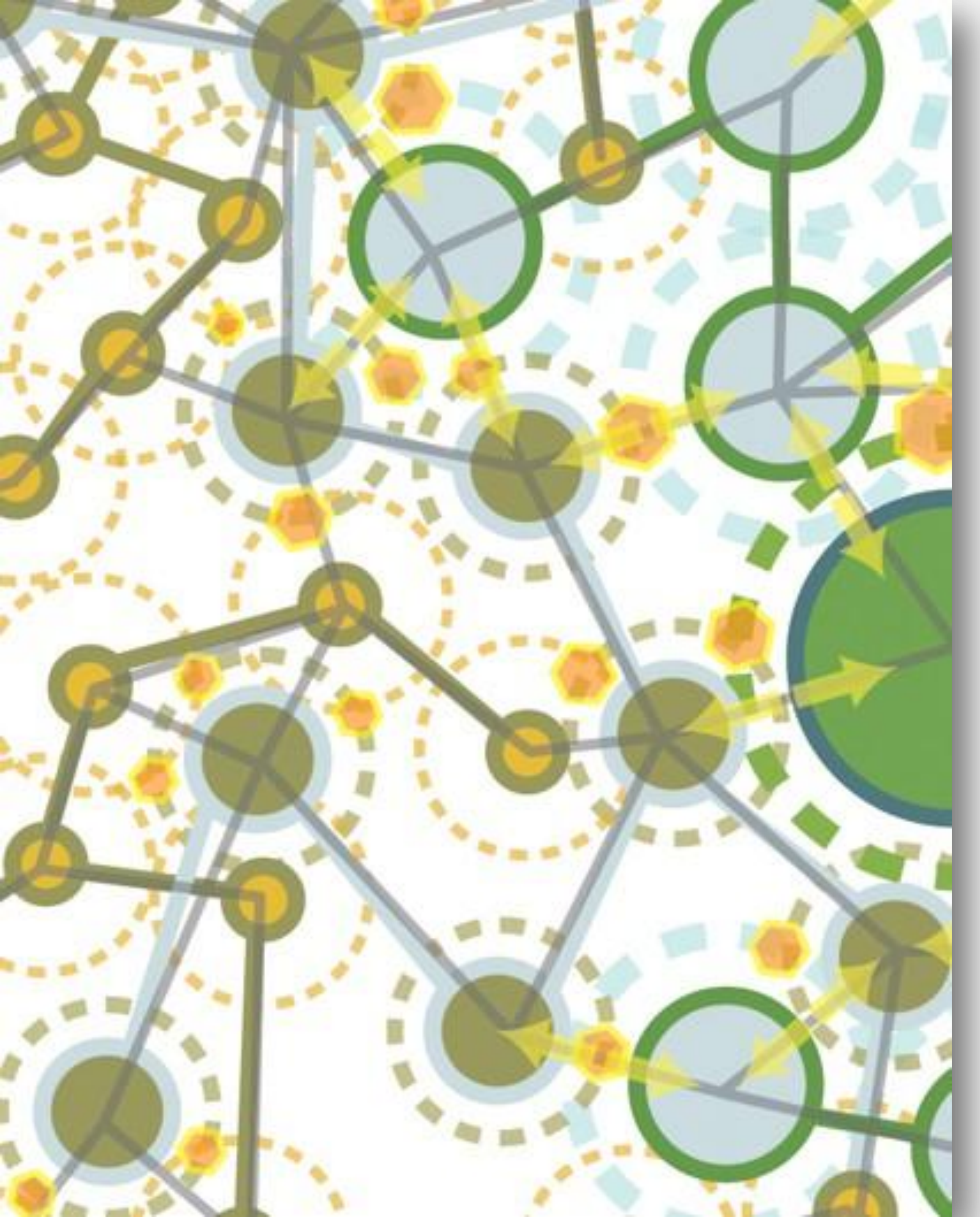
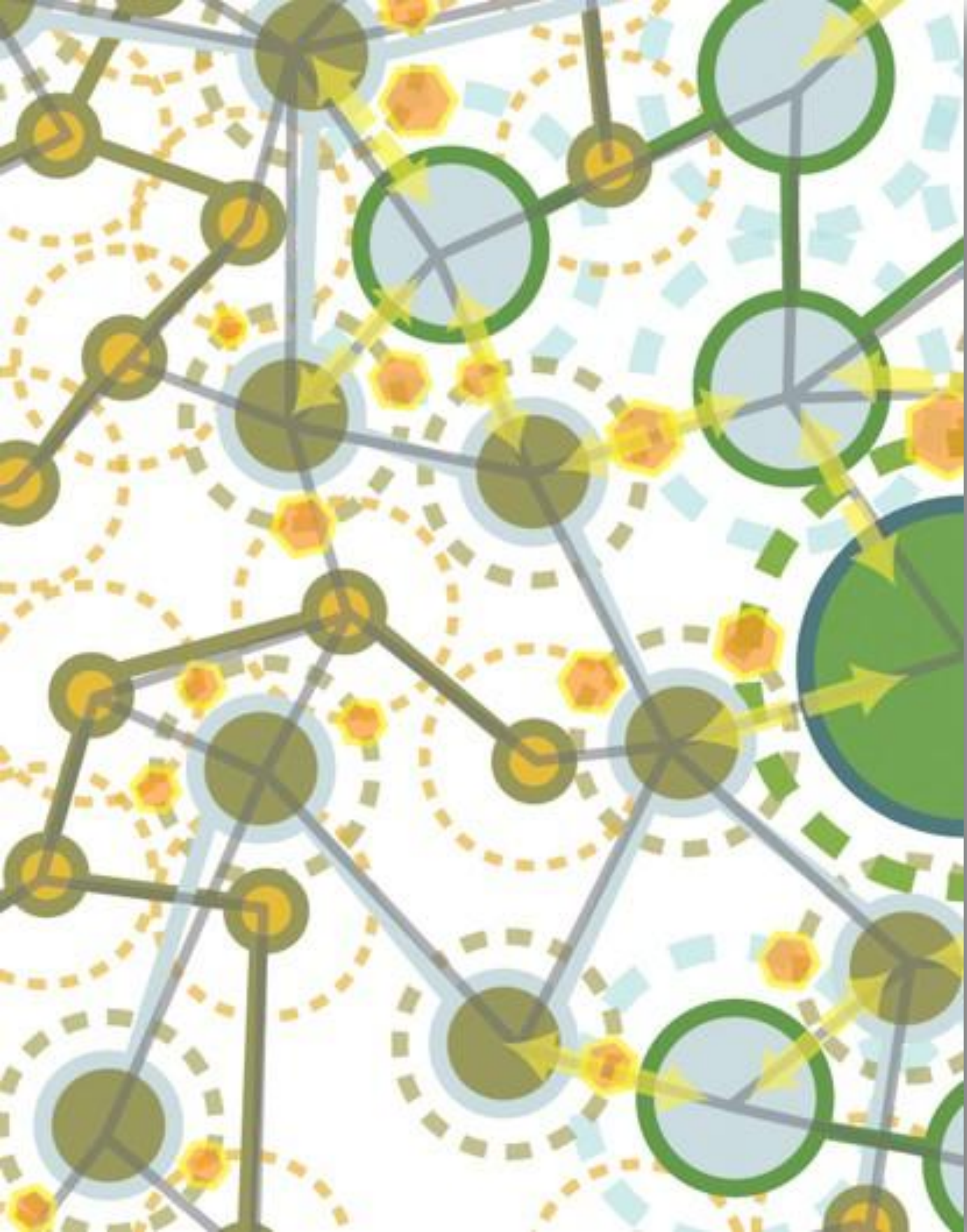


HVDC links in AC power system

Pierre Bornard

Deputy CEO | RTE



New challenges & drivers

❷

HVDC fundamentals

INELFE example

HVDC integration / issues

HVDC integration / R&D role

The European Power System: key-figures

34 (almost) interconnected countries

- Security of supply and reliability
- Economic optimization (IEM)
- Sustainability

41 Transmission System Operators

1 European association: entsoe

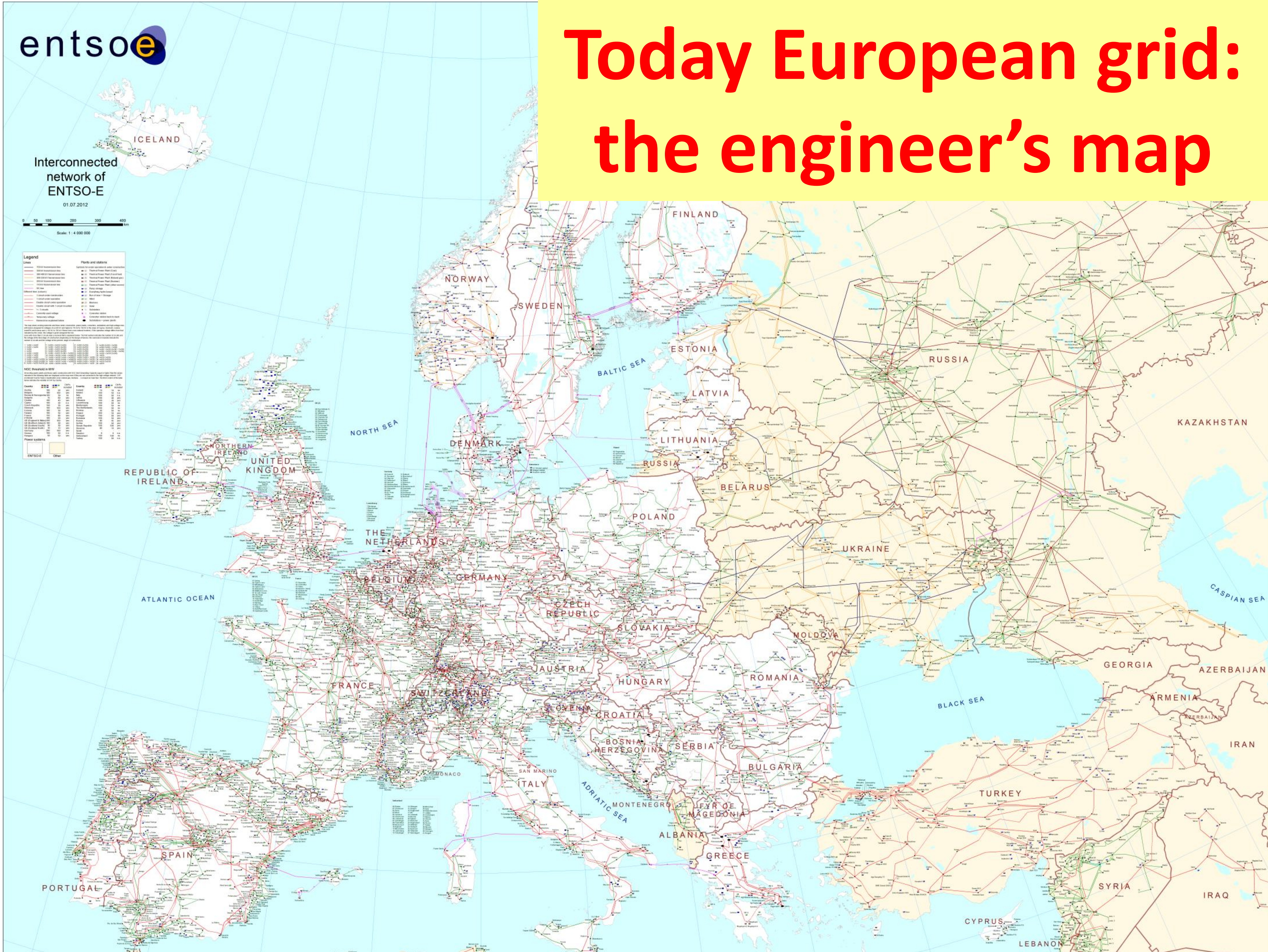
Legal mandate

Third Energy Package / Regulation (EC)714/200

Several synchronous areas

- Installed capacity ~ 880 GW
- Annual consumption ~ 3 300 TWh
- Annual exchanges ~ 380 TWh
- 300 000 km of lines of EHV circuits
- ~ 530 millions inhabitants

Today European grid: the engineer's map



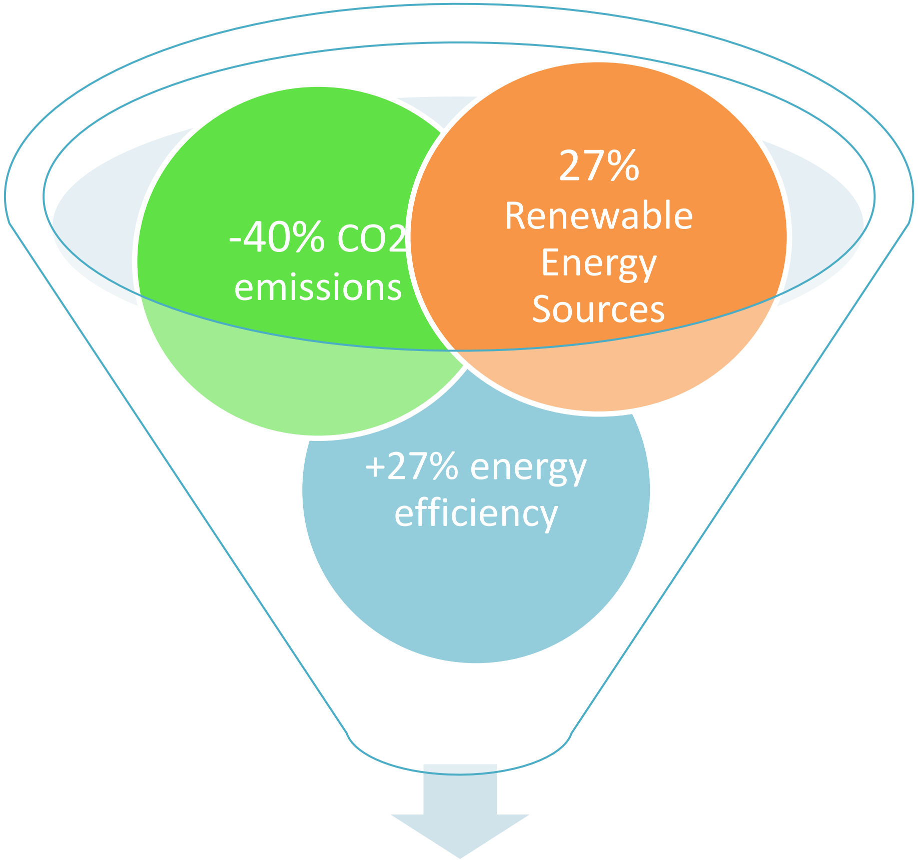
Tomorrow European supergrid: the poet's map

Source: FOSG

NEW CHALLENGES & DRIVERS

Source: Marc Didier

The 2030 EU Council targets


-40% CO2 emissions

27% Renewable Energy Sources

+27% energy efficiency

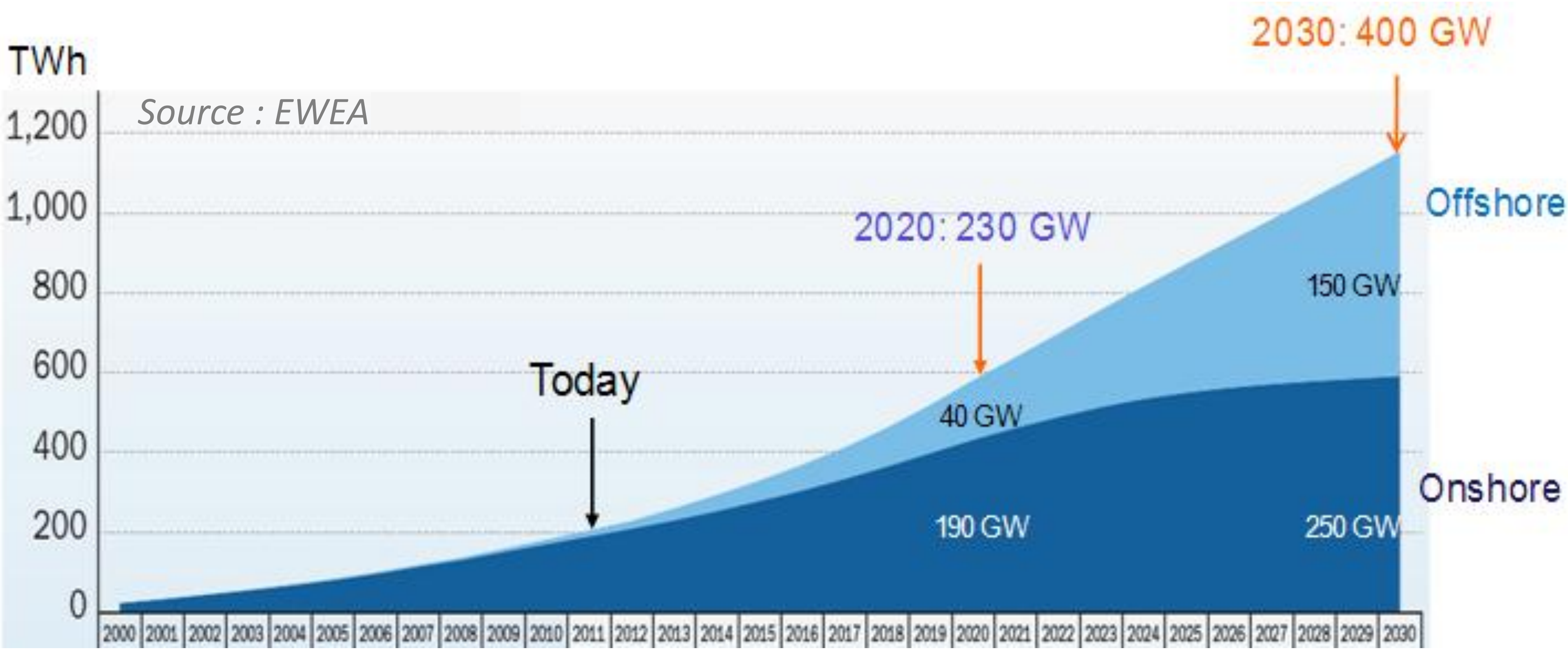
About 45% of RES generation in the electricity transmission system

