



Integratie meshed grid HVDC uitdagingen offshore, globale kader

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KU Leuven and EnergyVille

Where do we need to go?

300-> 450 GW of offshore wind by 2050

- +/- 50 GW of wind offshore installed to date (1/2 in Europe)
- ±120 GW by 2030
- North Sea: 300 GW by 2050
- Solar will see similar developments

Offshore requires massive investments (EC: 2/3rd of 800 BEUR by 2050)

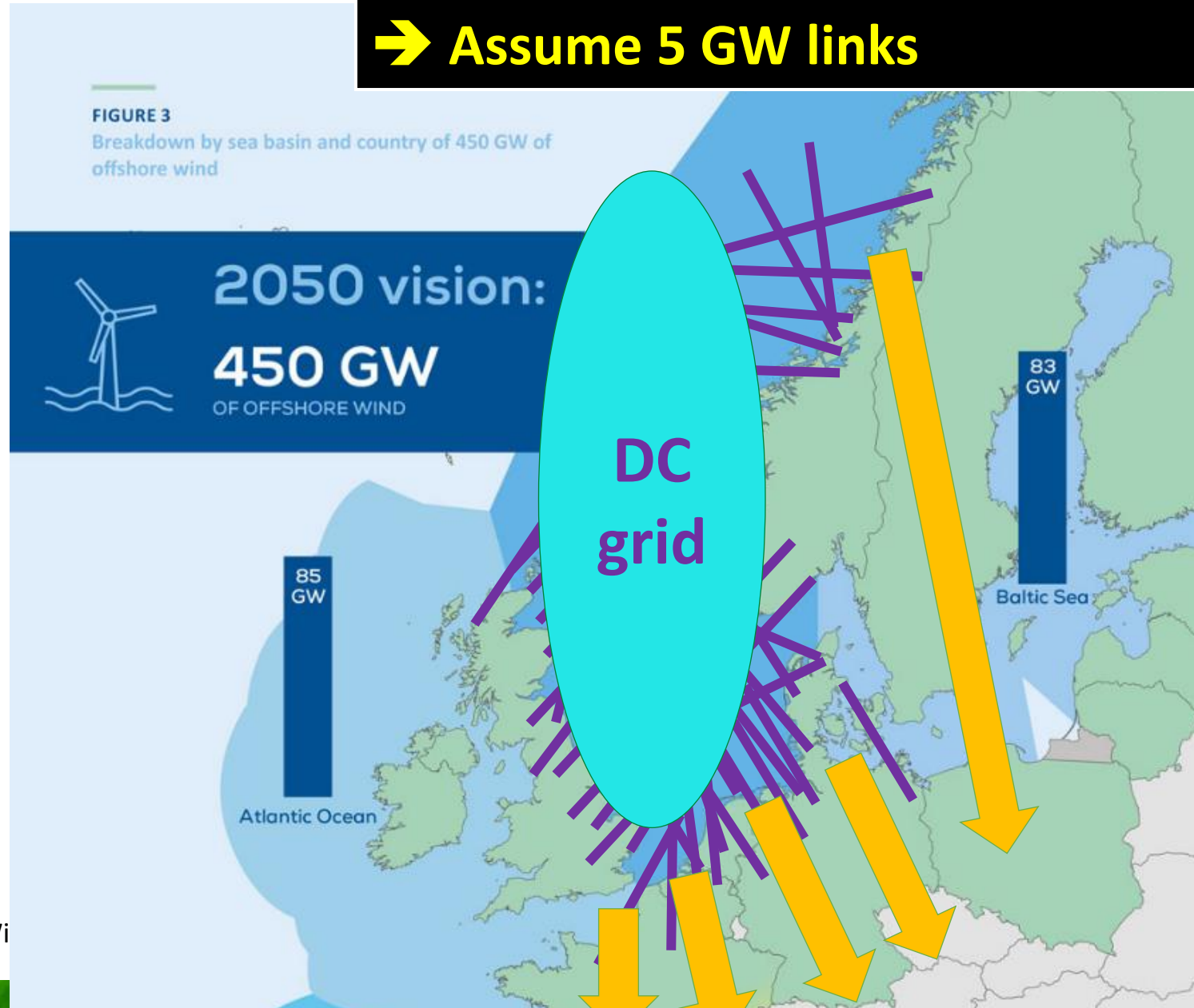
Meshed HVDC grids are the only realistic option:

- Connections are increasingly further from shore
- Needs to be integrated in the existing system (hybrid AC/DC)
- Towards new backbone grid



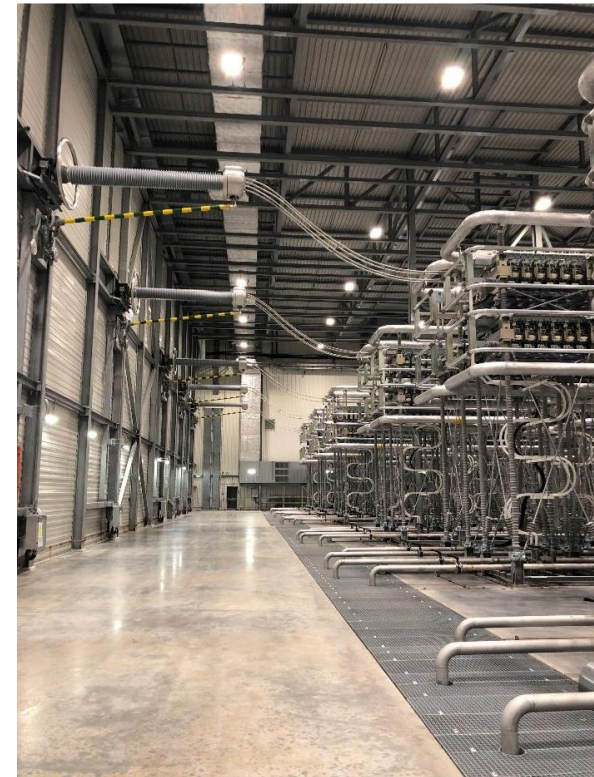
Figure: Wi

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



HVDC

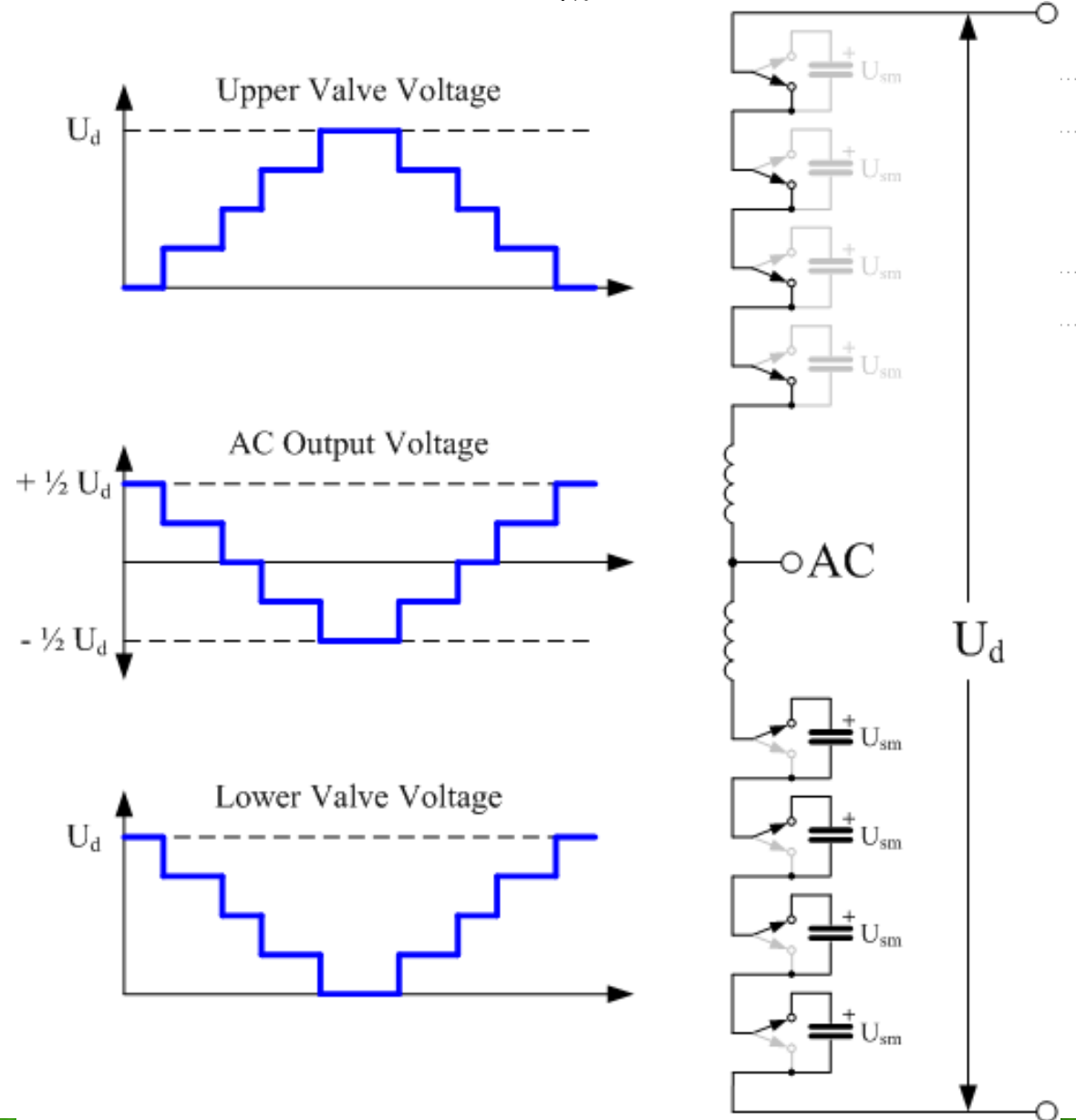
- 2 (3) cables in stead of 3 (4)
- No reactive losses
 - No stability distance limitation
 - No limit to cable length
- Lower electrical losses
- No need for maintaining synchronism
 - Connecting different frequencies and asynchronous grids
- Power flow (injection) can be fully controlled
- Main applications (traditional)
 - Long distance bulk power transmission
 - Connecting asynchronous systems
 - (Initially) Undersea (and now also) cable connections
- Extra transmission capacity through controllable power flows



