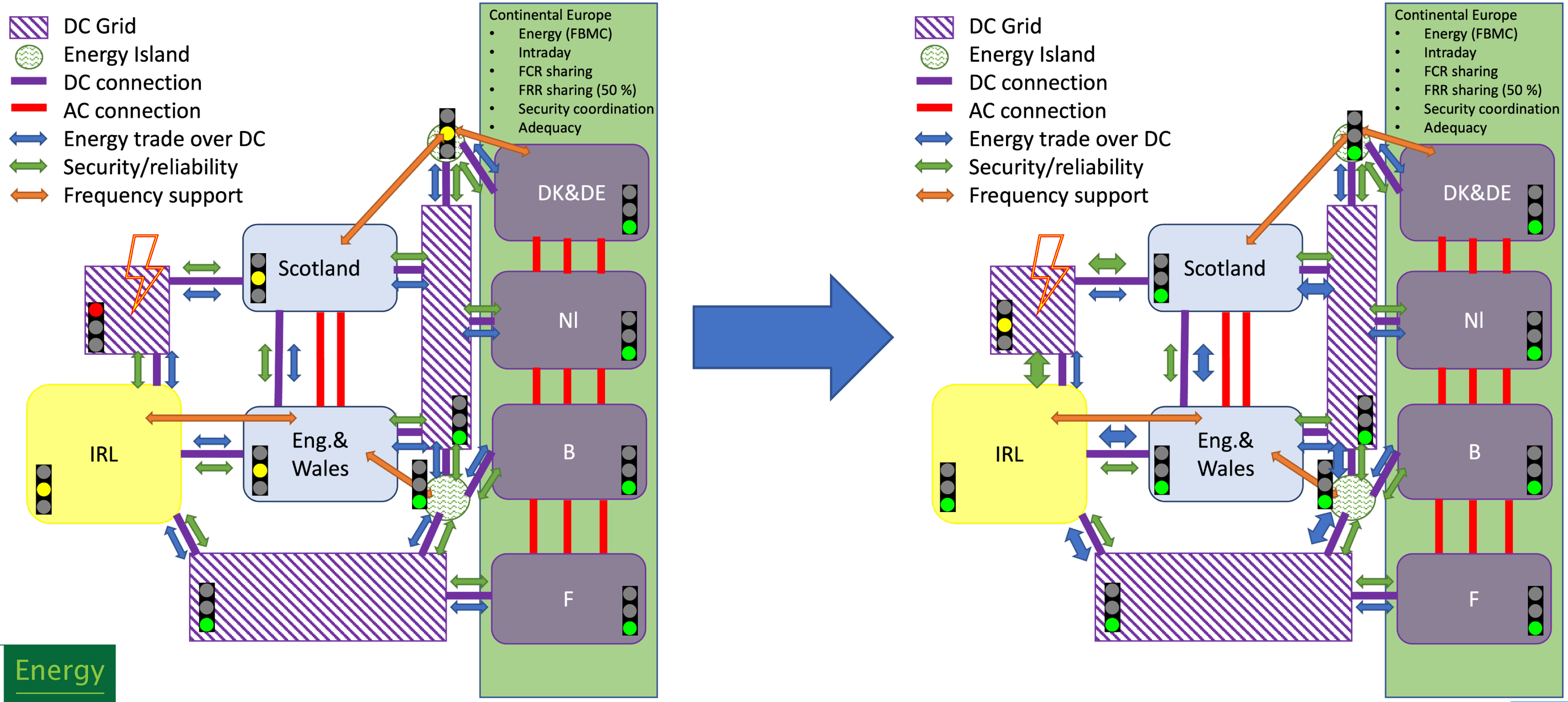
Agile system management to cope with failures

➔ new paradigm, grid-of-grids



Take - aways

- Multi-national HVDC grids will become the reality in Europe in the coming years, driven by the offshore wind developments
- Especailly for multi-national offshore grids there are uncertainties around the optimal market and grid design
- For achieving a least regret design, uncertainties from different sources need to be taken into account, e.g., RES, contingencies, market design, price evaluations, policy interventions, …
- For efficient system planning, coordination is key and aspects of stability and protection should be considered in the early planning stages
- New types of simulation models are needed to capture the high frequecy dynamics in power electronics dominated systems
- For effcient system operation, operational optimsition models need to bridge the gap between steady state and dynamic behaviour
- With increasing power ratings and large-scale offshore wind integration, a resilient design and operation of the system will be the next challenge and new paradigms such as the grid-of-grid concept will be needed for coordinated operation

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Thank you for your attention!

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