Natural resources

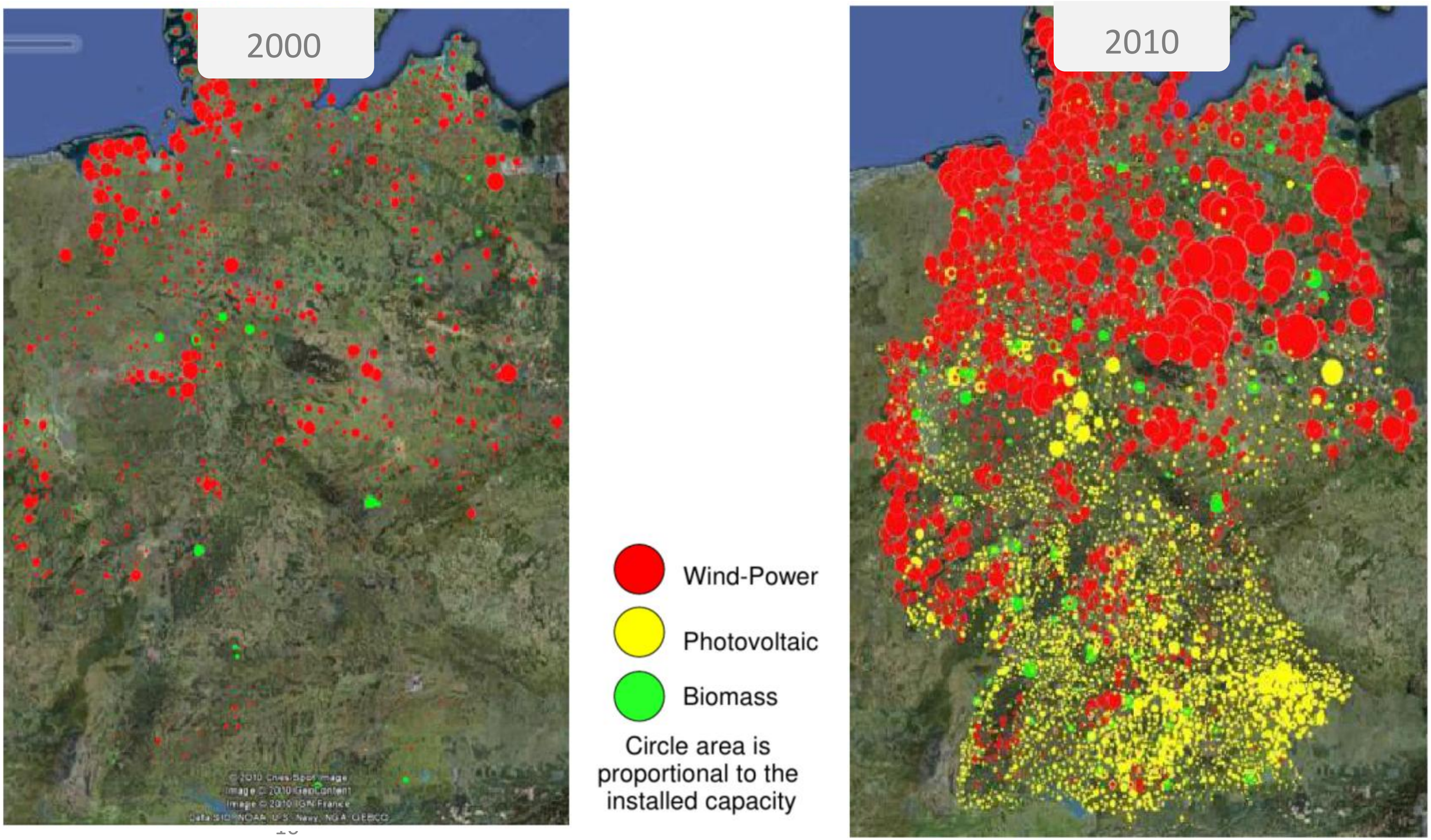
Wind power expansion

Wind share of demand:

- 2010 → 5%
- 2020 → 23%
- 2030 → 36%



RES boom in Germany



🟥 Wind-Power

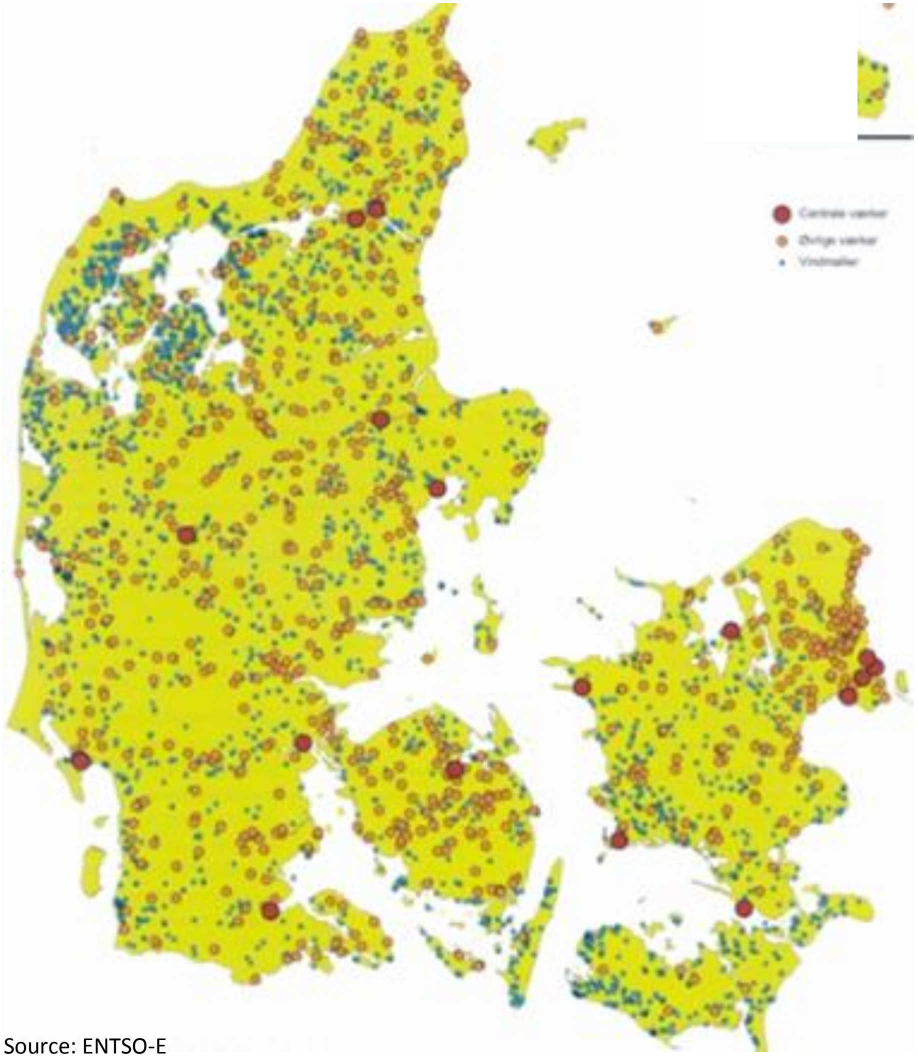
🟨 Photovoltaic

🟩 Biomass

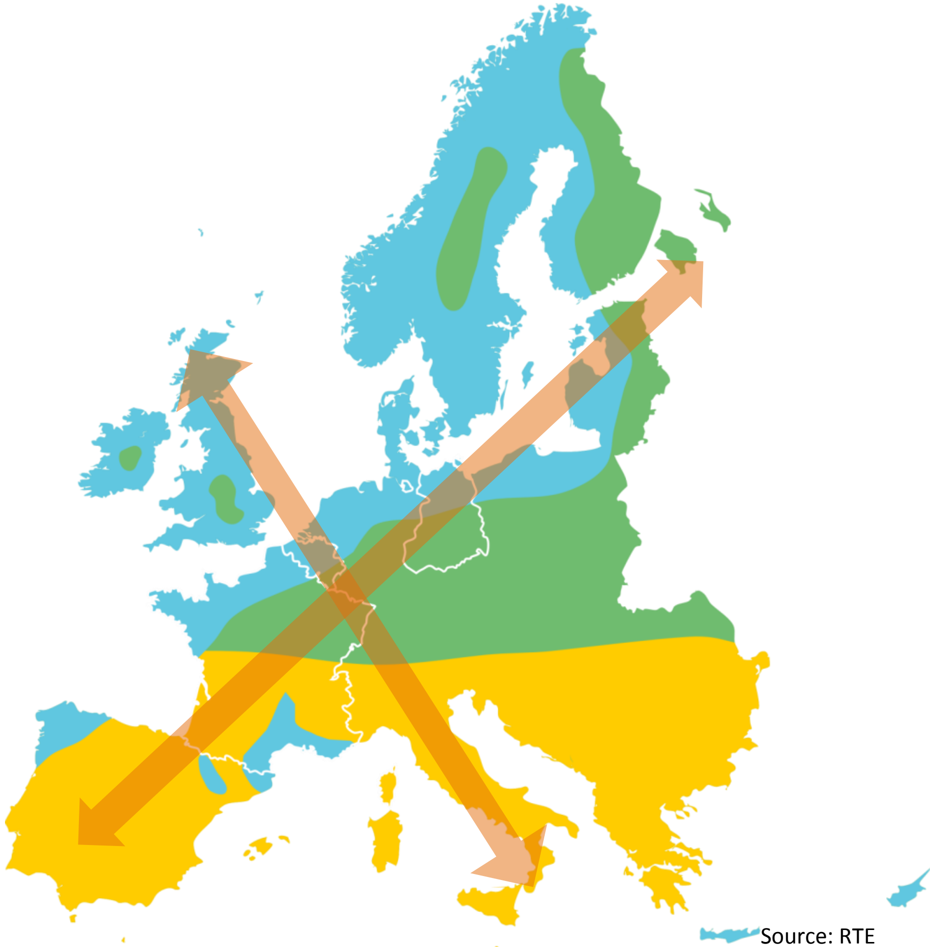
Circle area is proportional to the installed capacity

Decentralized generation but continental flows

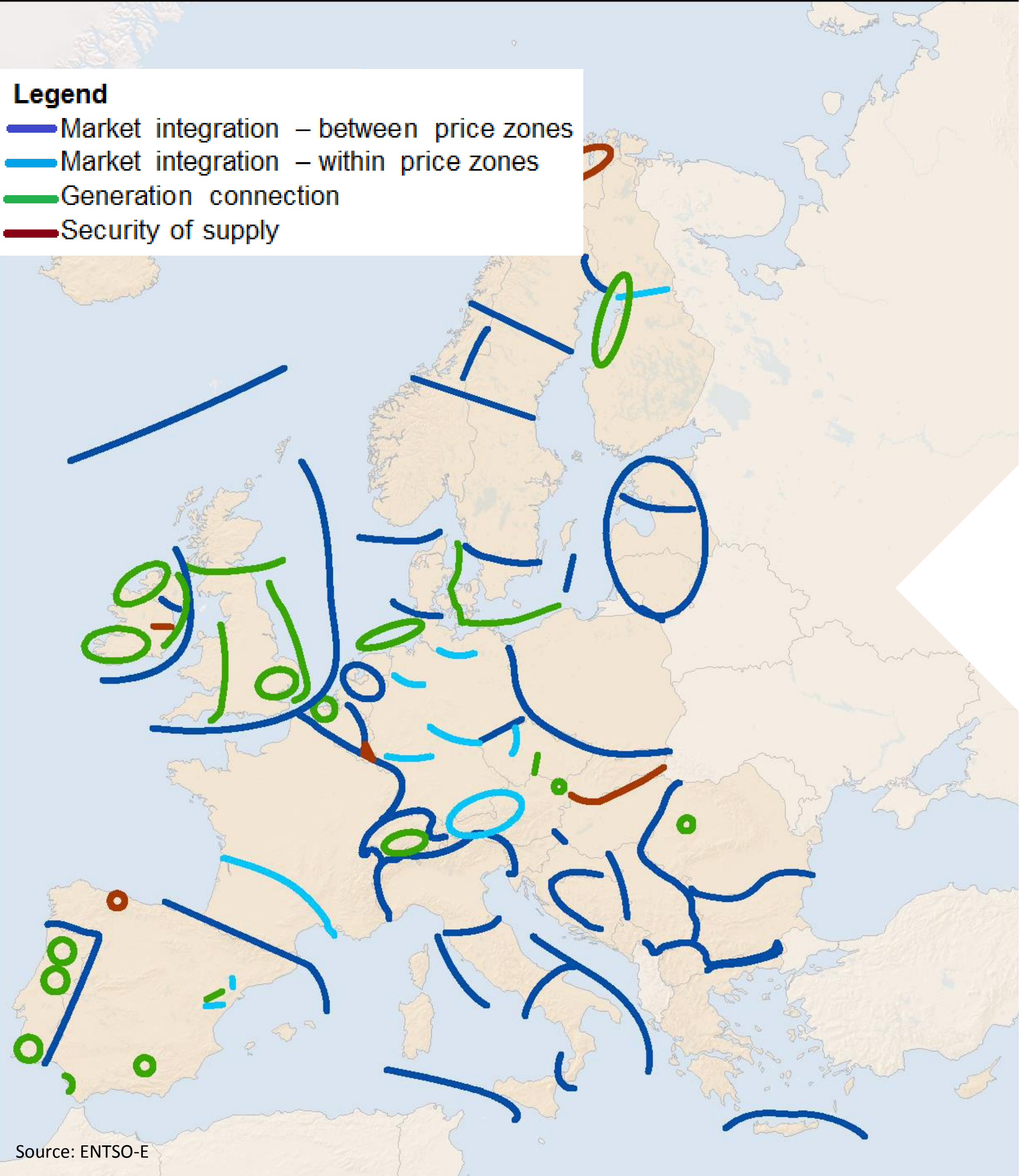
Thousands of small units → huge flows all over Europe



Source: ENTSO-E



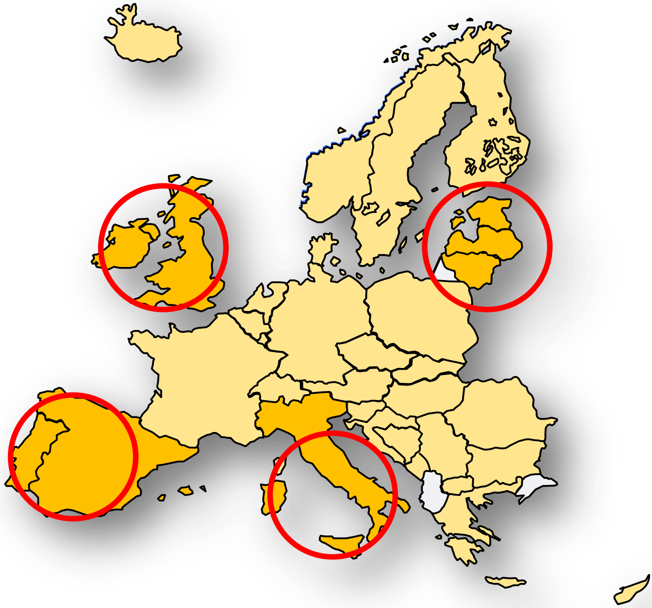
Source: RTE



Source: ENTSO-E

100 bottlenecks

which are impeding market integration, RES integration, security of supply



What does this energy transition require?