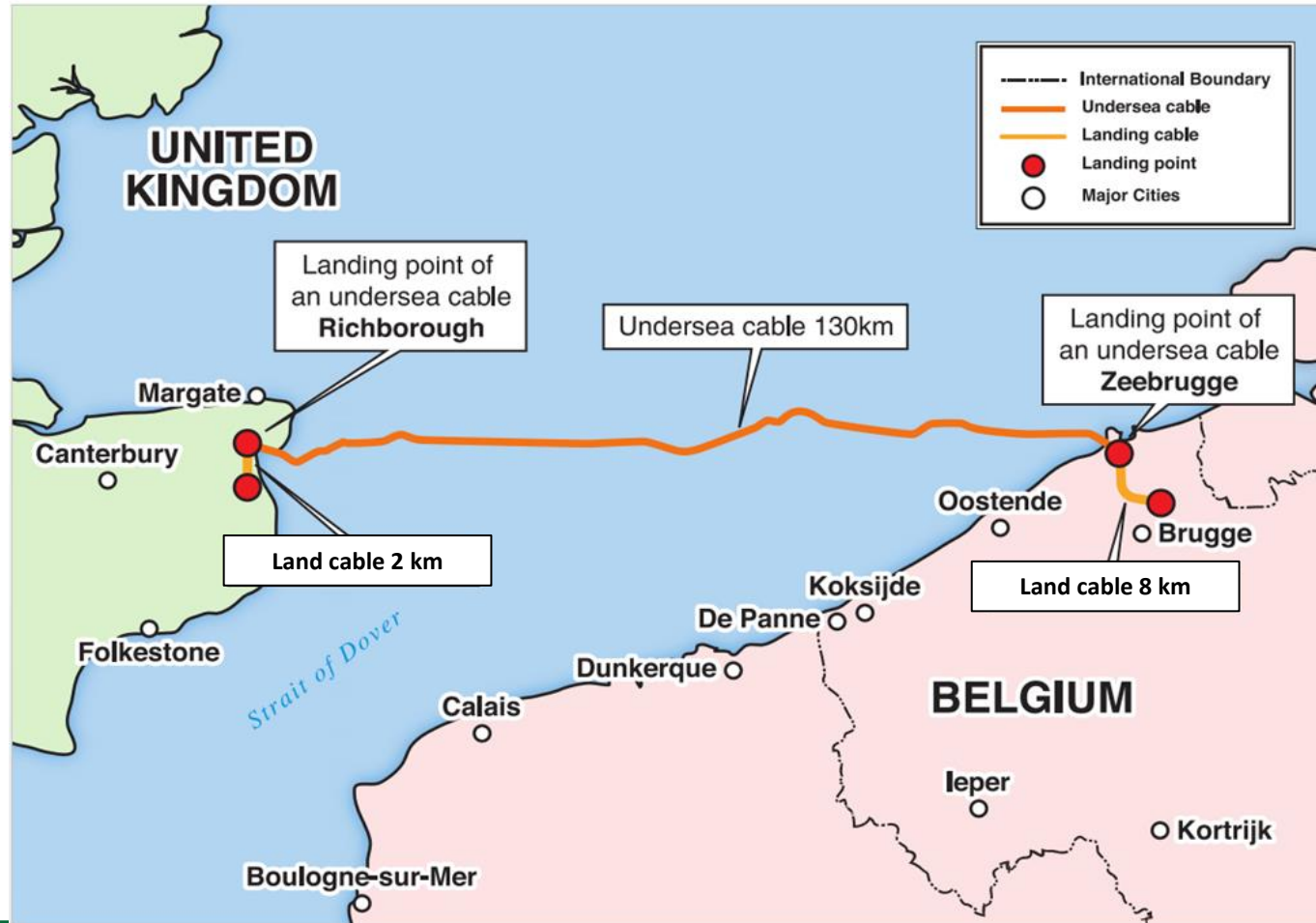
Alegro HVDC (source Elia)

Technology (focus voltage source converter)

- Power electronic converter transforms AC into DC and DC to AC
- First two-level (large frequency drive)
 - Series IGBT stack
 - Few kV per IGBT
 - PWM
- Now modular multi-level converter: MMC
 - Half-bridge or full bridge
 - Lower switching frequency
 - Higher efficiency
- Converter “draws” sinus

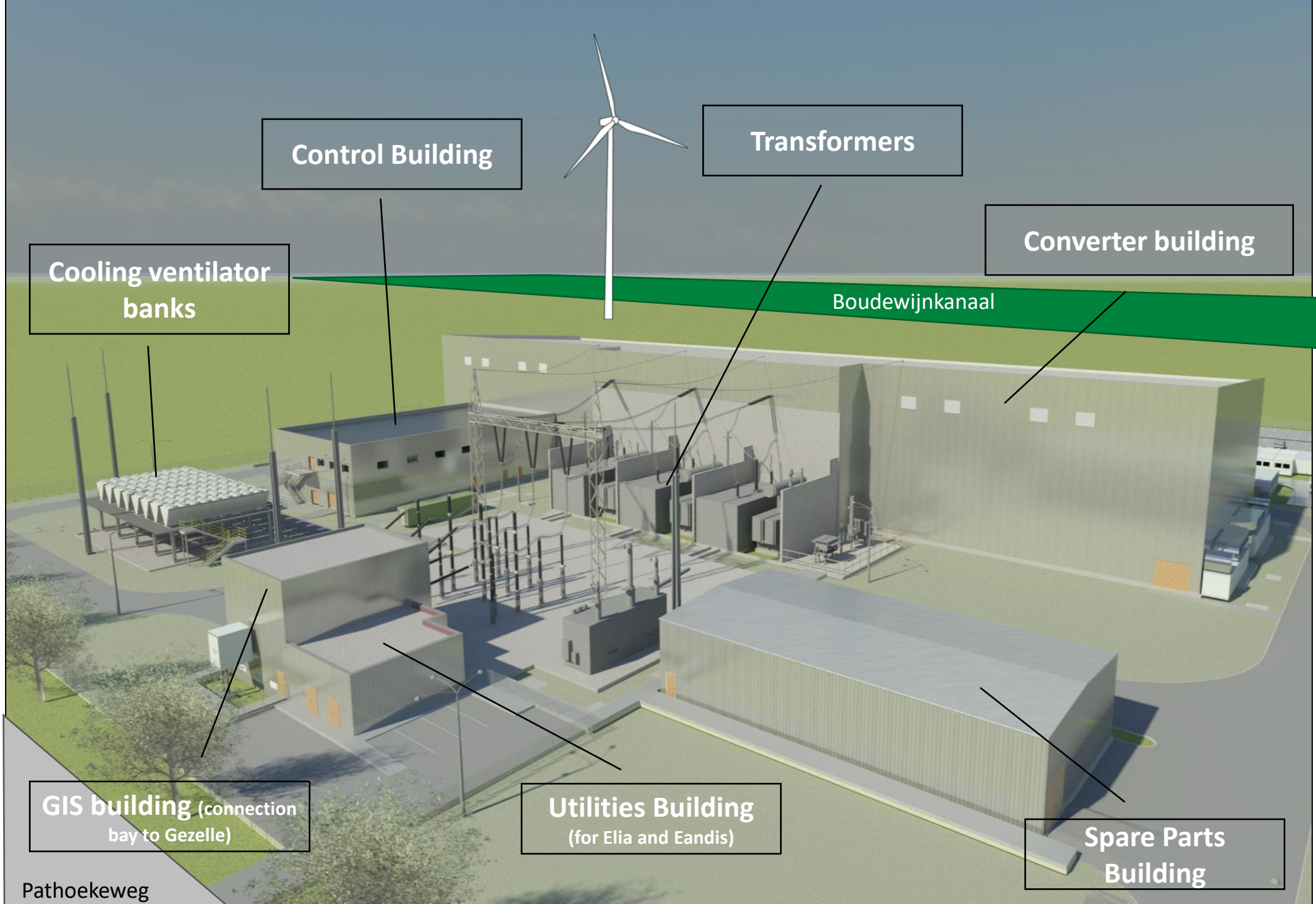


Example: Nemo



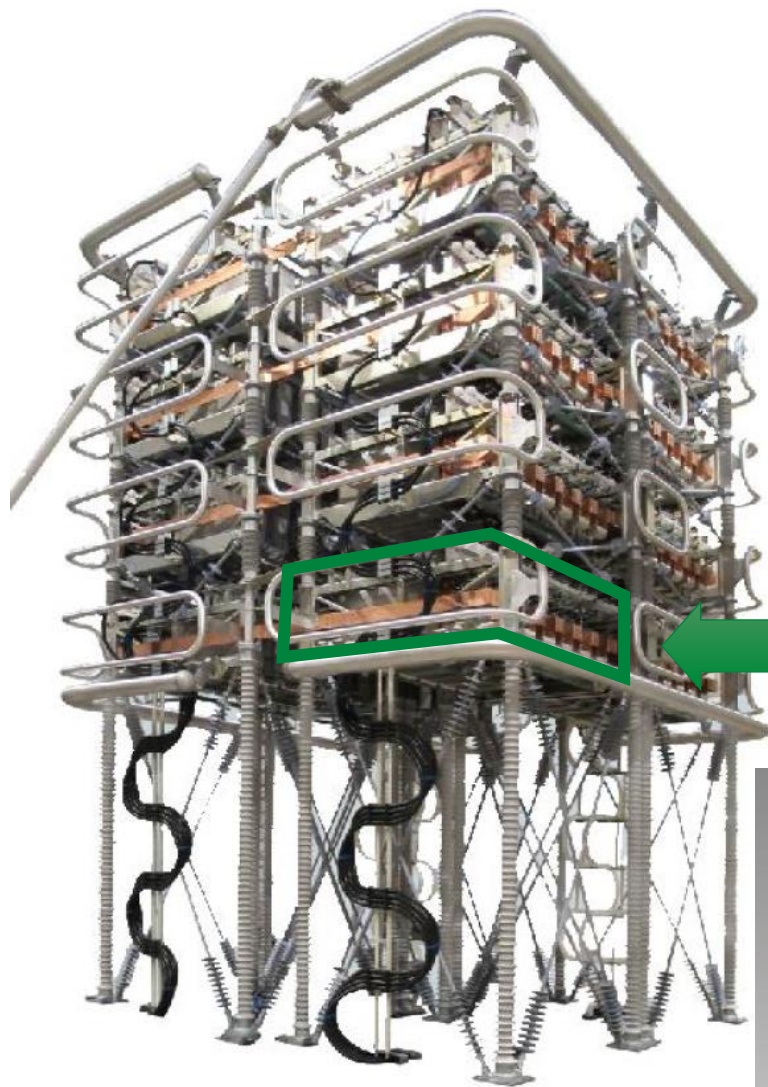
- First HVDC project for Elia
- 1000 MW – ± 400 kV HVDC
- €660m investment
- 130 km offshore cable
- 2 km onshore cable in UK
- 8 km onshore cable in BE
- Up to 60m water depth
- FID date: Feb 2015
- Start build: Sept 2016
- In service: Jan 2019



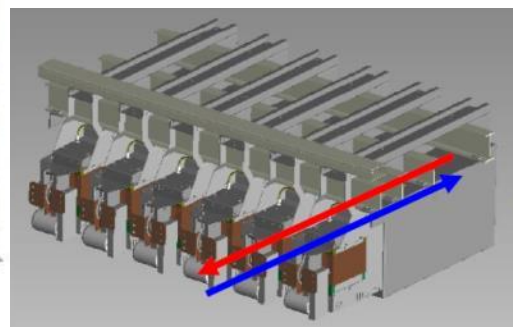
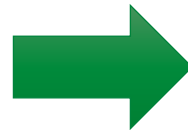




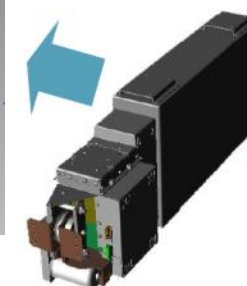
Source: Elia



Converter Tower
(24 per converter station)



"6-pack"
(16 per tower)



Sub-module
(6 per 6-pack)

Power module
(6 per 6-pack)

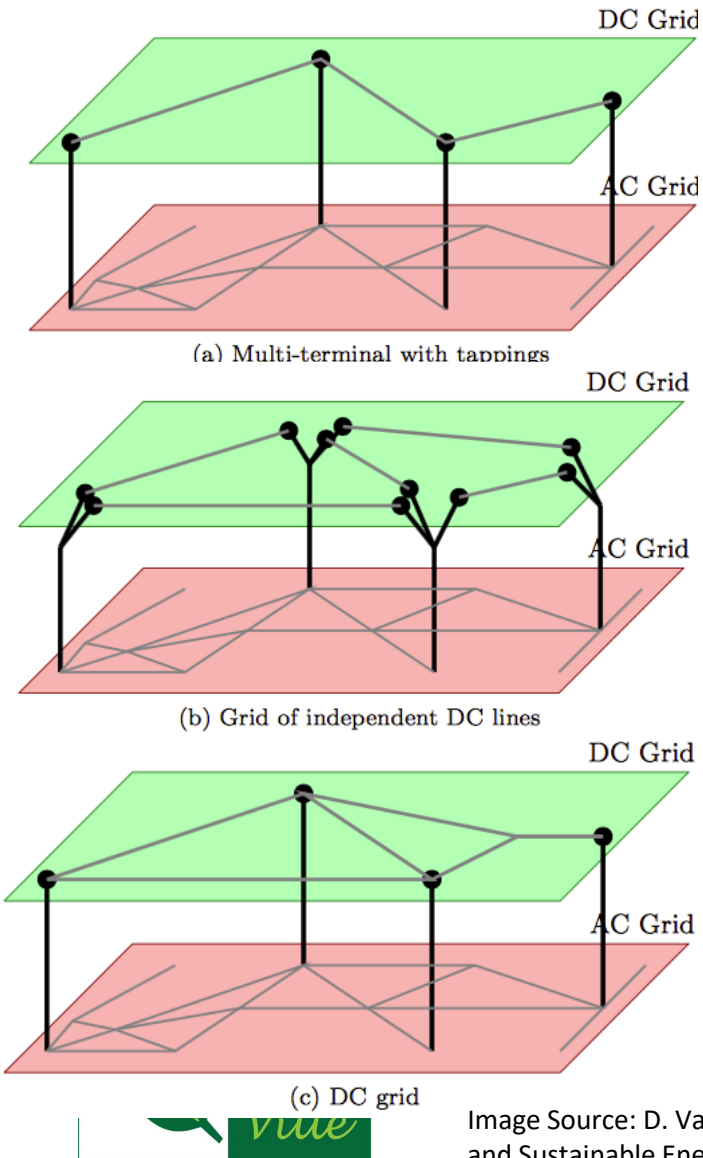


IGBT
(2 per power module)



$$\Sigma = 4608 \text{ IGBTs}$$

What is an HVDC grid, and why is it different?



- Connecting multiple HVDC lines
 - Multi-terminal (multipurpose interconnector)
- Redundant paths?
 - Meshes
 - N-1?
- Reduction of the number of converters needed
 - DC side nodes
 - Non-controlled DC flows
 - Reliable and cheap(er)
- Creating a hybrid AC/DC grid
 - Wheeling power over AC and DC systems

EnergyVille 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

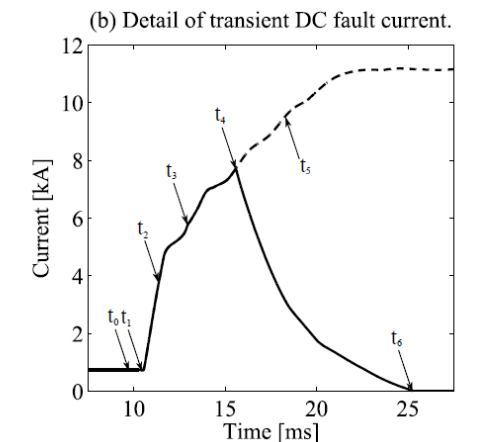
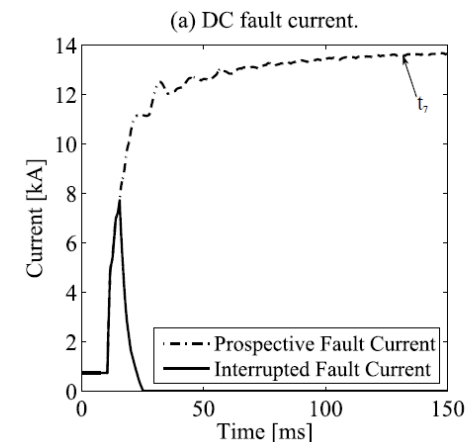
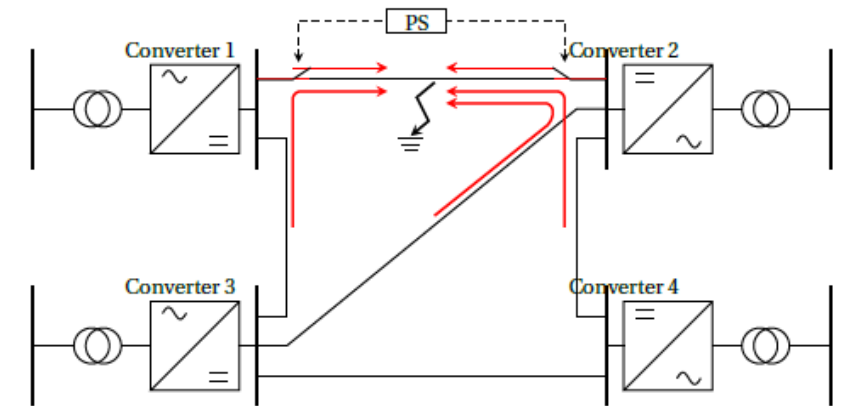
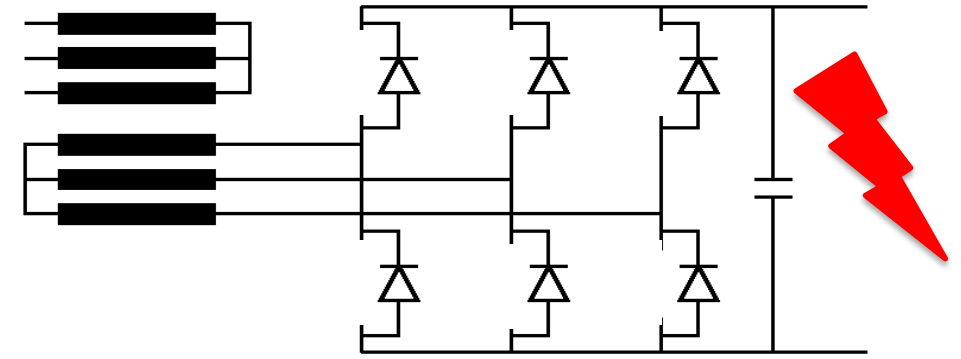




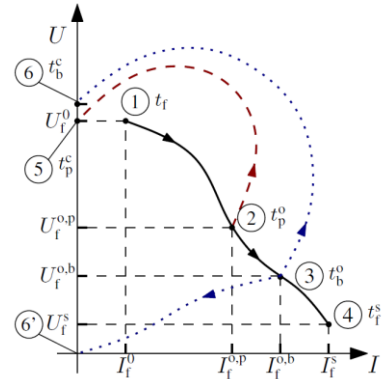
Some selected research outcomes

Protection of DC systems

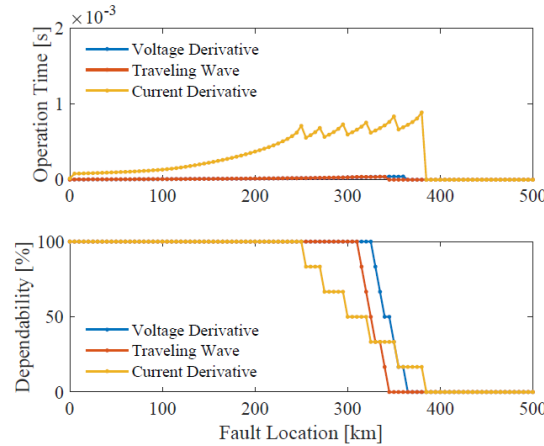
- Standard converters behave as diode rectifier when shorted and IGBTs are blocked
- High rate of rise
- Very high steady state short circuit current
- No zero crossings
- DC protection is a lot more difficult!



Effective protection algorithms for HVDC grid protection



Algorithm development +
Protection strategies
2012-2016



Algorithm evaluation

2016-2020



Academic testing



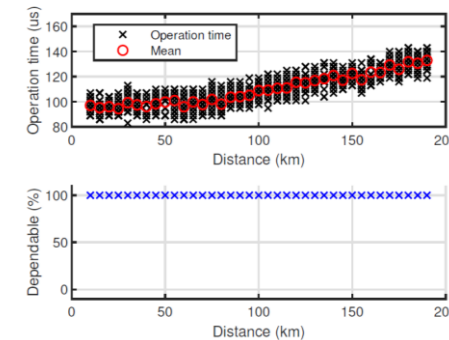
Industrial development



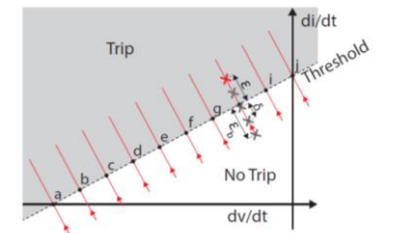
Standardisation
2022-2023



System level testing



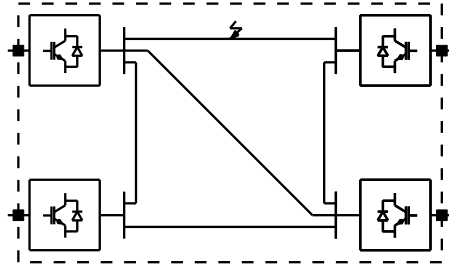
(b) Dependability for faults in protection zone (Cable L1)



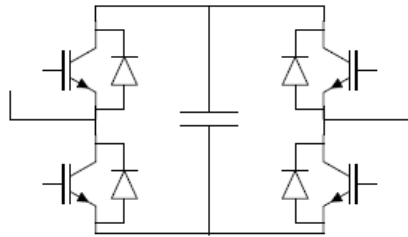
(a) Algorithm characteristic and perpendicular test ramps

Standalone functional testing

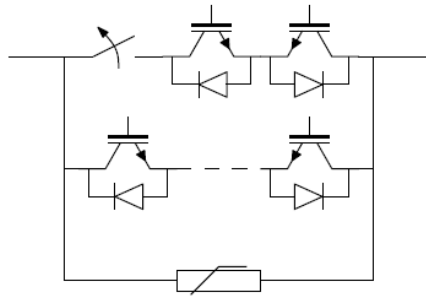
How to interrupt a DC fault current



- Converter ac breakers
 - As used in existing projects
 - Slow (40-60 ms opening time)
 - Not selective

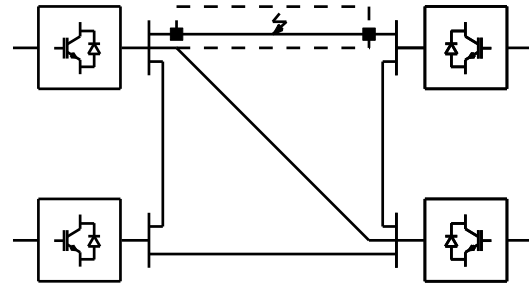


- Fault-current blocking converters
 - Higher losses compared with half-bridge
 - Fast (response within few ms)
 - Not selective

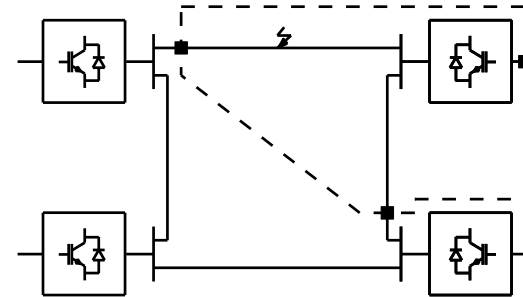


- DC Circuit Breakers
 - Operation times of 2-10 ms
 - Trade-off in losses vs. speed
 - Allows selective fault clearing
 - kA and KV

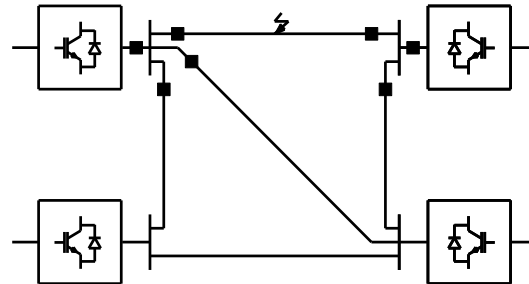
The use of different technologies leads to various fault clearing strategies



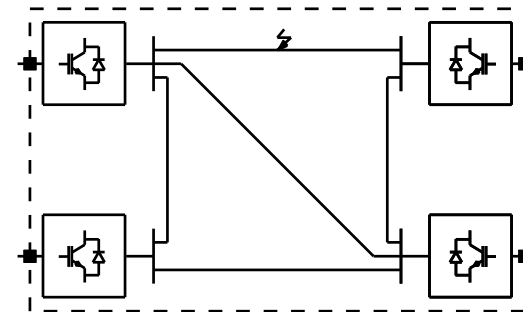
Selective (a,b): using
DC breakers in every line