New hardware

Investment in 50,000 km transmission lines

New software

10 network codes

EU council interconnection targets

2020

10%

2030

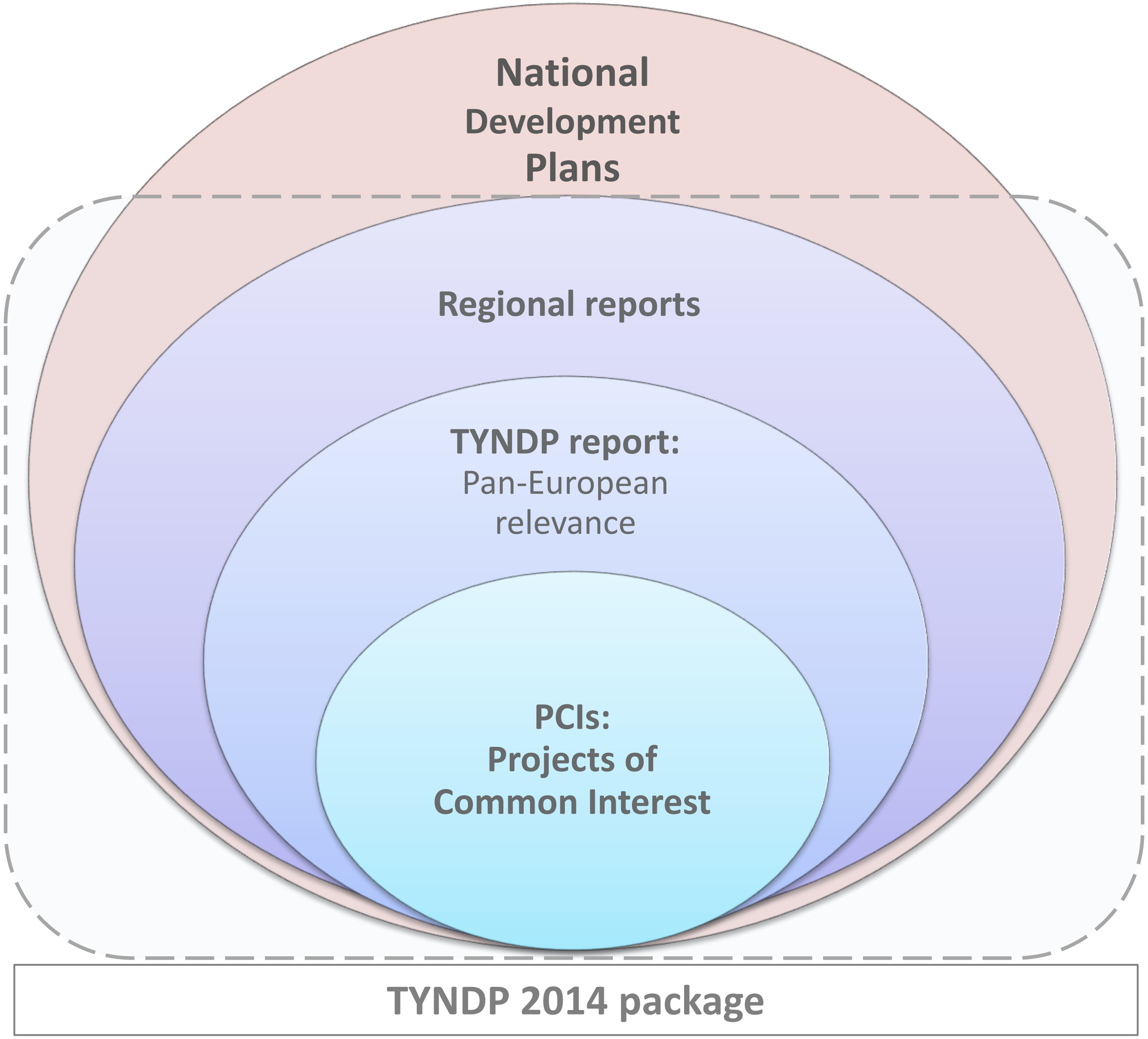
15% ?

Regional differences & needs must be considered

Ten Year Network Development Plan 2014

- Pan-European Expert Group set up to perform pan-European Market Studies
- Cost and Benefit Analysis (CBA) methodology for project of pan-European Significance
  - Multi-criteria approach
  - Indicators quantified from market studies & grid studies
- Increased stakeholder involvement in addition to the formal TYNDP consultation:
  - Creation of the Long Term Network Development stakeholder group
  - Early stage workshops on methodology and scenarios
- Sole basis for the Projects of Common Interest selection

TYNDP + EU list of PCI = consistency


National Development Plans

Regional reports

TYNDP report: Pan-European relevance

PCIs: Projects of Common Interest

TYNDP 2014 package

120 projects of pan-European relevance

⬇

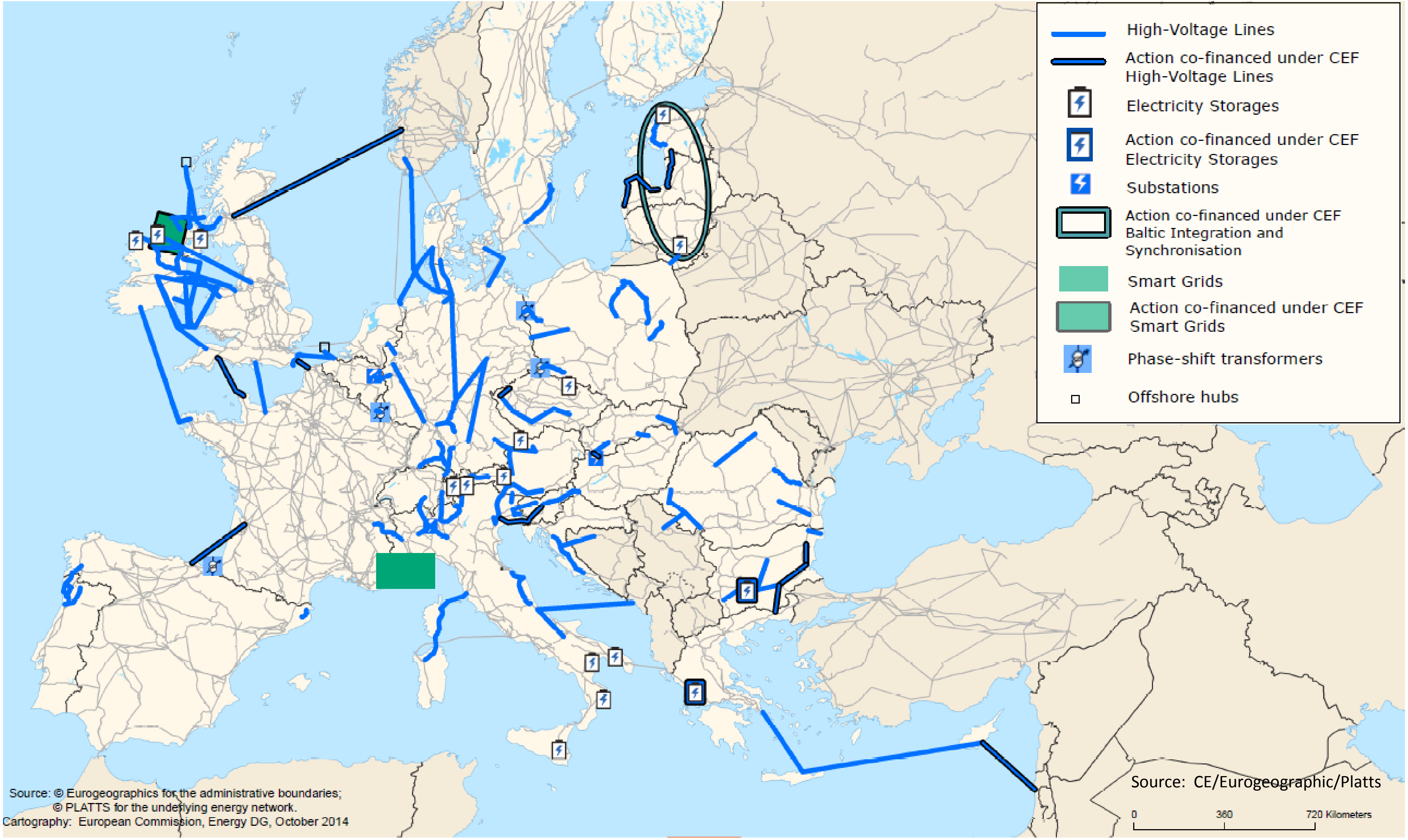
Incorporating **22 third party projects**

⬇

17 PCI projects assessed:
- 8 transmission projects
- 9 storage projects

PCIs

Projects of common interest – Electricity and Smart Grids

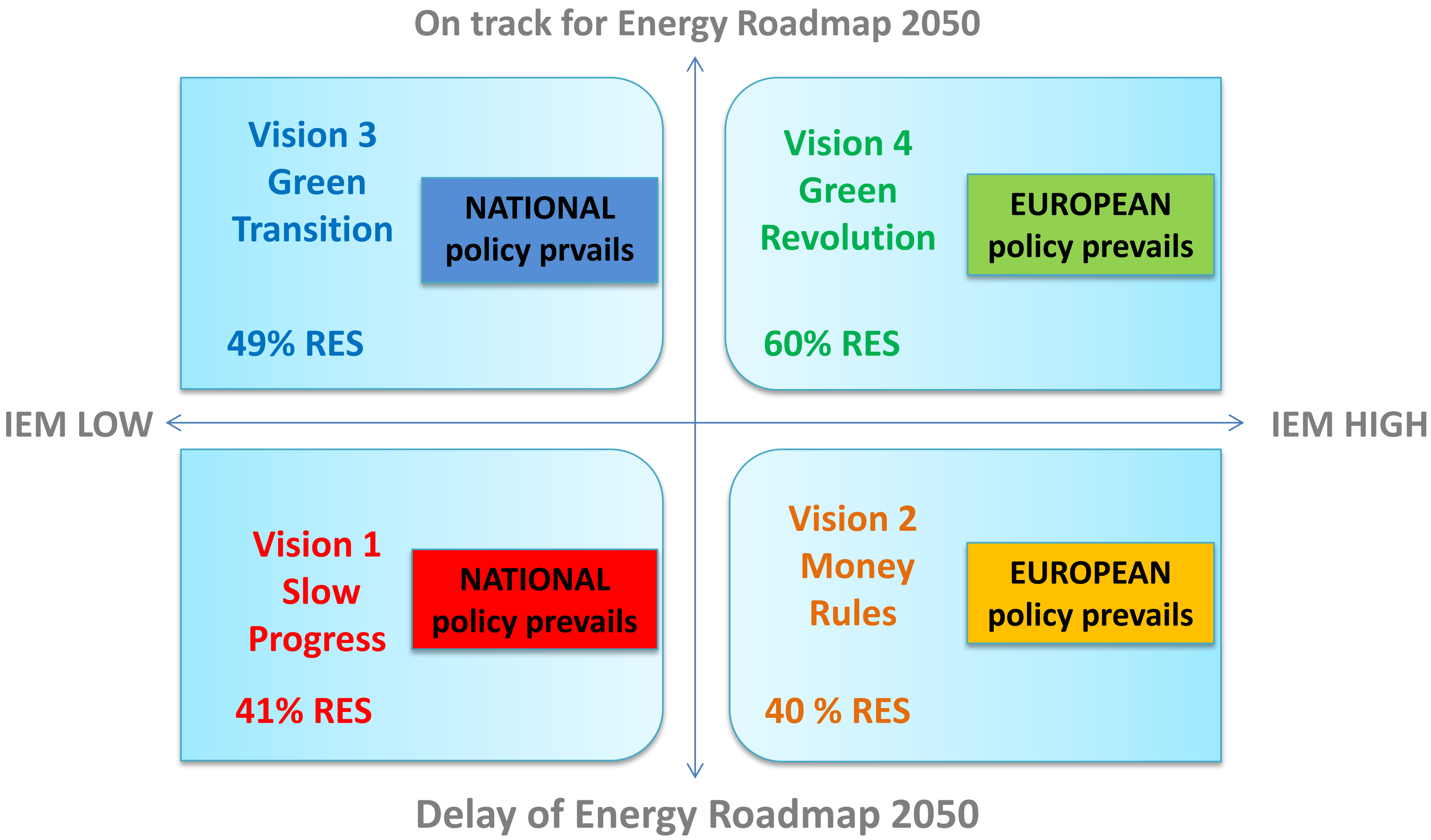


Source: © Eurogeographics for the administrative boundaries;
© PLATTS for the underlying energy network.
Cartography: European Commission, Energy DG, October 2014

Source: CE/Eurogeographic/Platts

TYNDP: Framing uncertainties to build the right infrastructure

80% investments driven by RES!



On track for Energy Roadmap 2050

Vision 3
Green
Transition

NATIONAL
policy prvails

49% RES

Vision 4
Green
Revolution

EUROPEAN
policy prevails

60% RES

IEM LOW

IEM HIGH

Vision 1
Slow
Progress

NATIONAL
policy prevails

41% RES

Vision 2
Money
Rules

EUROPEAN
policy prevails

40 % RES

Delay of Energy Roadmap 2050

TYNDP 2014 main findings

Costs of up to €150 billion for projects of pan-EU significance by 2030

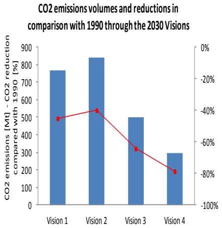
(1-1.5 €/MWh, about 1% of bill)

Savings of 2 to 5 €/MWh for bulk power prices by 2030

Up to 50,000 km of new or refurbished grid investments

(23,000km new overhead lines)

Optimised land use: the crossed urbanised areas account for less than 4% of the total km of lines



Mitigation of 20% of CO2 emissions for the European power sector

Accommodating up to 60% RES of total consumption in 2030

Focus on cross-border interconnection needs

120 pan-European projects

Red:

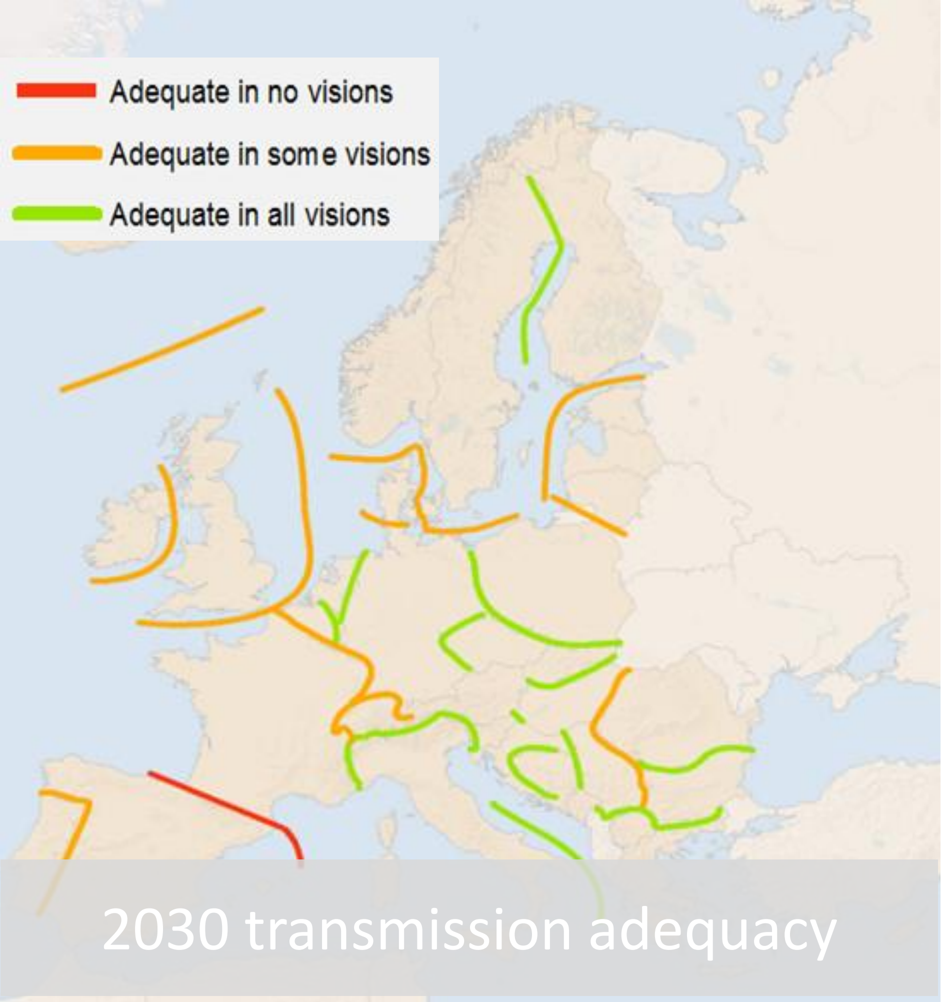
projects between the Iberian Peninsula and the rest of Europe, remain complex due to geography