Partially selective (d): split
DC grid in sub-grids



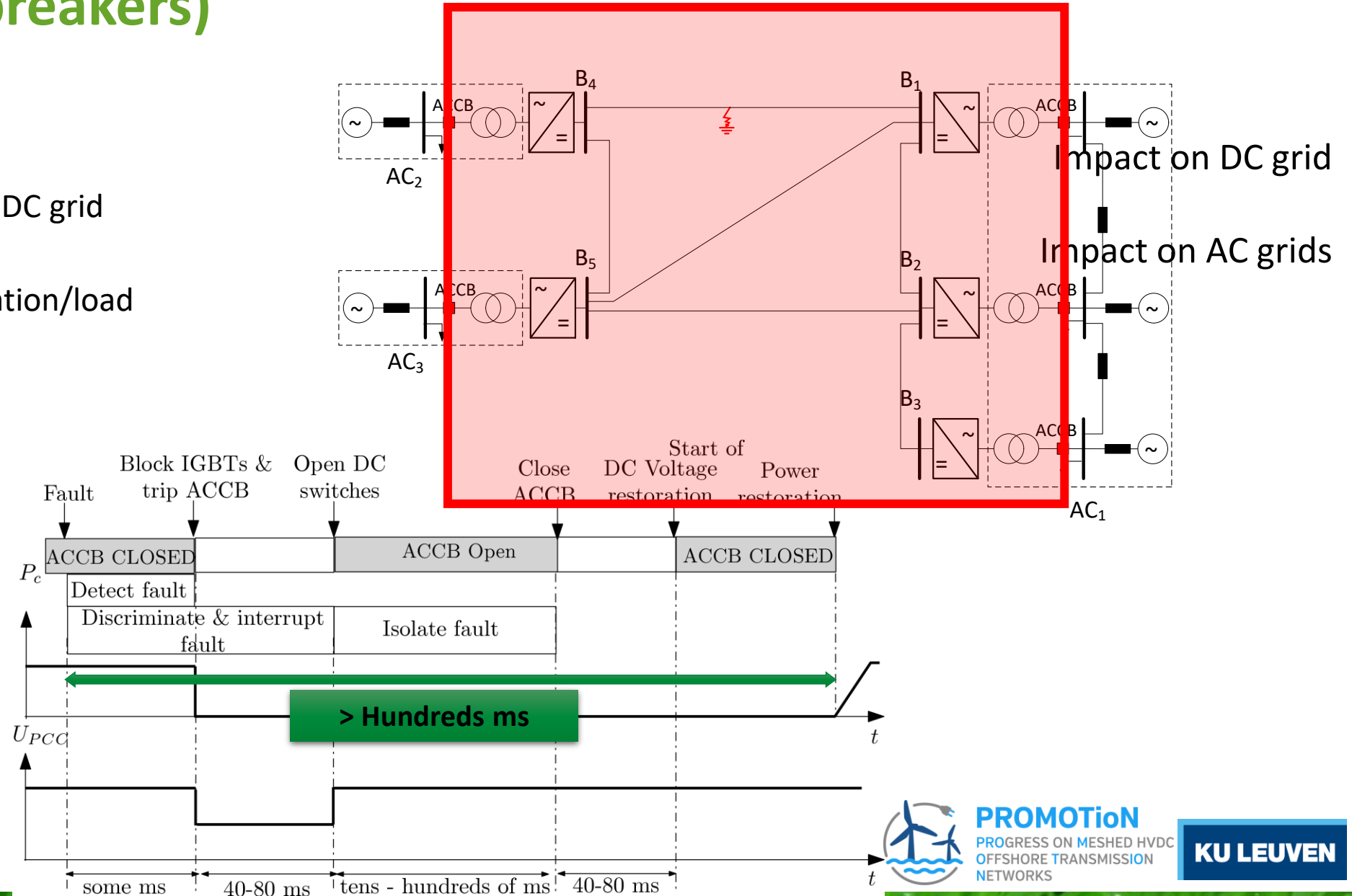
Open Grid (c):
alternative breaker sequence



Non-selective (e): shut
down the whole DC grid

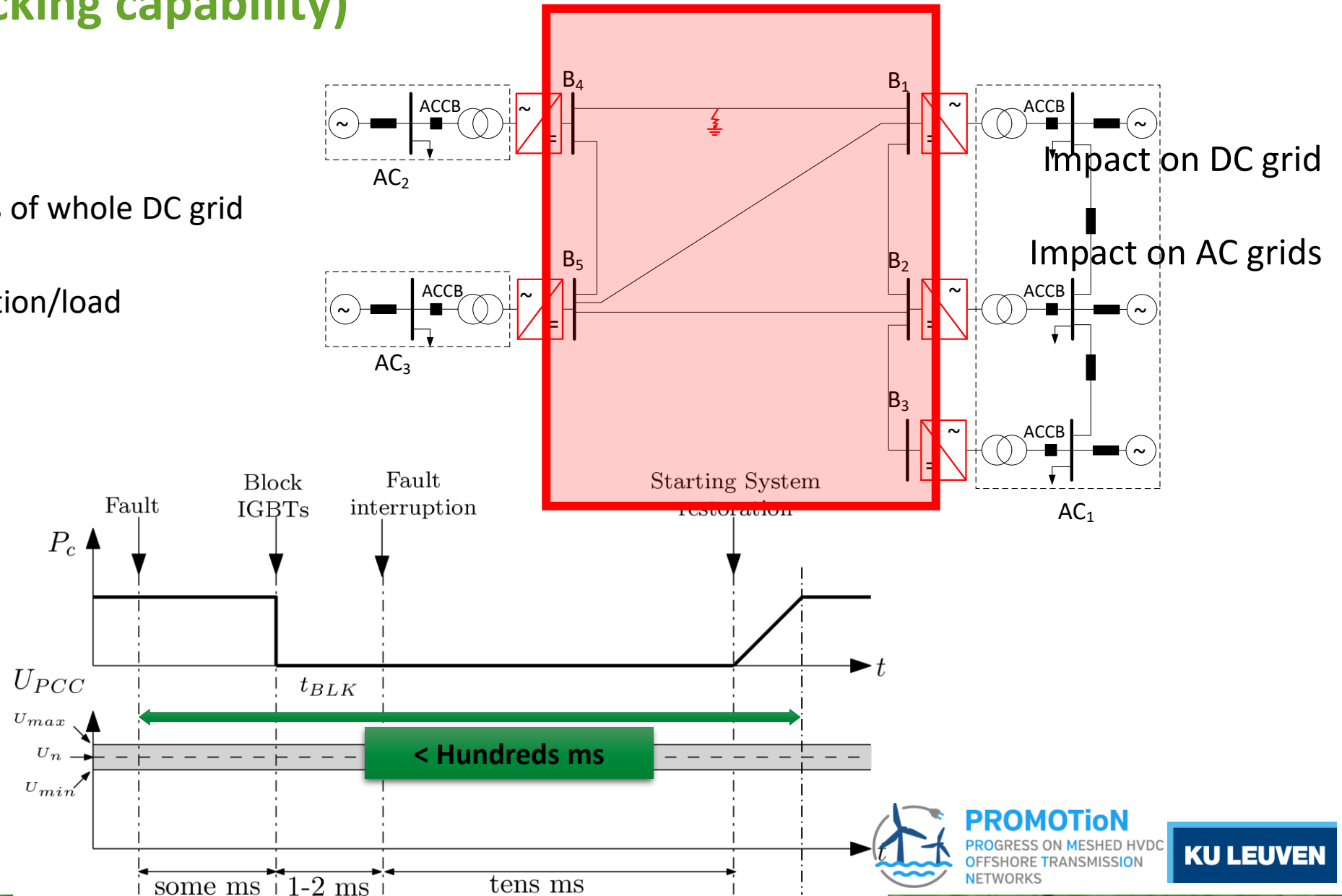
DC contingencies – DC fault using non-selective fault clearing (AC circuit breakers)

- Loss of whole DC grid
- Loss of generation/load



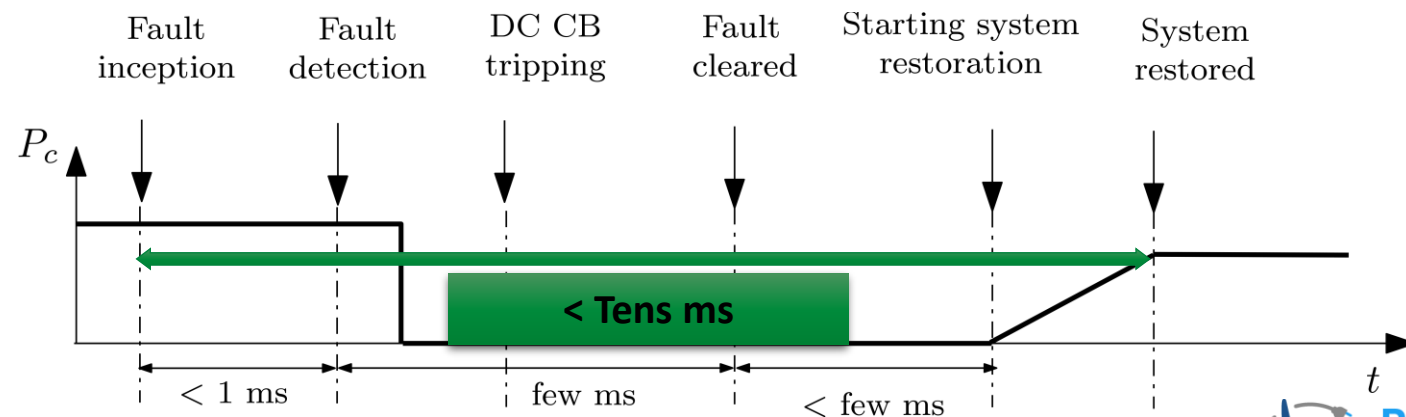
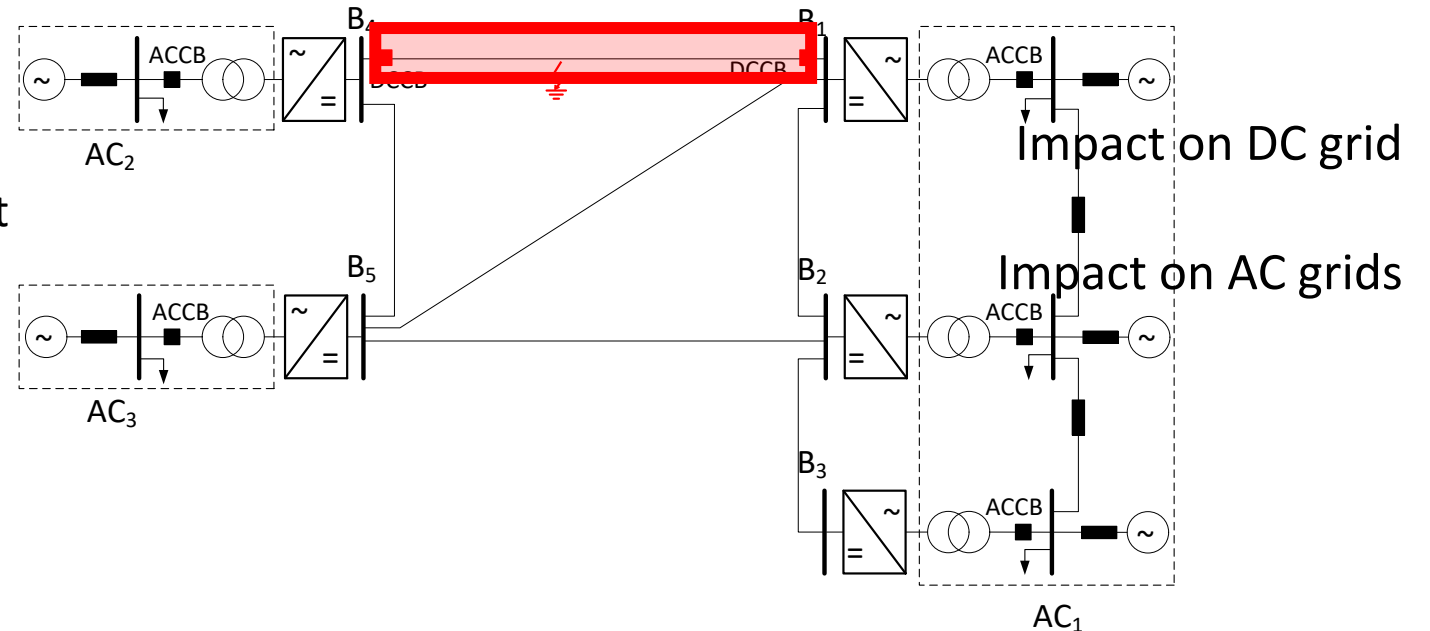
DC contingencies – DC fault using non-selective fault clearing (converter with fault blocking capability)

- Temporary loss of whole DC grid
- Loss of generation/load



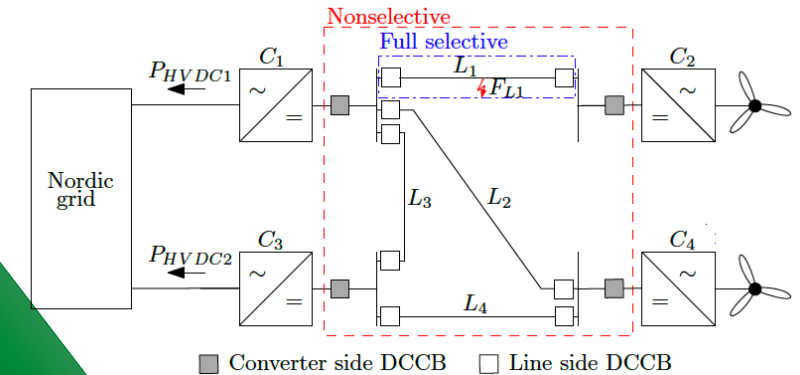
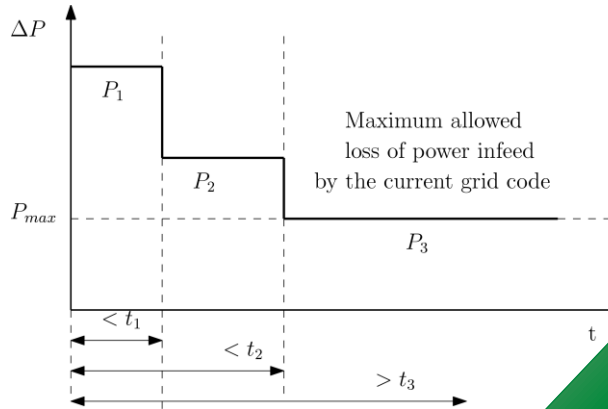
DC contingencies – DC fault using fully selective fault clearing

- Temporary power & voltage transient
- Very short transient
- Minimal loss of infeed

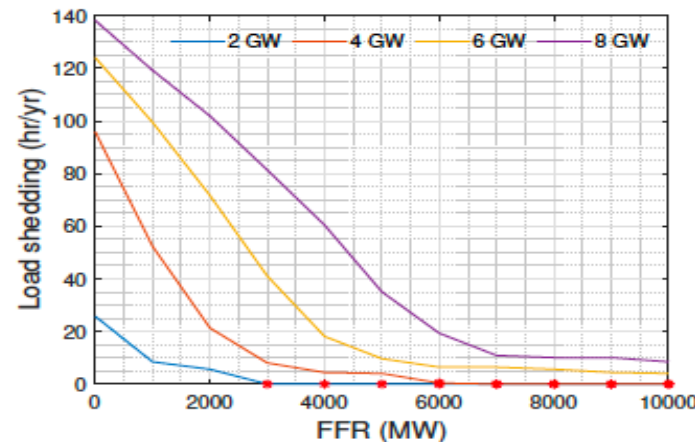


Design choices: New DC grid + different AC grid

DC grid protection requirements / DC grid protection costs



Reserve requirements / reliability costs



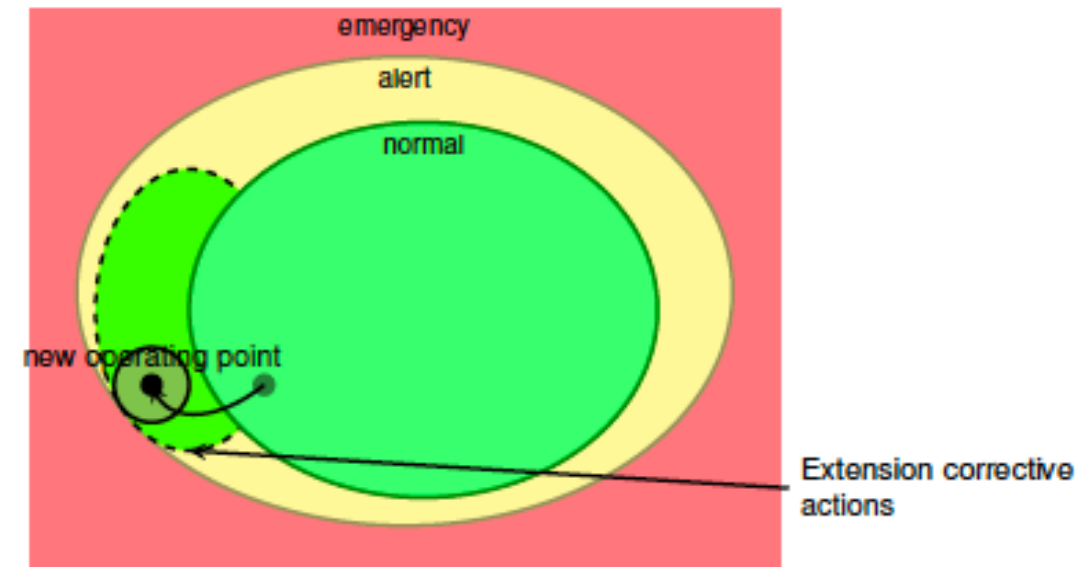
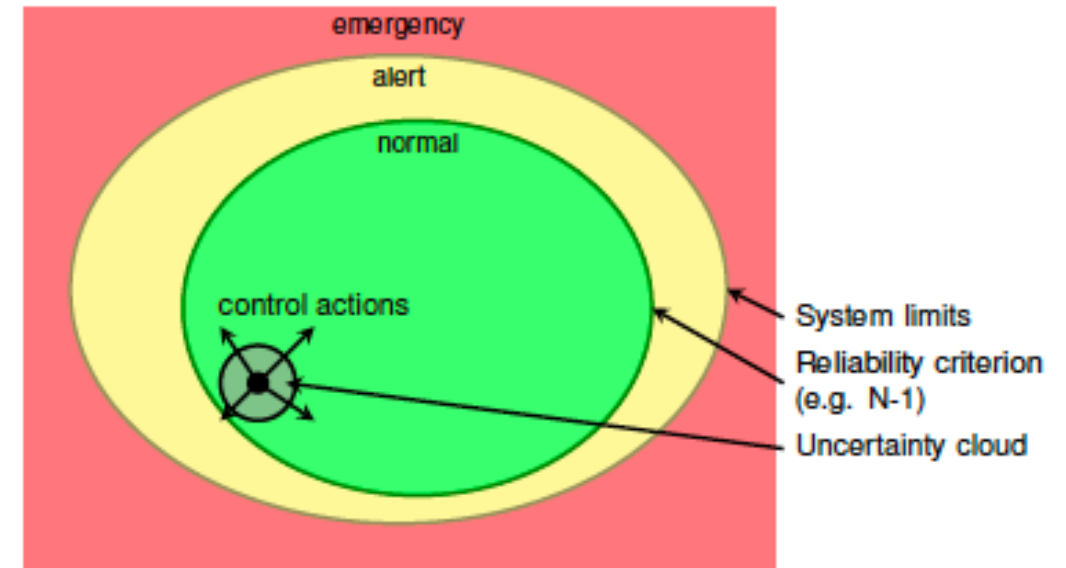
Grid Topology and technology



With the support of the Belgian energy transition funds

HVDC behaves differently from AC

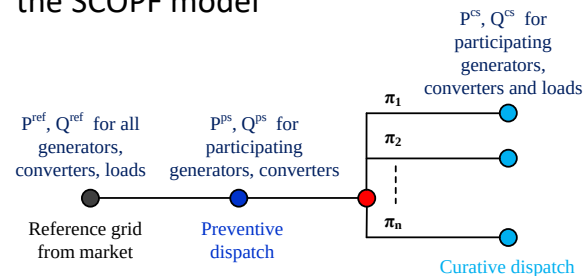
- Active power to converters is controlled
- Reactive power exchange at each converter can be controlled
- Highly dynamic control
- Flexibility through change in AC/DC converter set-points (active as well as reactive power)
 - Increase transmission capacity, Congestion Management, Voltage control
 - Controllable HVDC in preventive measures
 - Faster corrective control through HVDC (smaller time-constants)
 - More economical than re-dispatch, load curtailment
 - Flexibility through change in AC/DC converter set-points (active as well as reactive power)
- All power system aspects are influenced by HVDC controls



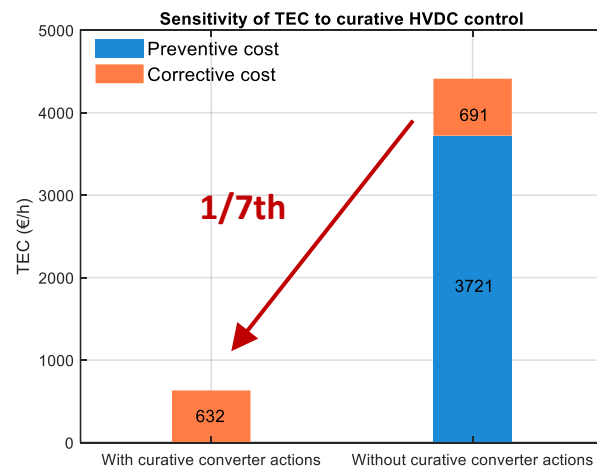
Flexibility of HVDC in reliable operations: new calculation models

Preventive-curative SCOPF model for AC/DC grid

- 2-stage (preventive and curative stage) optimization problem
- Inclusion of DC grid and converter model into the SCOPF model



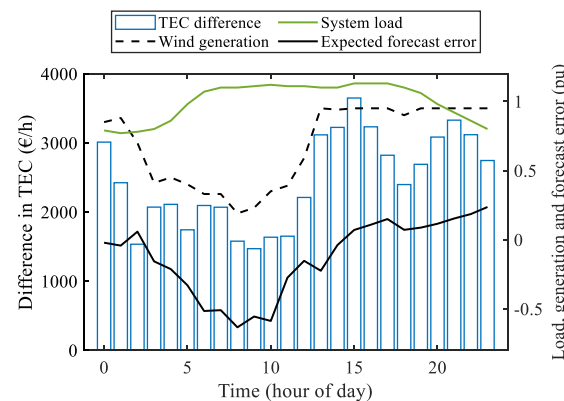
- Utilizing converter curative actions leads to savings in total expected costs (TEC)!