Orange:

additional grid reinforcements required for most ambitious scenarios of RES development

Green:

1/3 of all boundaries are solved



2030 transmission adequacy

Source: ENTSO-E

Main obstacles to timely infrastructure building

Permit granting

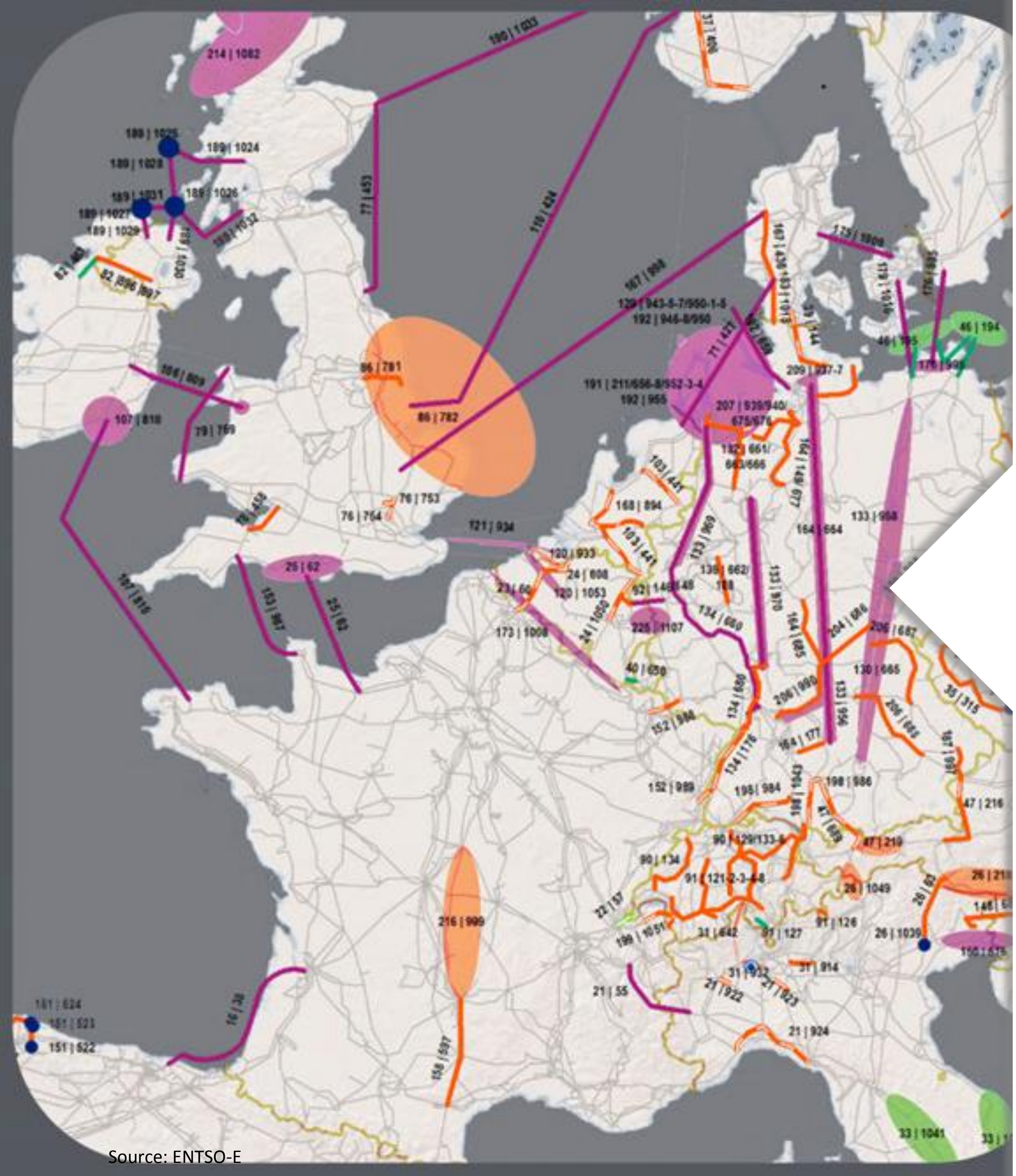
- Procedures are lengthy and often cause commissioning delay
- 30% of investments are delayed by 2 years

Public acceptance

- More effort to bring citizens and interest groups on-board and increase understanding of Europe’s energy needs

Financing

- Transmission infrastructure is a long term investment => a stable regulatory framework is crucial
- Tariffs must be adapted to support the energy transition

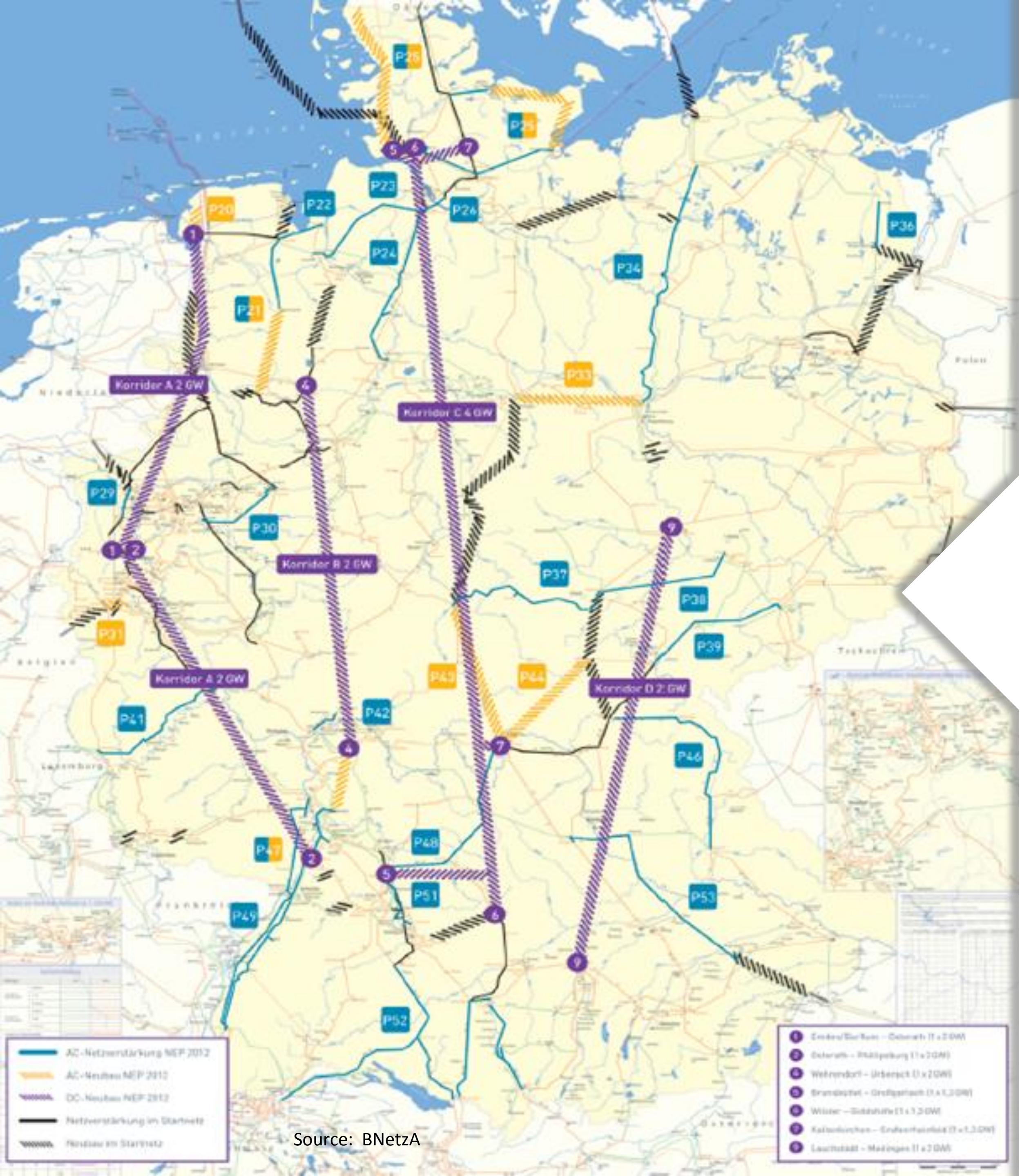


Source: ENTSO-E

New HVDC links are planned to be built all over Europe

Planned HVDC links are either:

- located between 2 asynchronous areas, which can thus exchange power
- embedded in a meshed synchronous area, where they enable bulk power transfer



Source: BNetzA

German NDP

4 HVDC (8 GW total)

AC corridors refurbishment

Electrical context of the grid

Evolutions of the European grid:

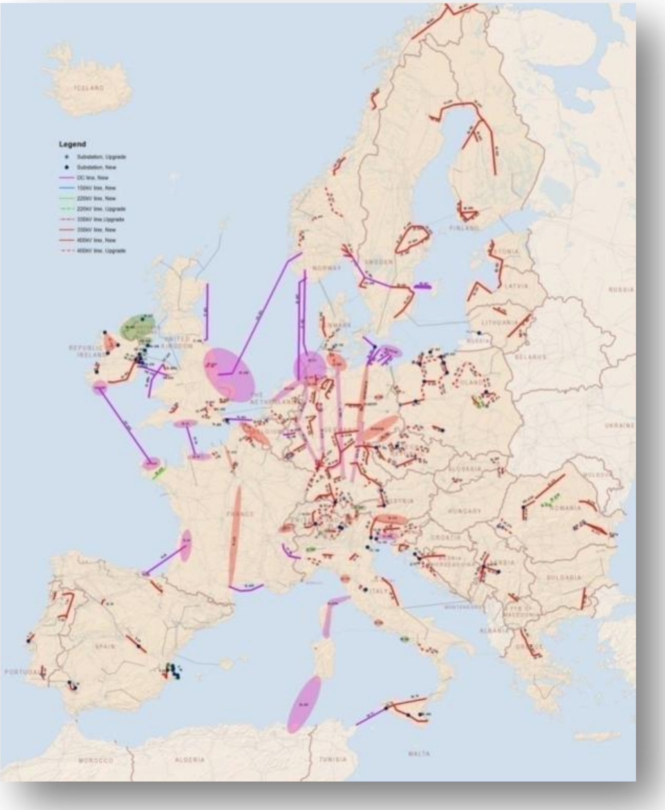
Development of renewable energy and in particular wind farms

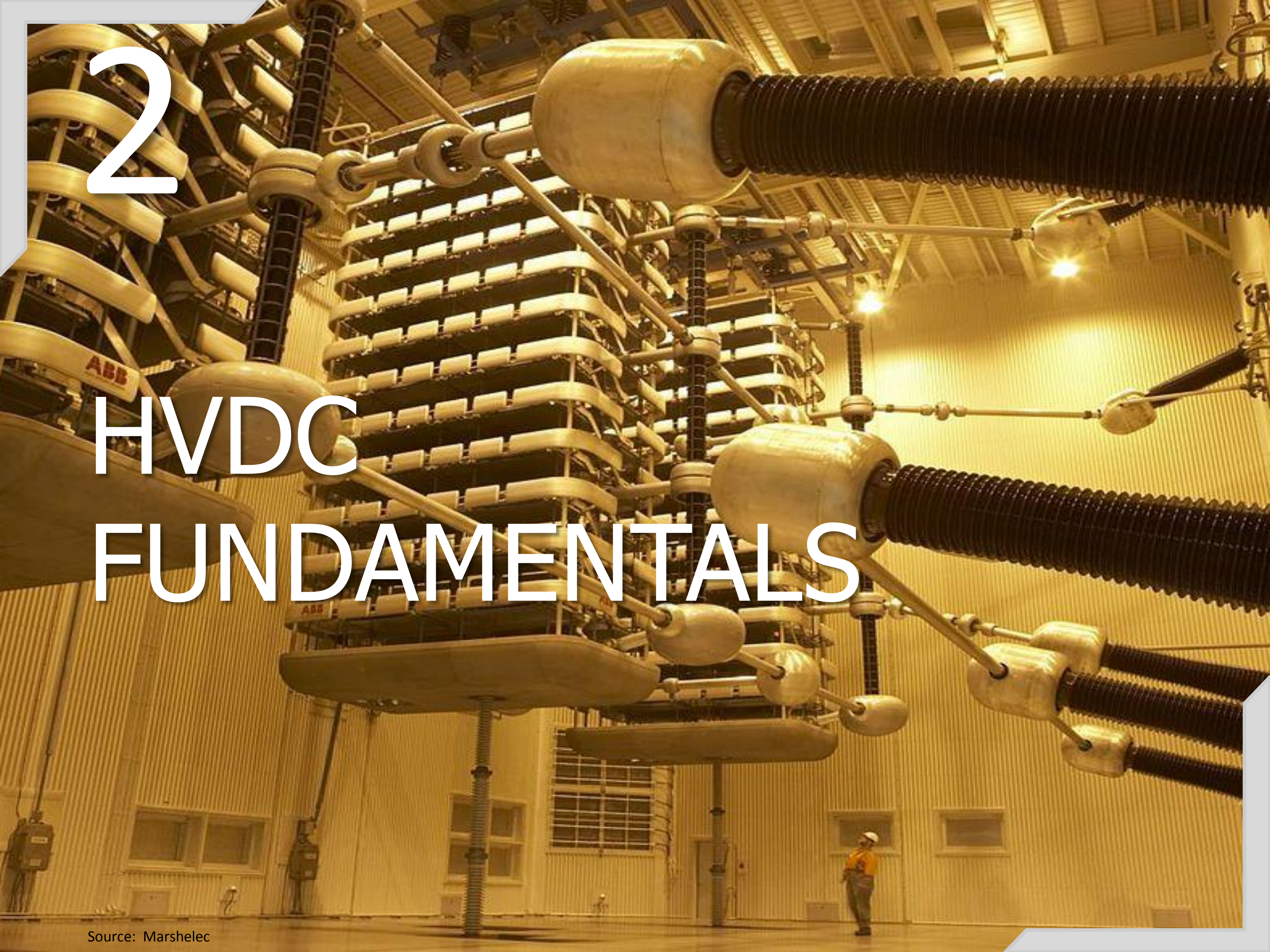
Underground and submarine cables

More interconnections and HVDC projects

Several SVC Projects for grid security

Power electronics to be used more and more





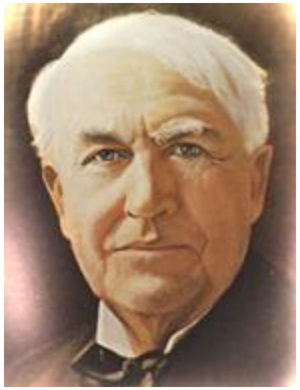
2

HVDC FUNDAMENTALS

Source: Marshelec

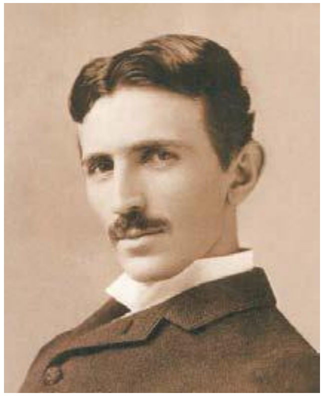
From alternating to direct current: a 130-year-old story

The current war



Thomas Edison: believer in DC

- 1878: incandescent lamp
- 1882: 1st DC distribution grid



George Westinghouse: in favor of AC

- 1885 : Importing transformer from L. Gaulard & J. Gibbs and AC generator from Siemens
- 1886 : 1st AC grid, hydro generator 500 V, transformer 3000 V, network of 100 V bulbs
- 1887 : 30 other electric lighting systems based on AC are installed
- 1888 : AC meters (O. Shallenger) et AC motors (N. Tesla) make the (temporary?) victory of AC

Source: Wikipedia

DC assets vs. AC

Better control of power flows in meshed networks

Stable connection of asynchronous networks

Connection of AC networks operating at different frequencies (e.g. Japan)

Transmission capacity of lines and cables is saved in DC thanks to the absence of reactive power