Source: V. Bhardwaj, H. Ergun and D. Van Hertem, "Risk-based preventive-corrective security constrained optimal power flow for ac/dc grid"

Stochastic SCOPF model considering intraday wind generation forecast error uncertainty and HVDC controllability

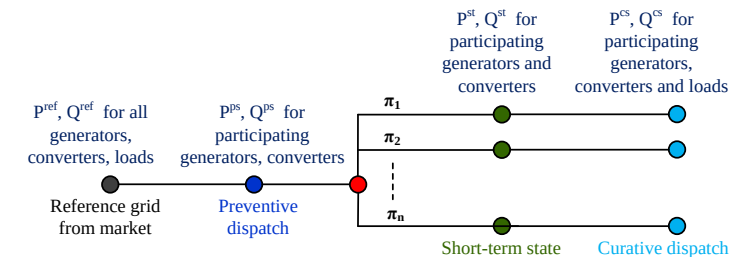
- Operational planning based on mean value of expected wind generation → forecast error in real-time
- Extension of 2-stage model to consider forecast error uncertainty in intraday operational planning
- Embedded HVDC as additional flexibility for secure intraday operation under uncertainty
- Use of curative HVDC control led to cost savings of 12.8 – 31.9 million euros per year for considered system!



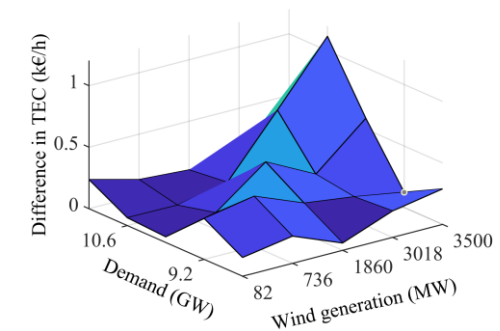
Source: V. Bhardwaj, H. Ergun and D. Van Hertem, "Mitigating intraday wind generation uncertainty with HVDC systems"

Three-stage SCOPF considering fast converter control and generator droop

- Smaller time constants of HVDC compared to traditional redispatch → additional flexibility alongside activation of frequency containment reserves (FCR)
- 3-stage model considers fast converter control



- Benefit in cost reduction by using HVDC flexibility; especially for constrained grid situations!



Source: V. Bhardwaj, H. Ergun, E. Heylen and D. Van Hertem, "A three-stage SCOPF considering fast converter control and generator droop"

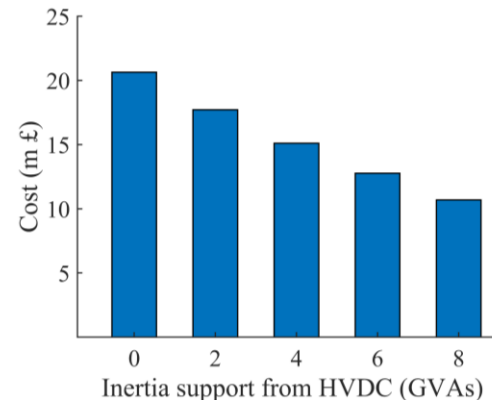
Value of using HVDC systems for service provision

Ancillary services can be provided by HVDC systems in a manner similar to or better than AC systems¹

Service \ System	Asynchronous		Synchronous		Offshore	
	LCC-based	VSC-based	LCC-based	VSC-based	LCC-based	VSC-based
Inertia	++	+++	NA	NA	++*	+++*
FCR	+++	+++	NA	NA	++*	++*
FRR	+++	+++	NA	NA	++*	++*
RR	+++	+++	NA	NA	++*	++*
Voltage/Reactive power control	-	+++	-	+++	-	+++
Black-start	-	++	-	++	-	++
Congestion management	+++	+++	+++	+++	-	-
Oscillation damping	++	+++	++	+++	+	+

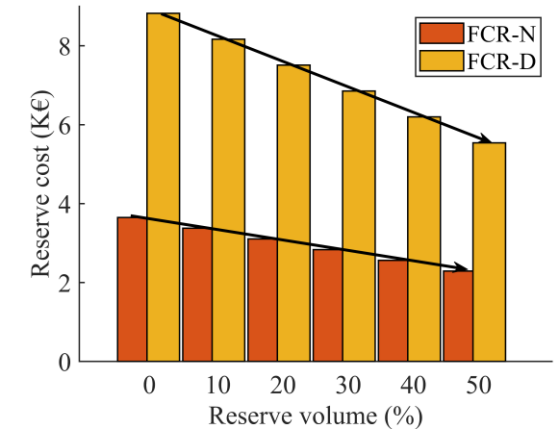
For Inertia support²

- 4 GVAs (100MW capacity on 2 HVDC lines) inertia support from HVDC → 27% reduction in annual inertia procurement cost for Great Britain



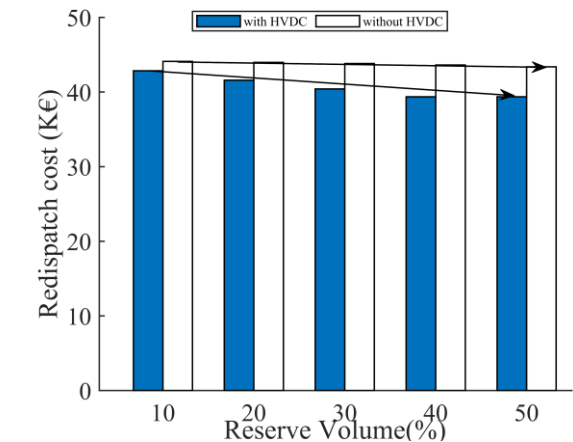
For FCR procurement³

- Use of HVDC → 37% reduction in cost w.r.t. local procurement cost



For FRR procurement⁴

- Procurement of 50% mFRR from outside → 11% reduction in the procurement cost



Unbalanced operation of HVDC grids

As of now DC side is always considered to be balanced (symmetric) → *same in future?*

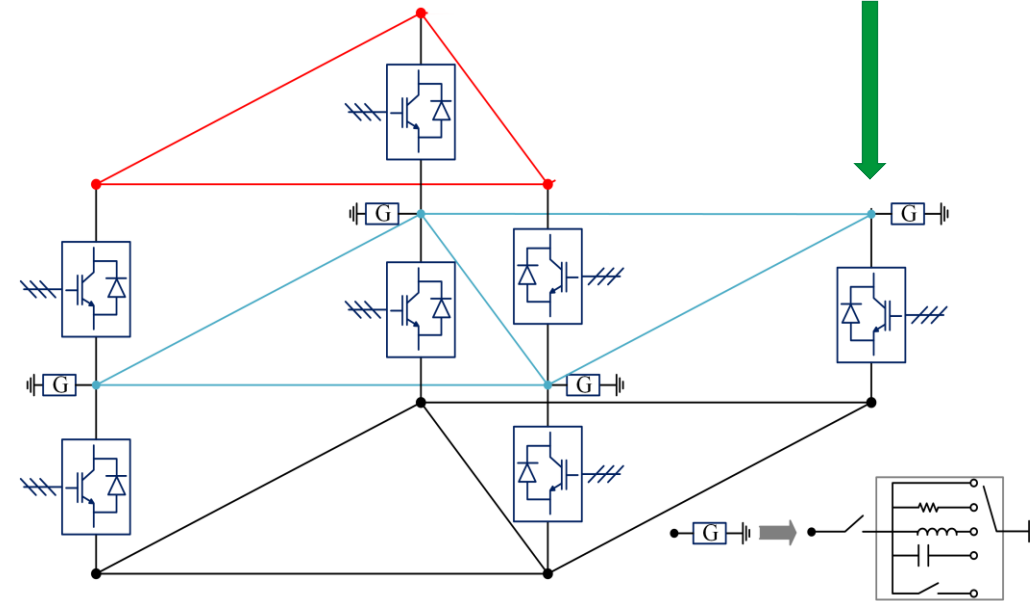
Single pole outage?

Monopolar tapping on a bipolar backbone:

Offshore wind

Operating mixed configurations causes unbalances in the DC grid

*Is it beneficial to build and operate such a system?
Can we compute the optimal operation?*



Open-source modelling tools

PowerModelsACDC.jl - A hybrid AC/DC OPF package

- Various AC/DC grid optimal power flow and transmission expansion planning models
- <https://github.com/Electa-Git/PowerModelsACDC.jl>
- Multi-conductor version
- <https://github.com/Electa-Git/PowerModelsMCDC.jl>

FlexPlan.jl - Transmission and distribution expansion planning considering storage and demand flexibility

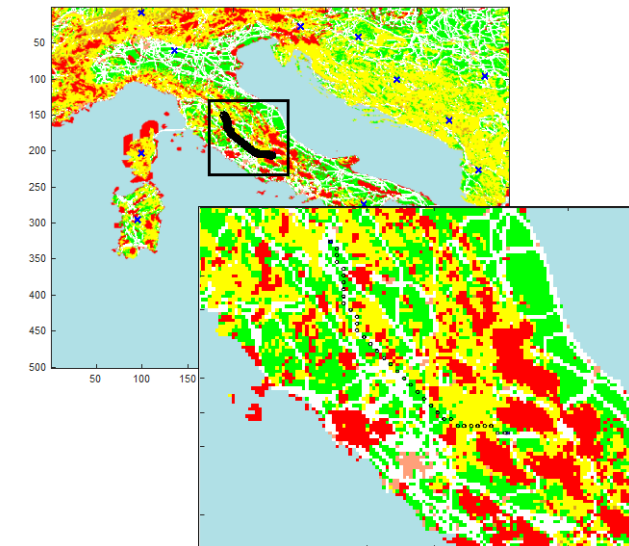
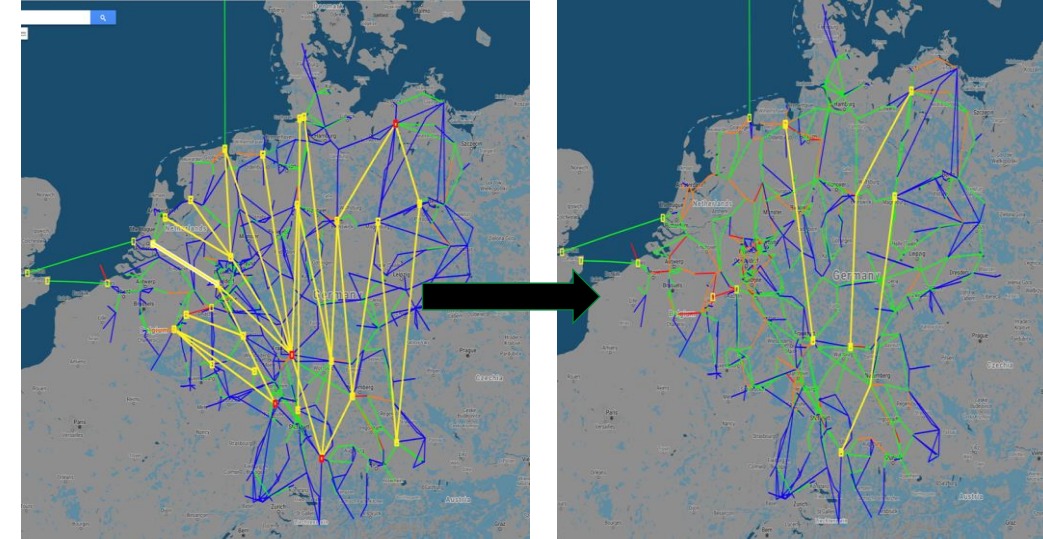
- Incorporates storage and demand flexibility models to find trade-offs between transmission investments & flexibility
- Extension to stochastic planning models for robust grid planning
- <https://github.com/Electa-Git/FlexPlan.jl>

OptimalTransmissionRouting.jl - Optimal transmission system routing for AC/DC OHLs and UGCs considering spatial information

- Applicable to partial undergrounding
- Separate routing for AC & DC technology
- Hybrid AC/DC extension will be implemented soon
- <https://github.com/Electa-Git/OptimalTransmissionRouting.jl>

CBAopf.jl - An optimal power flow tool for performing CBA analysis of AC/DC networks

- Extension of ENTSO-E CBA with HVDC, including stability
- <https://juliahub.com/ui/Packages/General/CbaOPF>