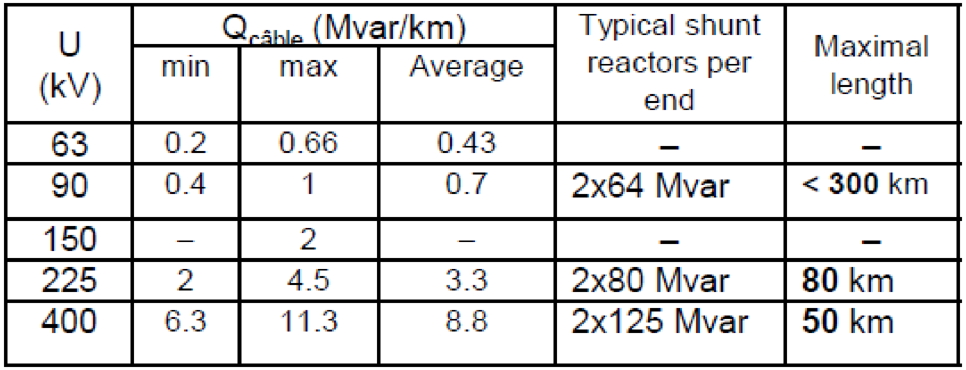
30% less copper in the DC conductors to transmit same power as in AC

DC overhead/underground links have smaller environmental impacts

Relative costs of DC compared with AC

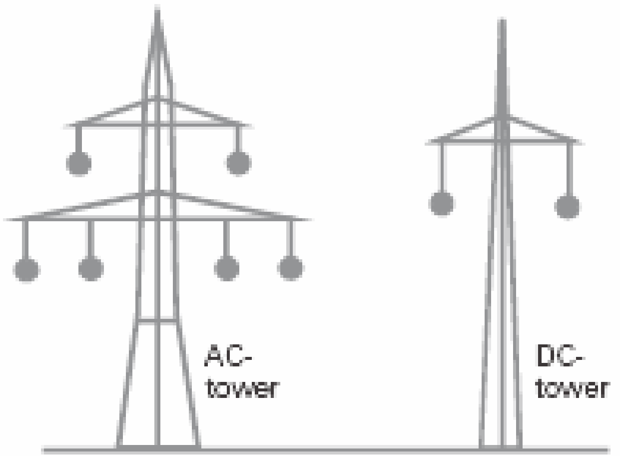
Converter stations significantly increase DC transmission costs

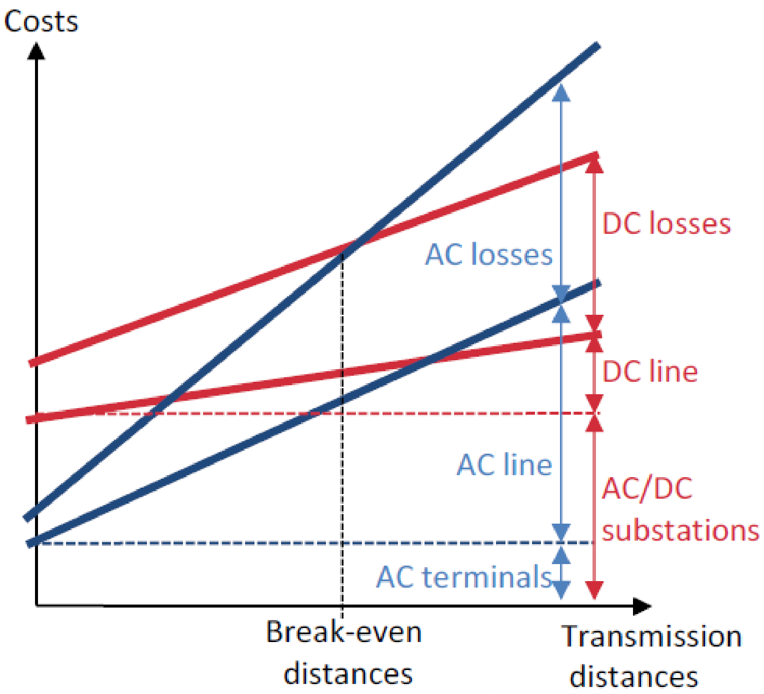
Break-even distances beyond which DC becomes cheaper than AC are around 40 km for cables and 500 km for OHL



U (kV)	$Q_{câble}$ (Mvar/km)			Typical shunt reactors per end	Maximal length
	min	max	Average		
63	0.2	0.66	0.43	–	–
90	0.4	1	0.7	2x64 Mvar	< 300 km
150	–	2	–	–	–
225	2	4.5	3.3	2x80 Mvar	80 km
400	6.3	11.3	8.8	2x125 Mvar	50 km

Possible lengths for Cable equipped at both ends with devices dedicated to 60% shunt compensation

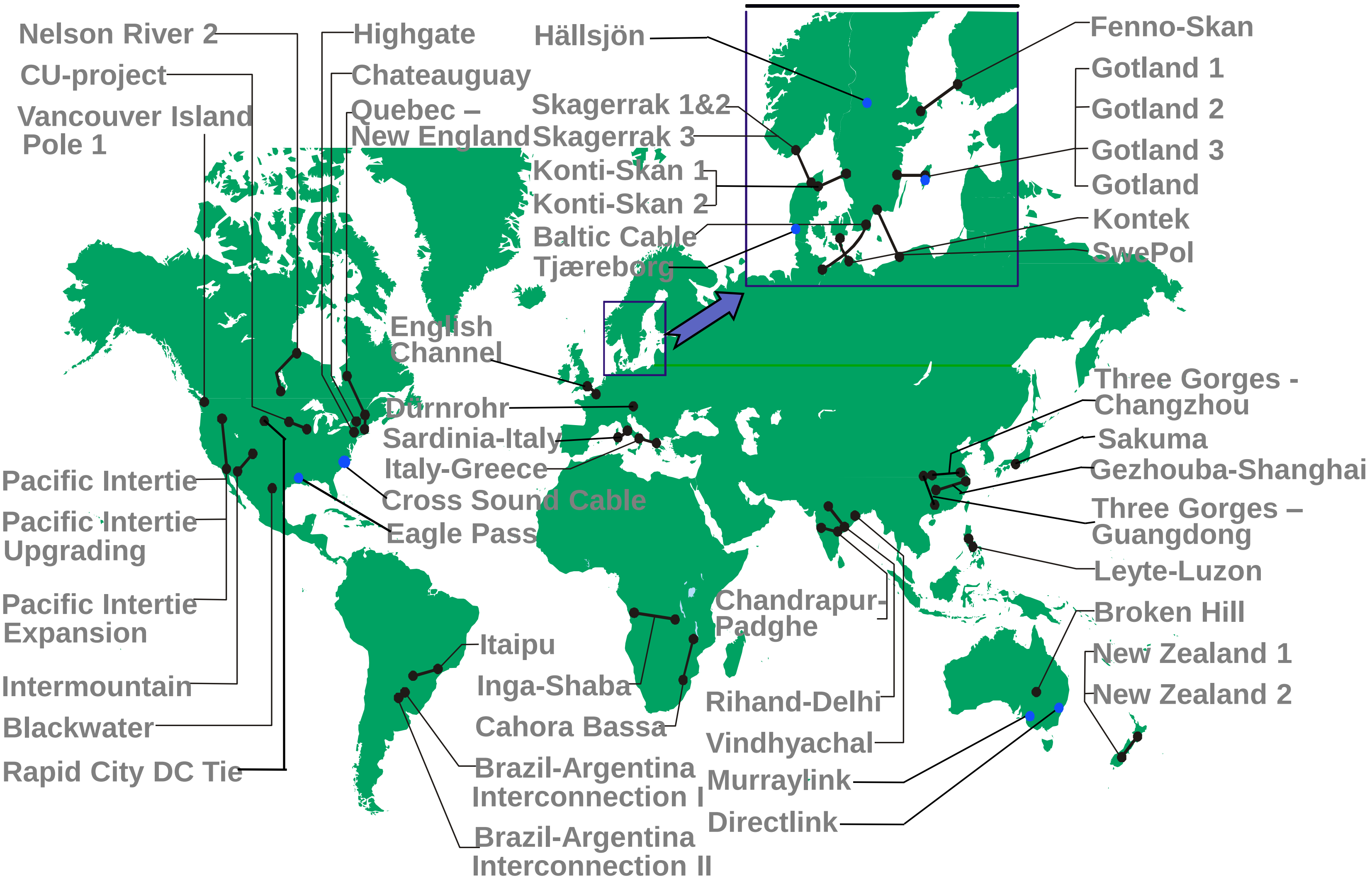




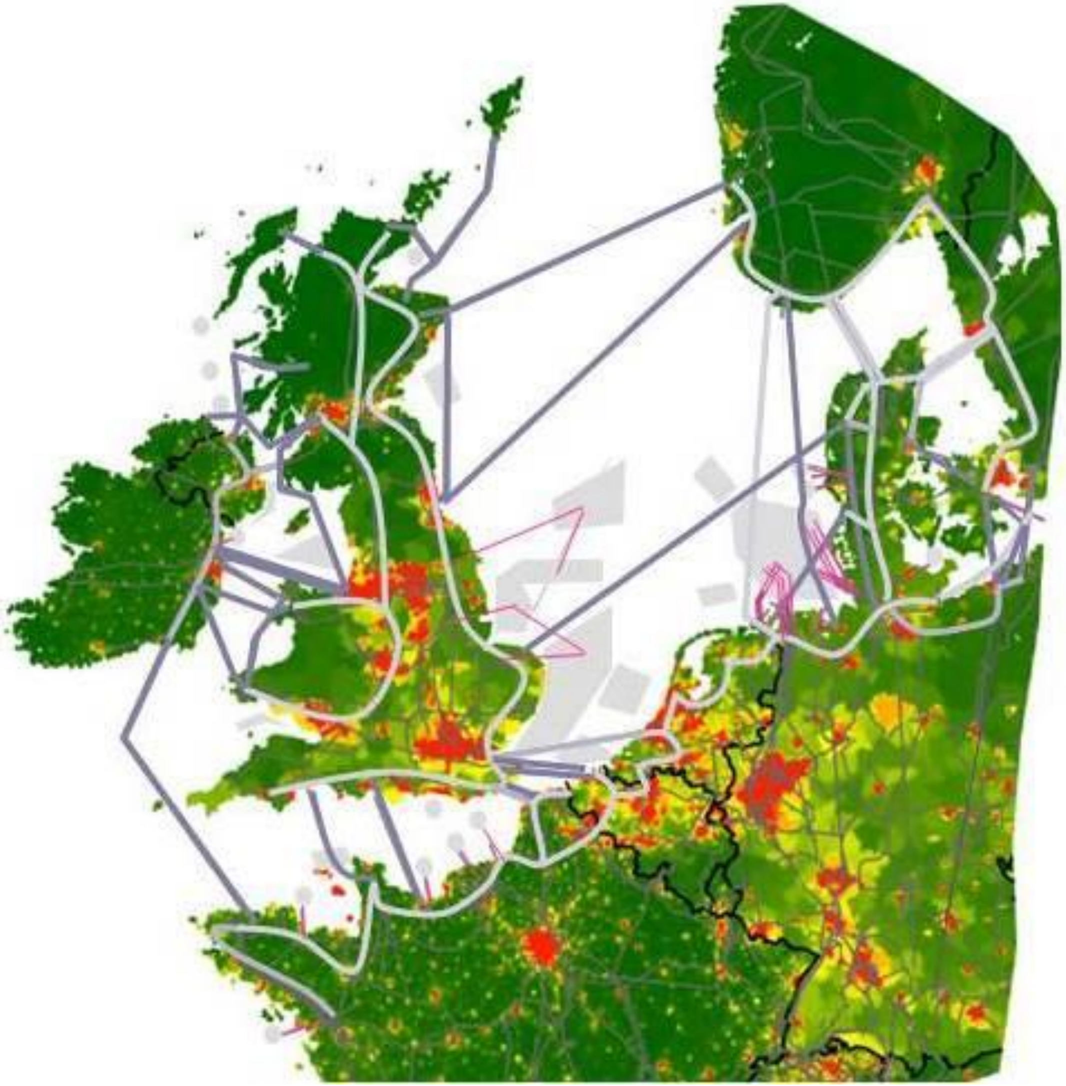
Cost orders of magnitude

	Power	Total costs	Cost by converter	Cost cable Incl. works
France-Espagne (67 km)	2 x 1000 MW	700 M€	150 M€	1,9 M€/km (excl. tunnel)
Savoie-Piémont (95 km France)	2 x 600 MW	460 M€ (France)	140 M€	3 M€/km (France)
IFA2 (240 km)	1000 MW	670 M€	100 M€	0,9 M€/km
Midi-Provence (220 km)	1000 MW	500 M€	100 M€	1 M€/km

A world-wide used technology



Booming in North-West Europe (2030)



Line Commutated Current sourced converters

Converting stations using Graëtz bridge thanks to thyristors

Voltage Source Converters

Converting stations using IGBT
(*Insulated Gate Bipolar Transistor*)

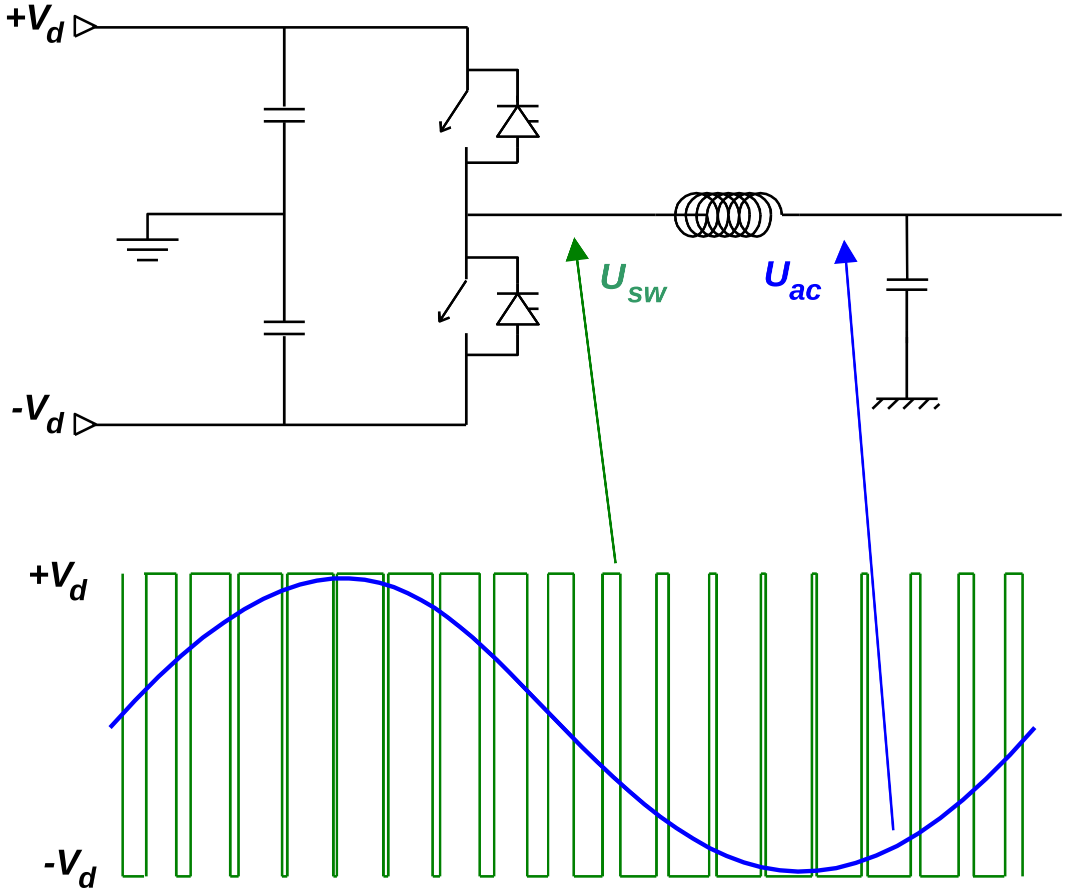
3300 V / 1200 A Mitsubishi

Comparison LCC vs. VSC

	LCC	VSC
Semi conductor	Thyristors "natural" commutation	IGBT forced commutation
Equivalent	Current Source	Voltage Source
Power reversal	By polarity reversal of the DC voltage	Reversal of the flowing current direction
Line or Cable	Overhead lines or mass-impregnated cables or oil filled cables	OHL or XLPE cables – cost effective and environmentally friendly
Reactive power	Absorbs Q (~0,6 P)	Supplies/Absorbs an adjustable Q
AC grid sensitivity	LCC is subject to AC sags and can cause AC swells	Lesser sensitivity to AC sags
DC faults clearing	Quick clearing without breakers	Low clearing due to AC breakers operation