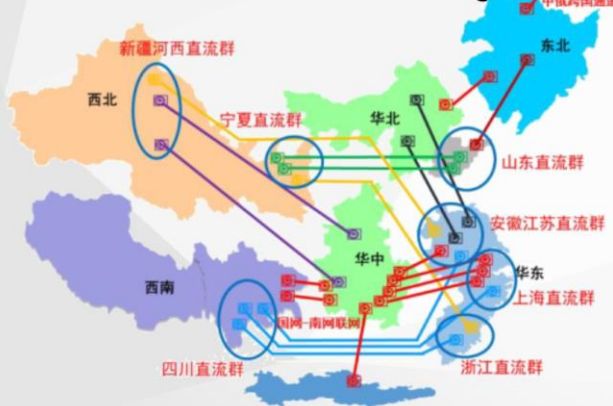


Global perspective

Not just in Europe: China

By the end of May 2022

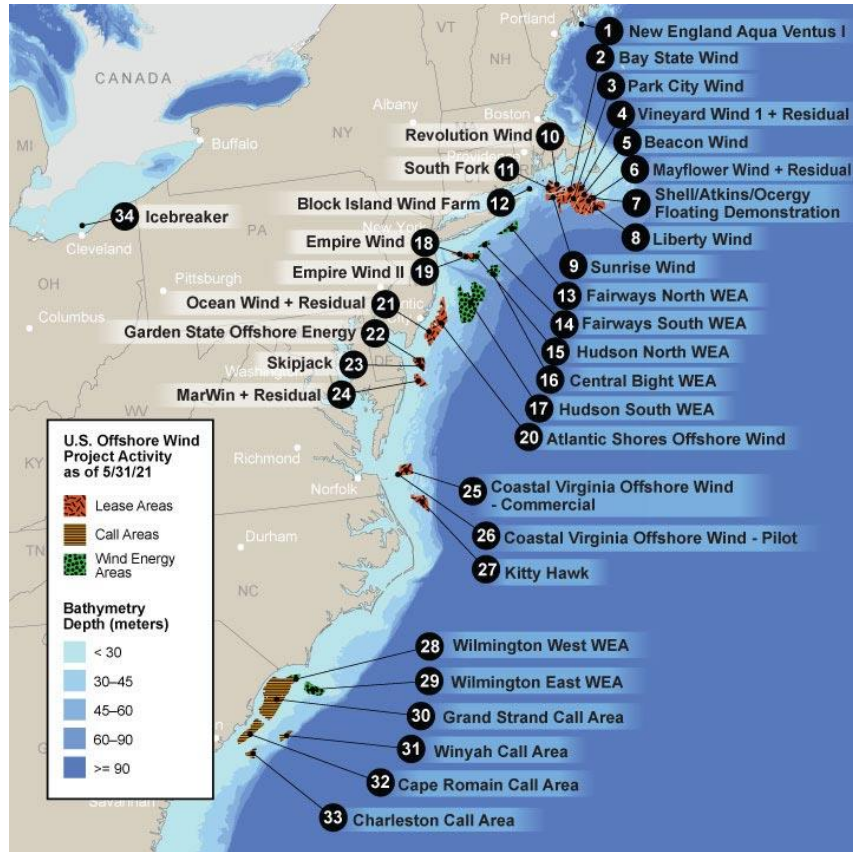
- **48,000 km** of UHVDC Transmission Lines
- **2.9 million** Renewable Energy Power Connected
- **550 million kW** Renewable Energy Capacity



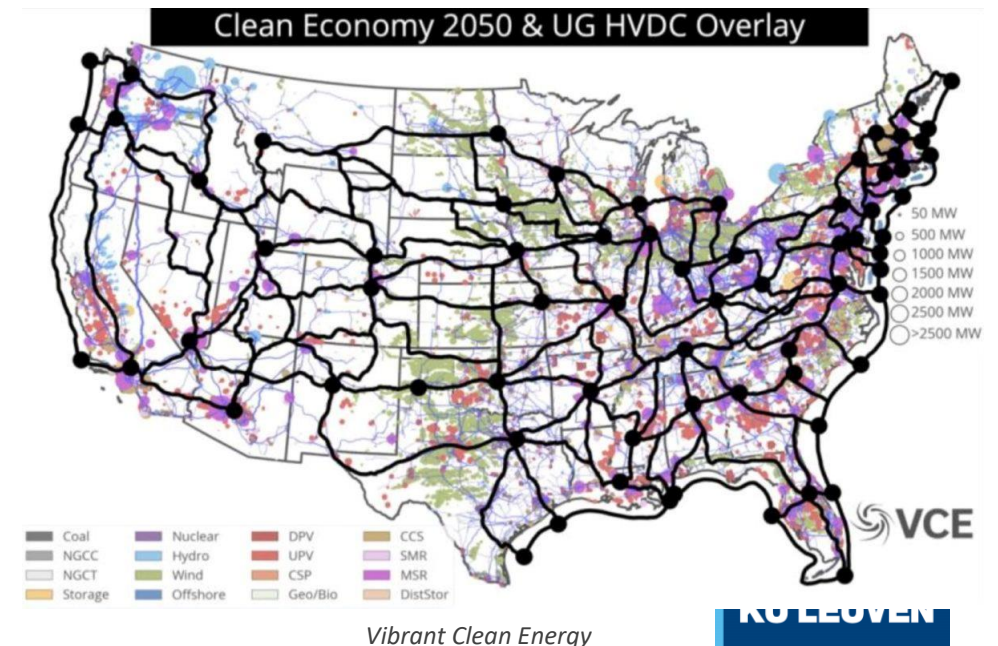
www.narig HVDC Grid Schematic of SGCC



Not only in Europe: North America (starting)



- First offshore
- Disconnected synchronous zones
→ macrogrid
- Acceleration with the inflation reduction act



The locations of the current U.S. Atlantic Coast offshore wind Projects being considered or developed as of April 30, 2021.

Image from the NREL Offshore Wind Market Report: 2021 Edition



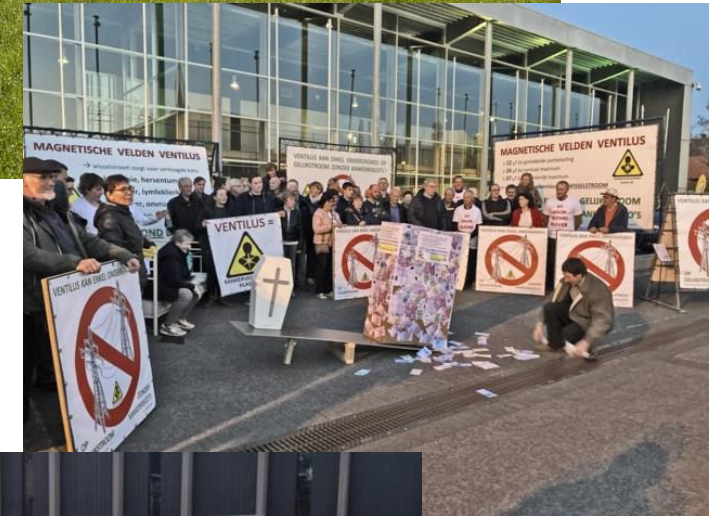


Upcomming challenges

More investments, preferably underground



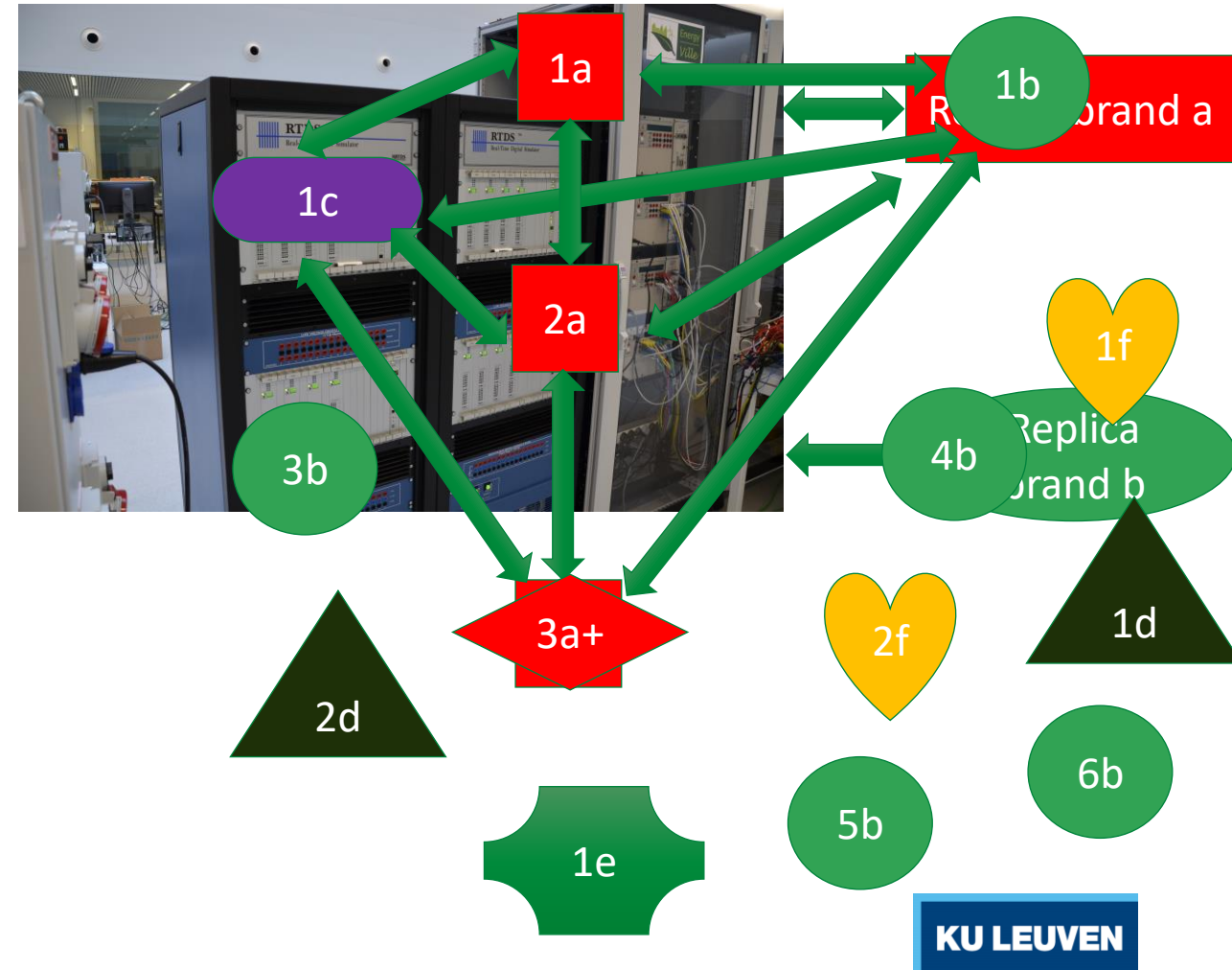
1 Ventilus like connection /19 km by 2050
1 Ventilus project between De Panne (B) and
Kiel (D) per year
Picture illustrates investment needs till 2040