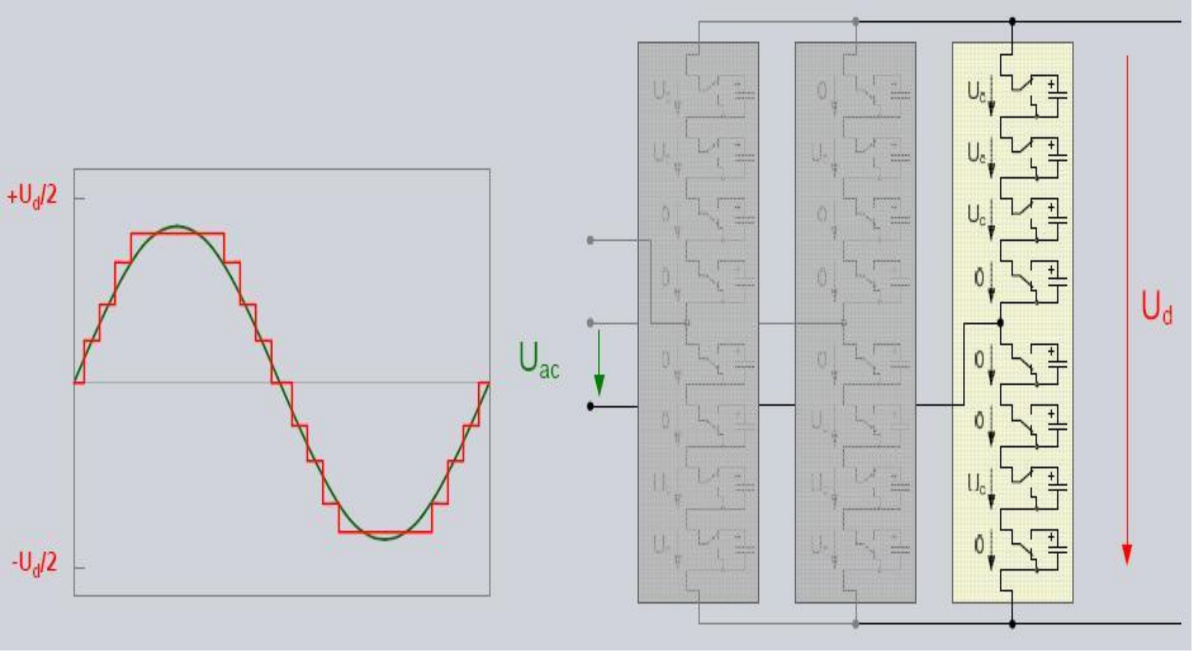
VSC / Pulse Width Modulation (PWM)

High frequency Commutation (1 – 2kHz)



VSC / Modular Multi-level Converter (MMC)

Series connection of hundreds of modules independently controlled to build an ideally sine voltage wave



Major functionalities for TSO

Current

Power inversion flexibility

Voltage

U or Q control for each converting station, independent from P

Stability

Good dynamic and possibility for damping

Separate network

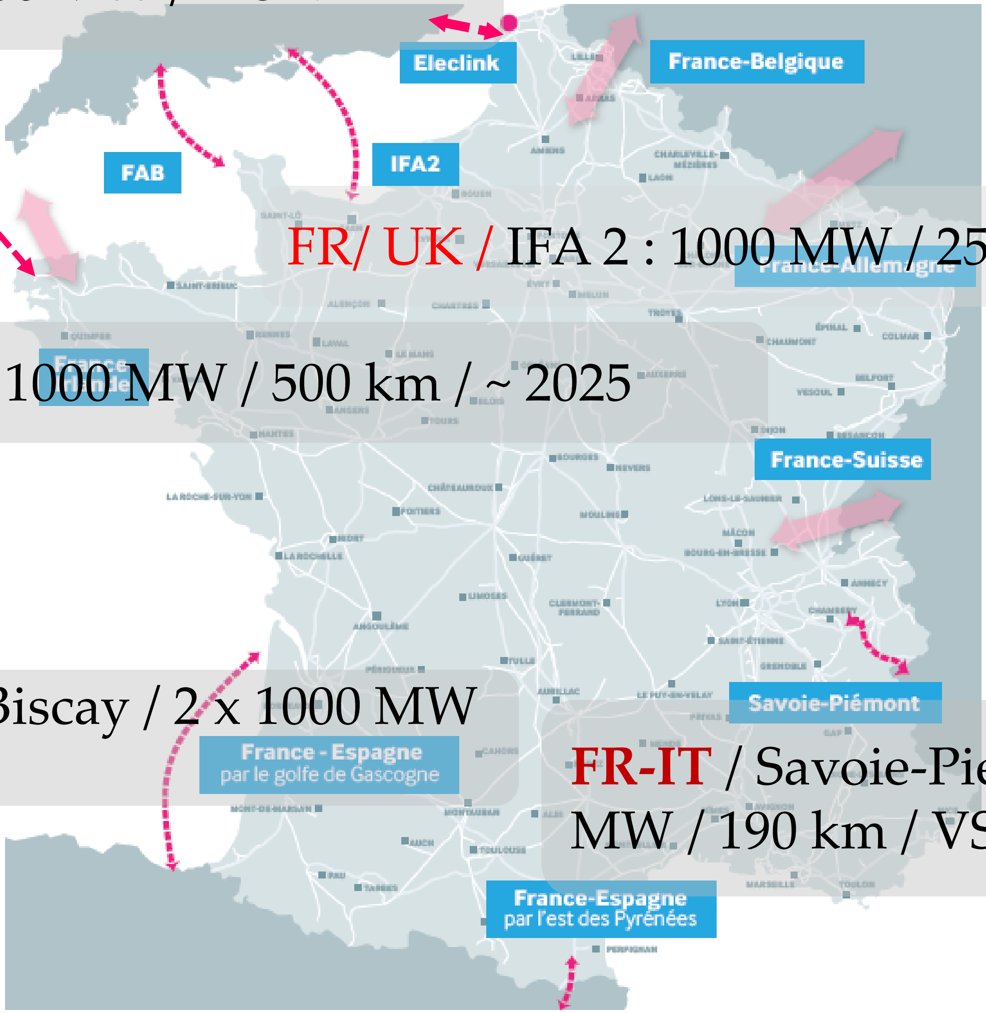
Black-start

Frequency control for a separate network

Key interconnection projects

FR-UK / FAB 1400 MW / 225 km

FR-UK / ElecLink 1000 MW / 50 km



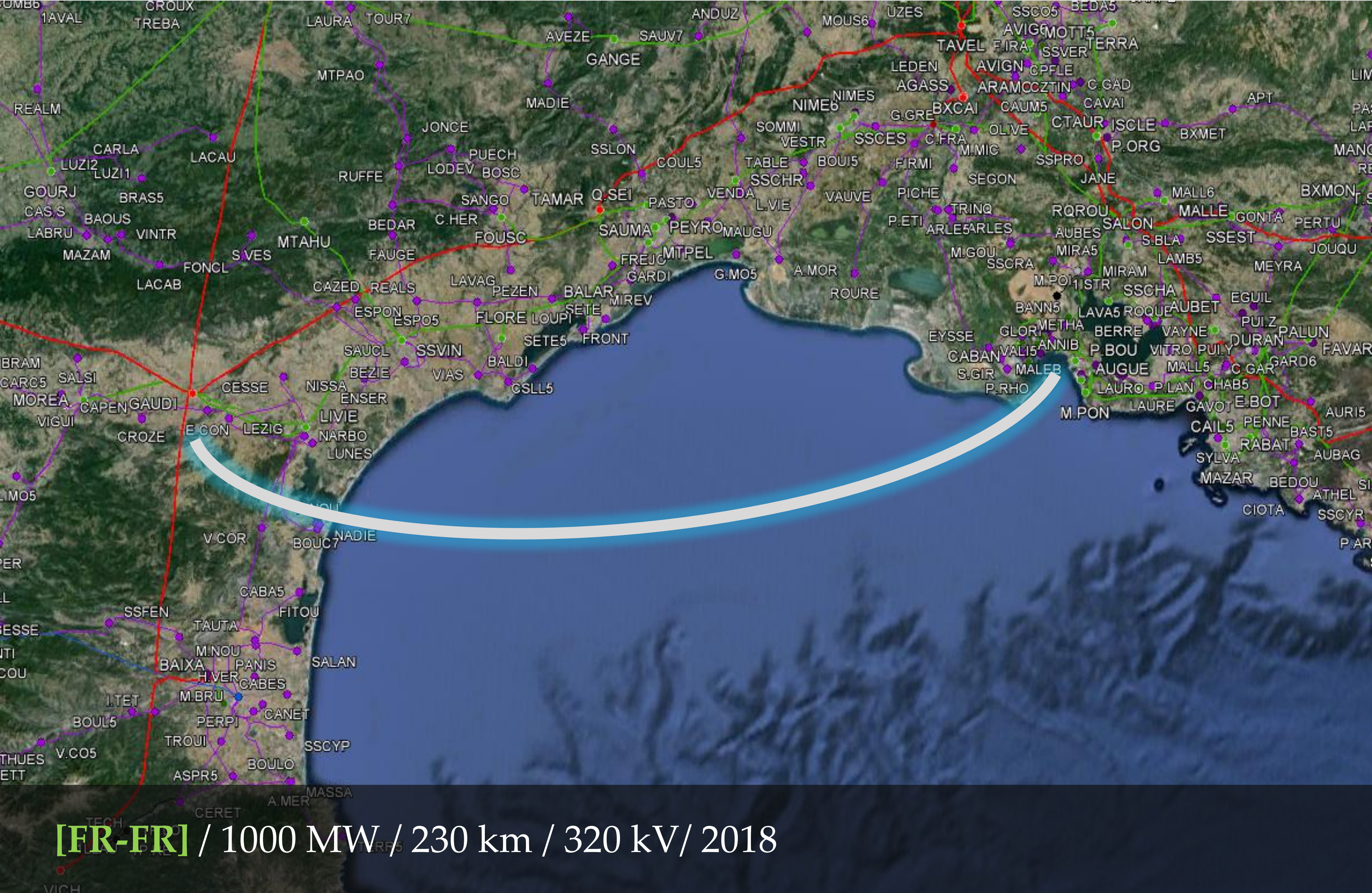
FR/ UK / IFA 2 : 1000 MW / 250 km / ~ 2020

FR-IRL/ Celtic : 1000 MW / 500 km / ~ 2025

FR-ES / Bay of Biscay / 2 x 1000 MW / 360 km

FR-IT / Savoie-Piemonte / 2x600 MW / 190 km / VSC / 2019

Midi-Provence

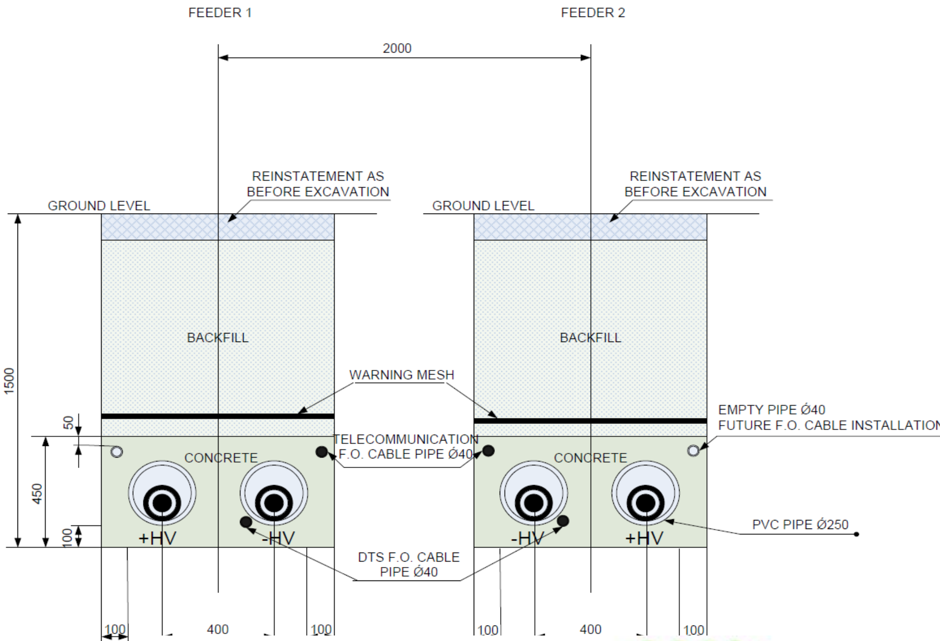


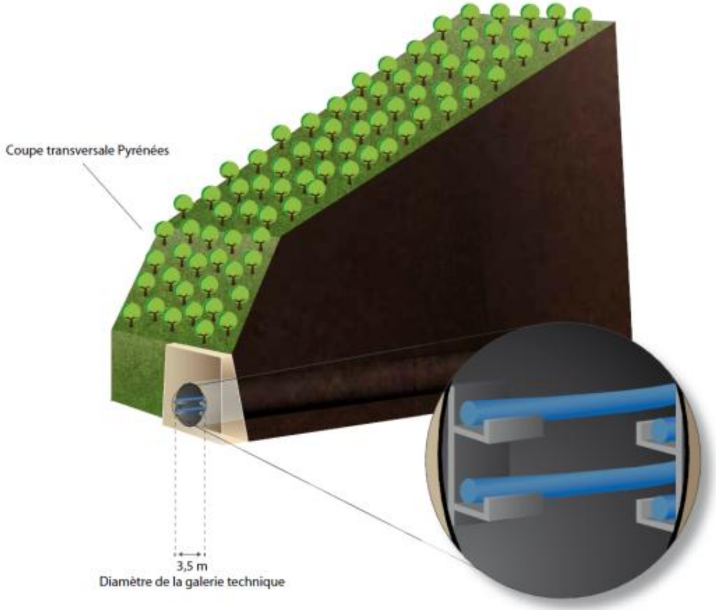
[FR-FR] / 1000 MW / 230 km / 320 kV/ 2018

3

INELFE EXAMPLE

INELFE cable description





Route of the DC link

Underground connection between the BAIXAS substation (in Perpignan, France) and SANTA LLOGAIA (Figueras, Spain), following the motorway and high-speed train line

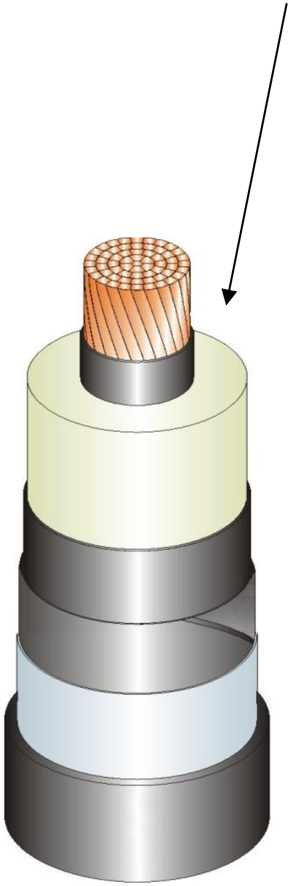
Length = 65km

VSC/MMC technology

2,000 MW (2 x 1,000 MW) / ±320kV

XLPE cables / 2500mm^2

Tunnel length = 8.5km



XLPE insulation

Tunnel


inelfe
Interconnexion électrique France-Espagne
Interconnexió elèctrica França-Espanya
HVDC tunnel
DRAGADOS
EIFFAGE TP