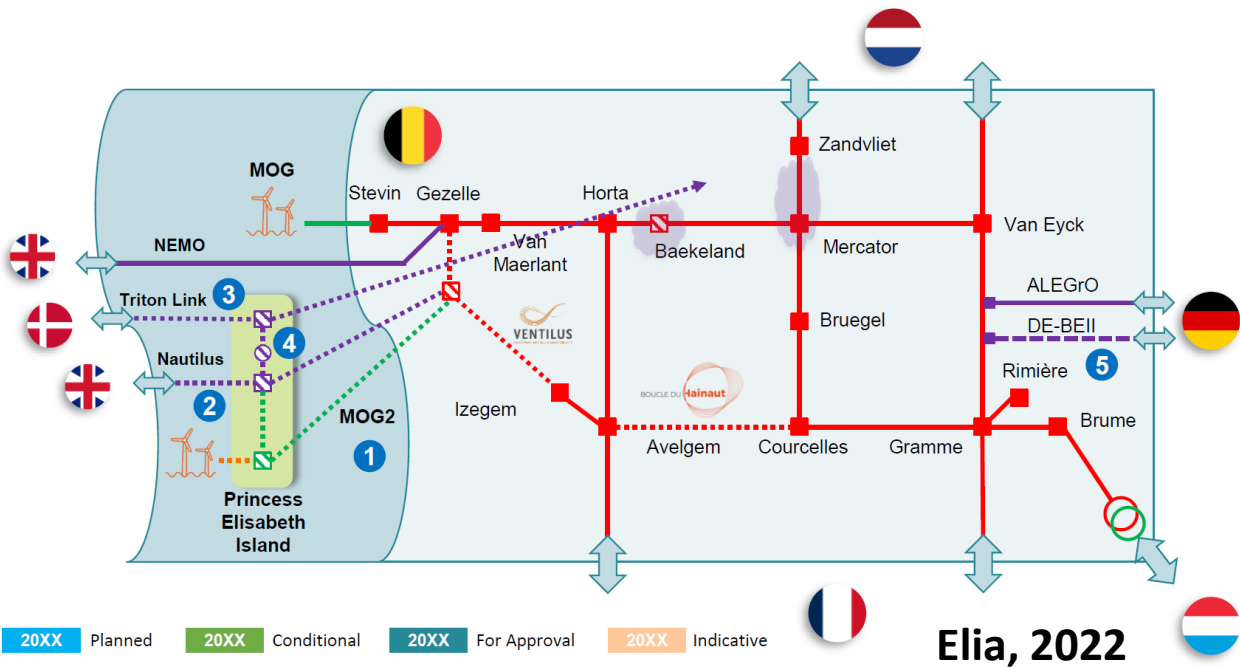
Interoperability (controller/harmonic stability)

- Many converters connected
 - HVDC but also wind
- Very low damping
- In practice, we do not have perfect 50 Hertz + dynamic
- Multi-vendor systems are desired but not straightforward
- Converters are black boxed → interactions + influence protection
- Acceptable as long as HVDC installations are relatively rare and unique projects
- What can we do for future pan-European power system?

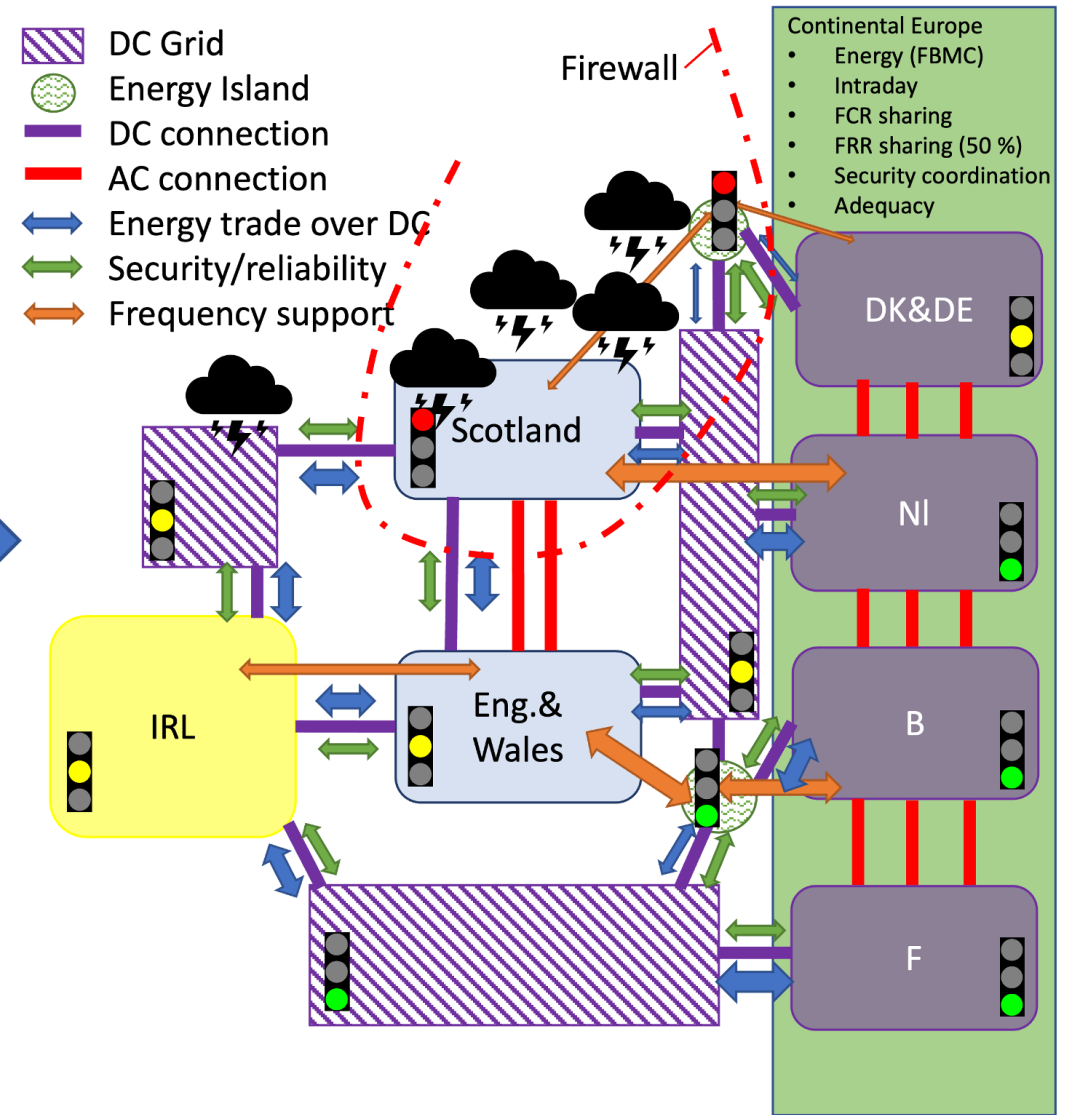
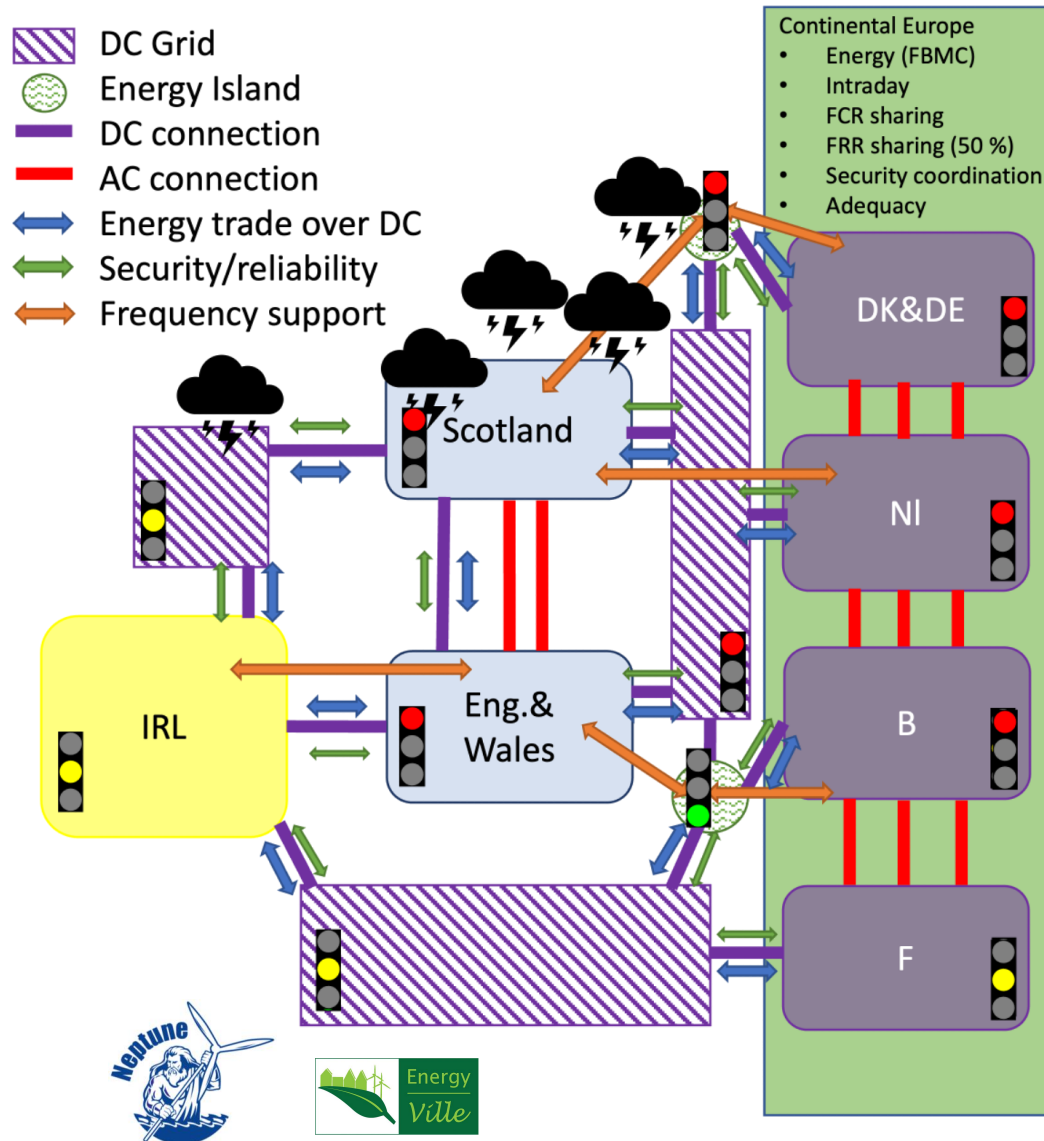
Solvable? Yes, but



Energy islands/hubs



HVDC grids and resilience: rearranging system based on weather



Towards a more resilient system → new paradigm, grid-of-grids

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**
→ Energy Island as a subgrid?



HVDC Cable and underground cable competence centre

Start: 2023

- WP1: underground cables in the transmission grid
- WP2: Protection of underground systems
- WP3: Control-interactions between converters
- WP4: Robust HVDC grids
- WP5: Building a simulation centre to bring innovation to the next level and derisk future energy systems
- WP6 Competence centre
 - Develop international competence centre
 - Development R&D roadmaps
 - Professional operation
 - Technology watch
 - Workshops and training
 - Link with industry



Key takeaways

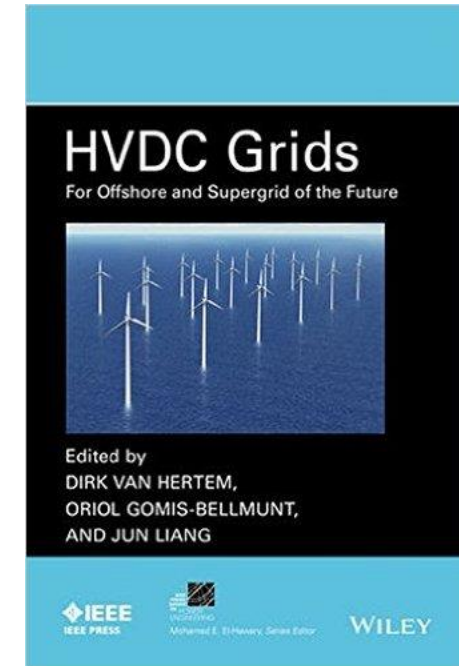
- HVDC grids are possible
 - With some challenges!
- Research needs on planning and operations, protection and controls
 - Advances are being made, yielding new tools and methods
 - Current day tools are not suitable to address tomorrows problems
- HVDC research is alive and kicking in Flanders

It is not because we do not know exactly how the future will look like that we should not start with it today

Questions?



Contact:
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With the support of the Belgian energy transition funds



HVDC and Underground Cable Competence Center