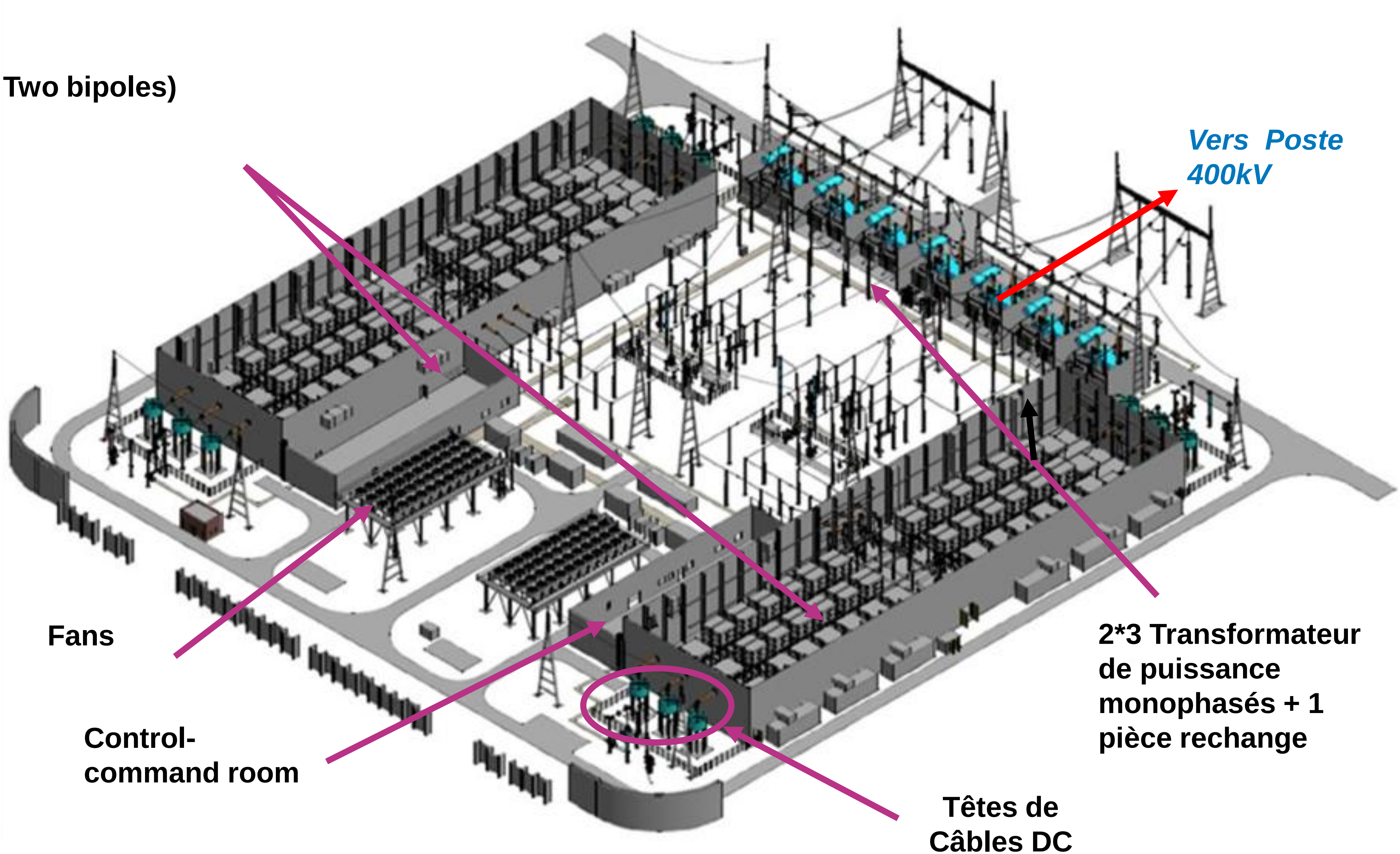
Converter station in France

Converter station in France

The converter stations

Two independant symmetrical single pole VSC (2x1000MW)

VSC Siemens



Two bipoles)

Vers Poste 400kV

Fans

Control-command room

2*3 Transformateur de puissance monophasés + 1 pièce rechange

Têtes de Câbles DC

4

HVDC INTEGRATION >>> ISSUES TO BE ADDRESSED

4 stages of increasing complexity

Stage 1 (in the past)

Only one HVDC link between 2 asynchronous networks…

FR-GB HVDC link until 2011

… or inside 1 synchronous network but with a huge electrical distance between the 2 converters

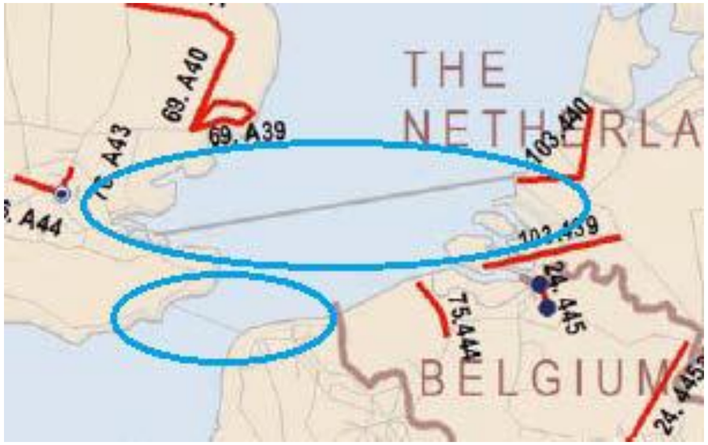
Italy-Greece HVDC link since 2001

Stage 2 (recent years)

Several HVDC links in parallel between 2 asynchronous networks

HVDC links between Norway and continental synchronous zone

FR-GB HVDC link + BritNed since April 2011



4 stages of increasing complexity

Stage 3 (now)

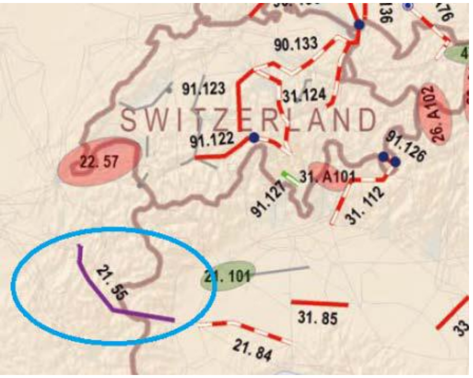
HVDC links embedded in a meshed AC network
Inside stage 3, there are also several stages of increasing complexity:

- one HVDC link embedded in a meshed AC network and influencing 2 countries

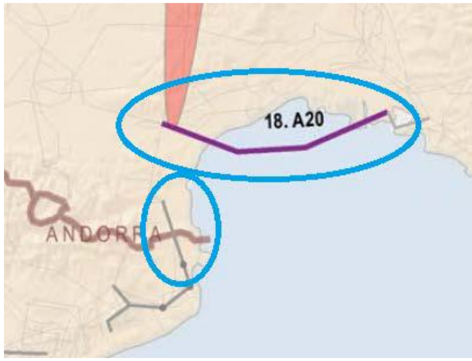
  France-Spain HVDC link (2015)

- one HVDC link embedded in a meshed AC network and influencing more than 2 countries

  France-Italy HVDC link (2019)



- two HVDC links embedded in a meshed AC network and electrically close to each other
  Midi-Provence HVDC link



Stage 4 (to be designed)

HVDC grids

Operation of embedded HVDC: opportunities

HVDC technology offers many new opportunities to operate the system. How to make the most of them?

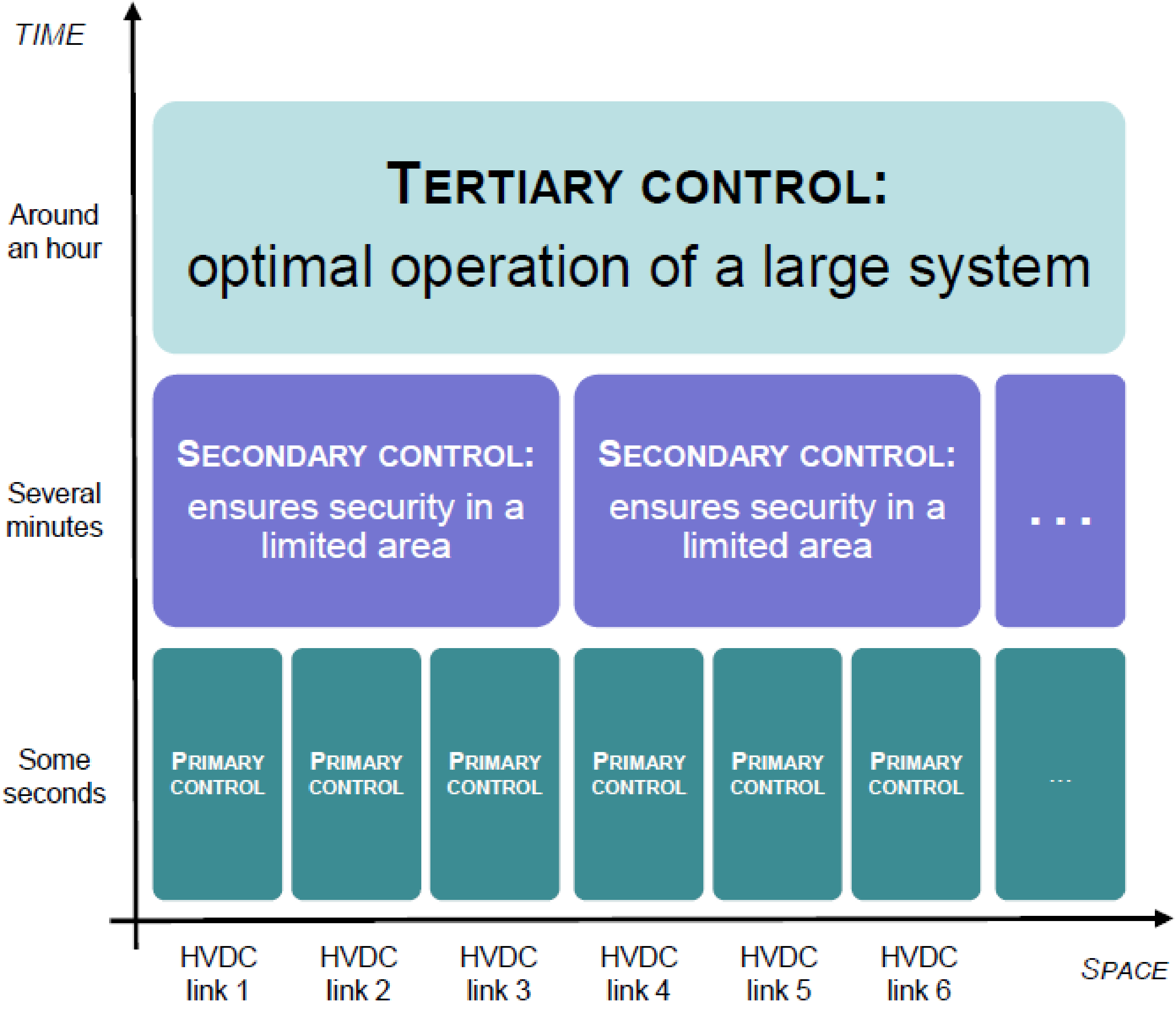
- Fast power reversal
- Injection of reactive current during faults
- Settable active power flow
- AC voltage control
- Supply of passive networks
- Independent control of active and reactive power
- Black-start capability
- Damping of electromechanical oscillations
- Frequency control

Embedded SVC HVDC: more opportunities and... complexity

- May improve AC flows controllability
- Requires much more complex assessment in operational planning, e.g. cross-border capacity calculation
- Sophisticated coordination required when neighboring converters of several HVDC links

Active power management of embedded HVDC links

Towards a hierarchy of controls for HVDC links?



TIME

Around an hour

Several minutes

Some seconds

TERTIARY CONTROL:
optimal operation of a large system

SECONDARY CONTROL:
ensures security in a limited area

SECONDARY CONTROL:
ensures security in a limited area

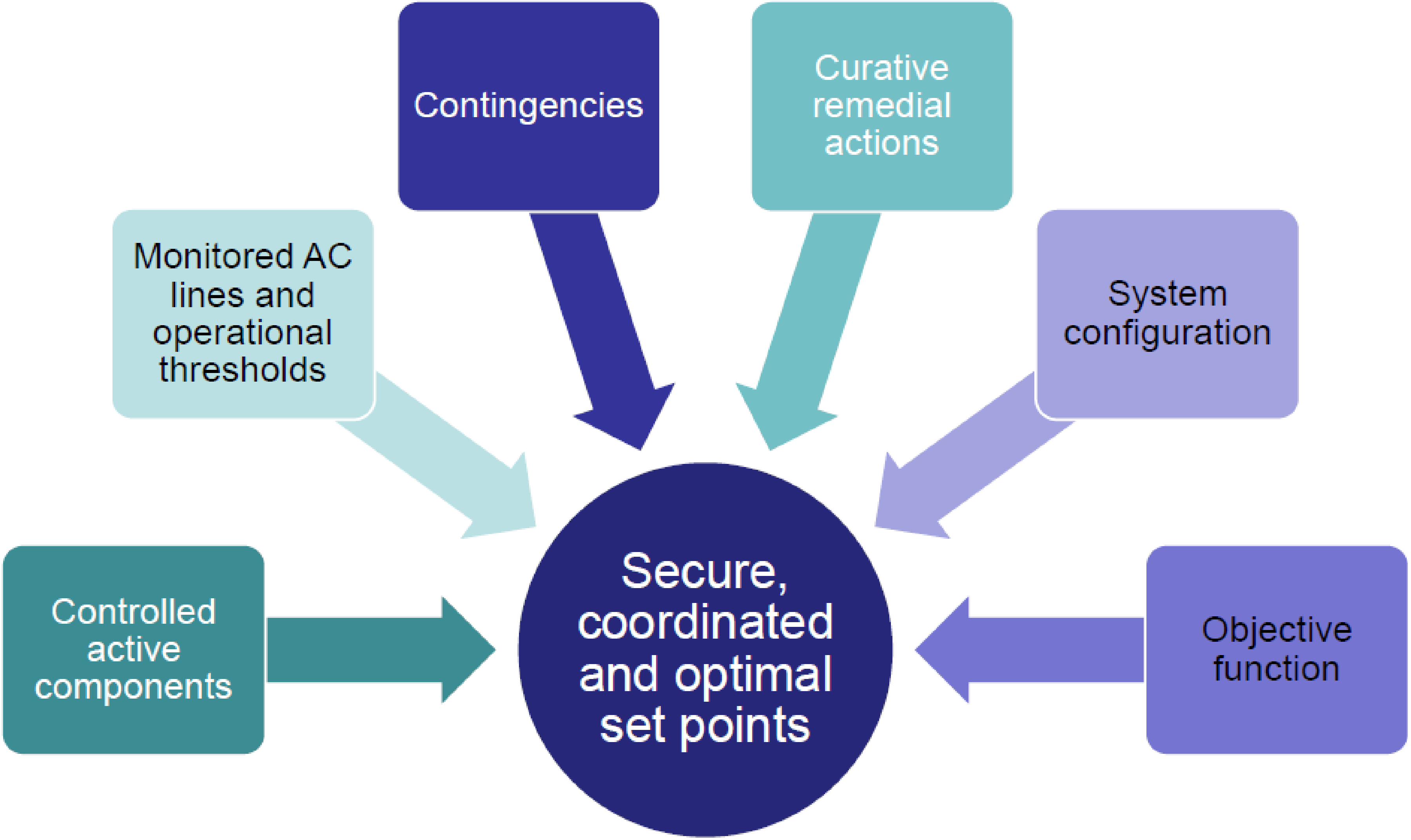
. . .

PRIMARY CONTROL	PRIMARY CONTROL	PRIMARY CONTROL	PRIMARY CONTROL	PRIMARY CONTROL	PRIMARY CONTROL	...
HVDC link 1	HVDC link 2	HVDC link 3	HVDC link 4	HVDC link 5	HVDC link 6	

SPACE

Active power management of embedded HVDC links

Tertiary control – Optimal operation of a large system



Contingencies

Curative remedial actions

Monitored AC lines and operational thresholds

System configuration

Controlled active components

Secure, coordinated and optimal set points

Objective function

A nice mixed integer linear optimization problem (MILP)!

FR-ES link example

The secondary control could monitor:

- the AC interconnection lines
- the supplying and evacuation lines of the HVDC link

The tertiary control could enable the operators to:

- coordinate the set point of the HVDC link with the tap of Phase Shifters
- calculate the admissible range of the HVDC power set point
- or even maximize security margins on AC interconnection lines

Another solution

AC emulation

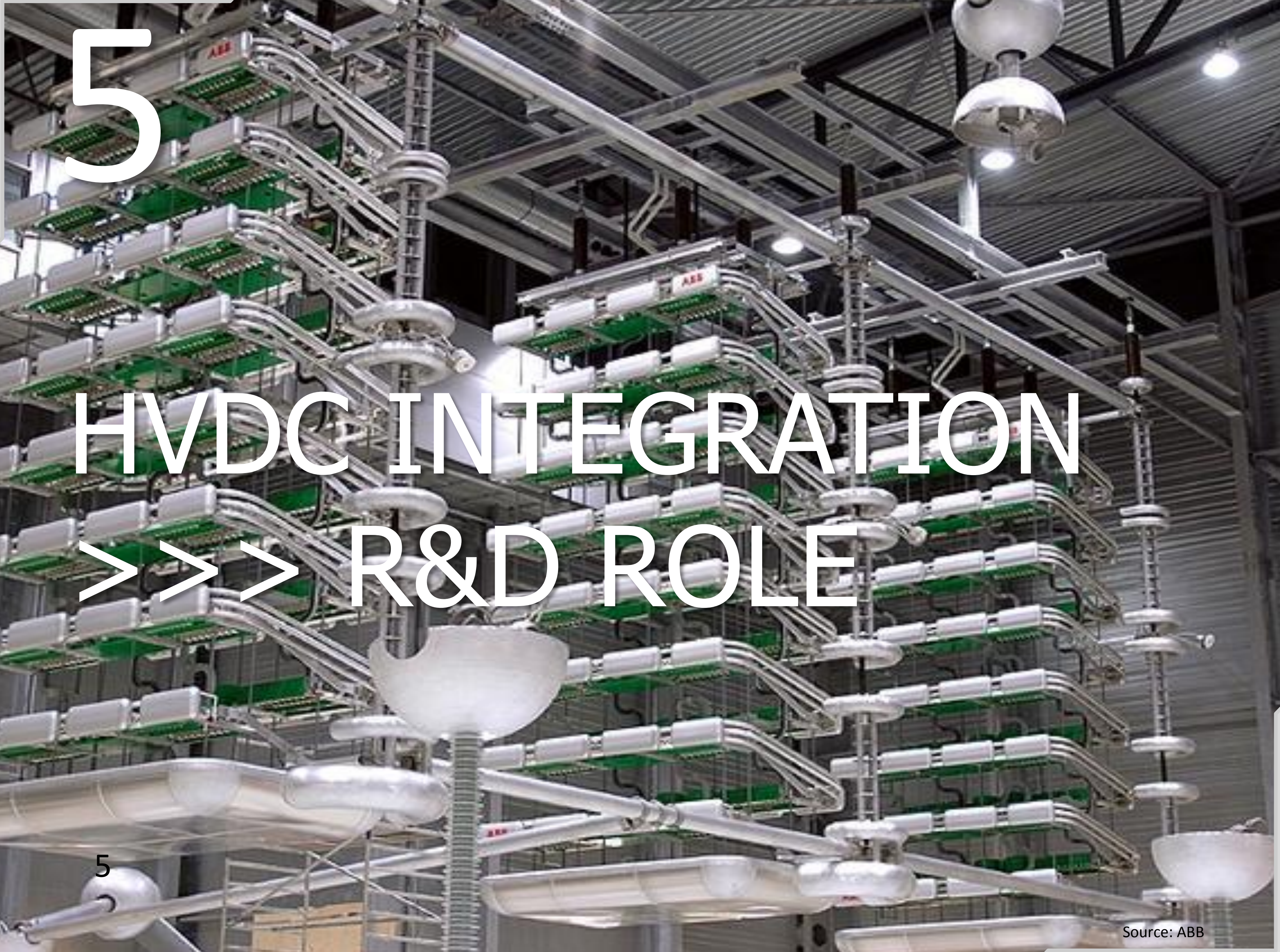
$$P_{HVDC} = P_0 + K * (\delta_{BAIXAS} - \delta_{StLlog})$$

Further development needed…

Coordination will be essential when several HVDC links, possibly interacting with each other or with other active components, will be embedded into meshed AC networks

Innovative control necessary for a more global coordination of HVDC links that will offer more flexibility to the power system

Operation of embedded HVDC links is only beginning. Other challenges will have to be met as embedded HVDC links are commissioned



5

HVDC INTEGRATION >>> R&D ROLE

Source: ABB

SIMULATION

Dynamic tools for off-line simulation

Voltage Stability

Take into account tap changers and slow controllers

Valid at 50Hz

Modeling of French or European grid

Ex : ASTRE

Transient Stability

+ AVR + speed regulators

Valid at 50 Hz

Modeling of French or European grid

Ex : EUROSTAG, PSS/E, DIgSILENT

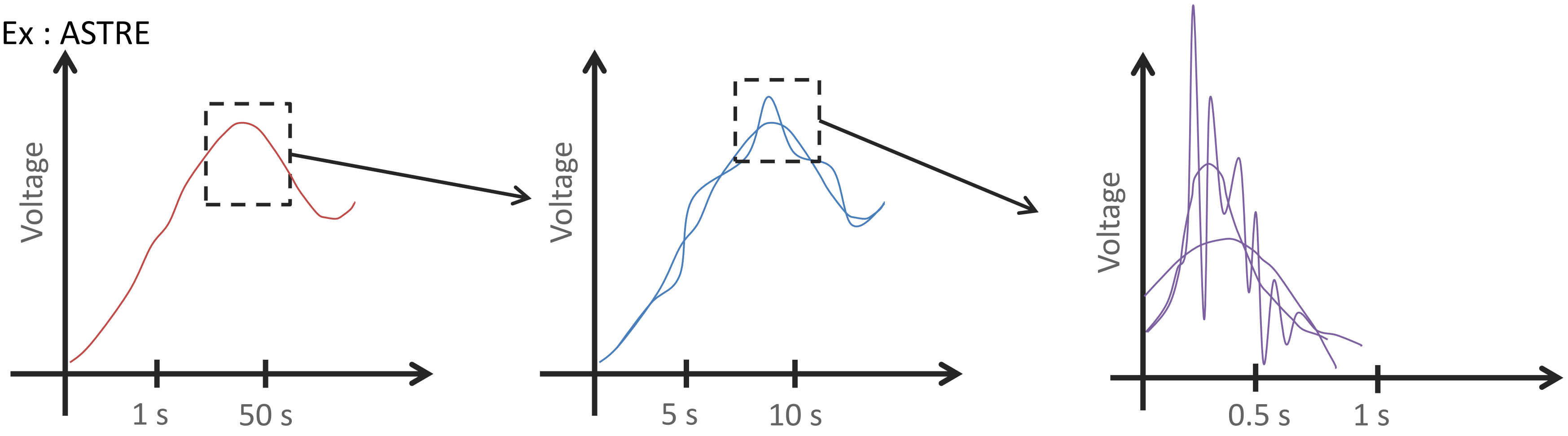
Electromagnetic Transients

+ electromagnetic nature of equipment

Valid over a broad range of frequencies (depends on models)

Modeling of several substations

Ex : EMTP-RV, PSCAD, ATP



"Phasor domain" type of tools

"EMT" type of tools

Difficulties with off-line simulations

Issues related to power electronic based equipment

Dynamic performances depend on complex control systems which are very difficult to model:

- algorithms running on multiple cores with several time steps
- proprietary algorithms → confidentiality issues
- excessive computing times on standard CPU

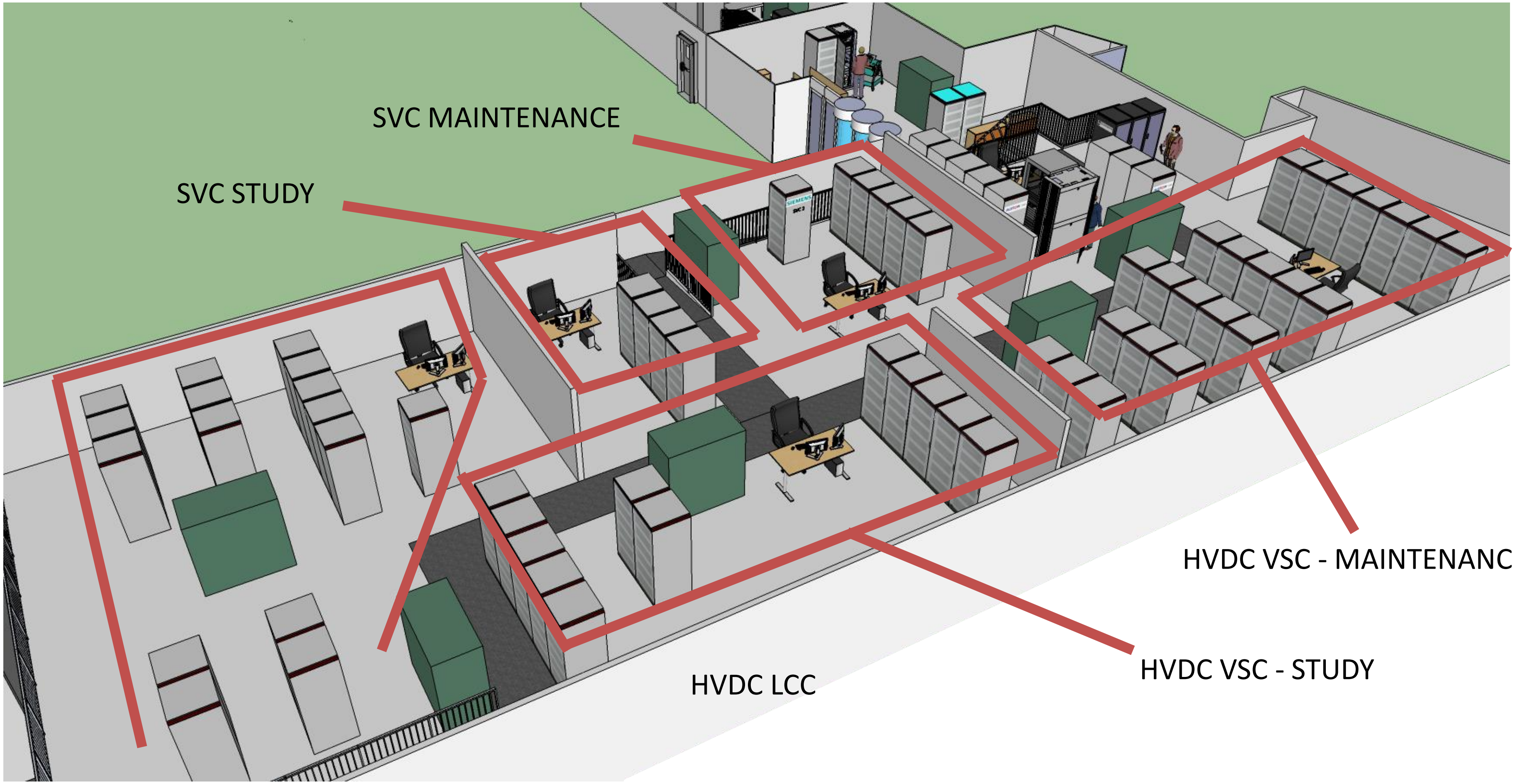
→ Need to use replicas of the real control system

Control System Replica

Hypersim Simulator

Real-time simulation platform at RTE for HVDC & FACTS studies created in 2012, it houses currently 5 SVC replicas

RTE real-time simulation laboratory



DC CIRCUIT BREAKER

The DC high power circuit breaker: a bottleneck

Key component of meshed grid for offshore wind farms

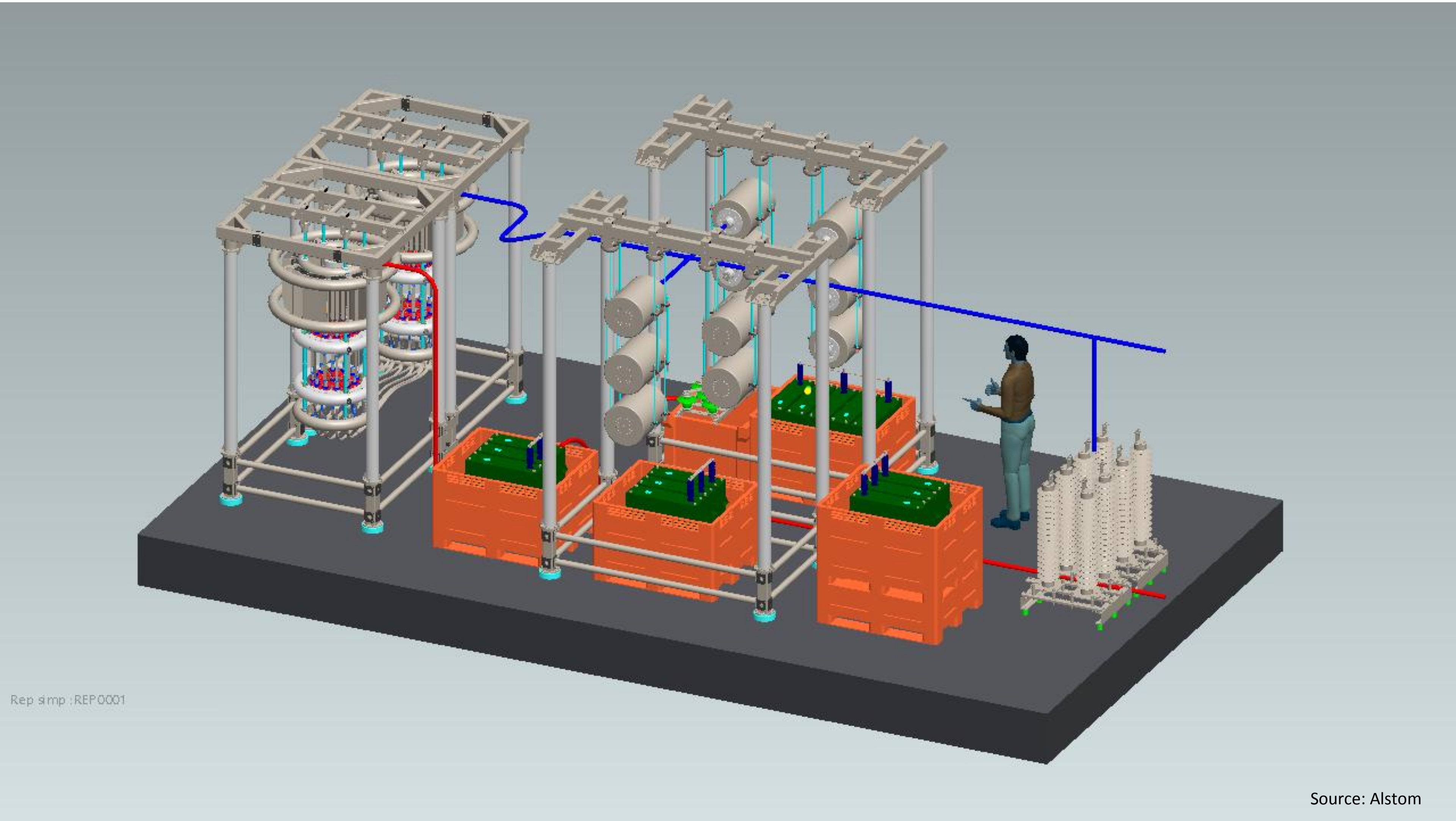
Target:

320 kV DC in 2018

Today:

5273 A / 160 kV / 5,3 ms / 1,2 MJ

Alstom DC circuit-breaker



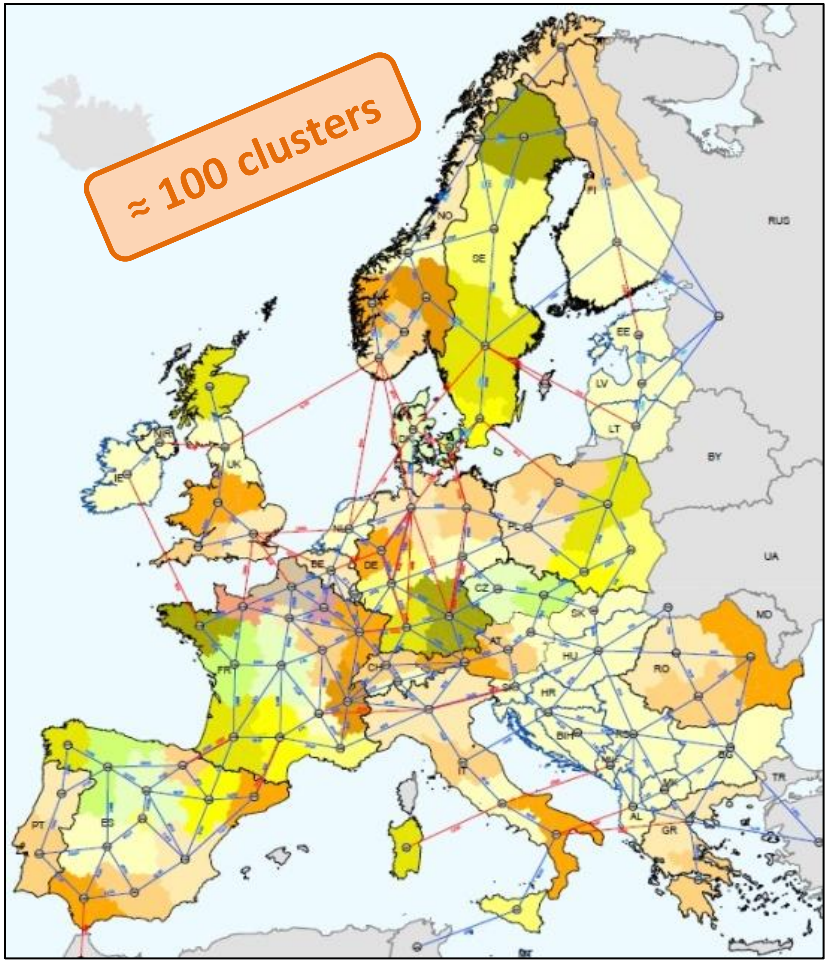
Source: Alstom

E-HIGHWAY 2050 PROJECT

e-Highway2050 project

"Planning for European Electricity Highways to ensure the reliable delivery of renewable electricity and Pan-European market integration"

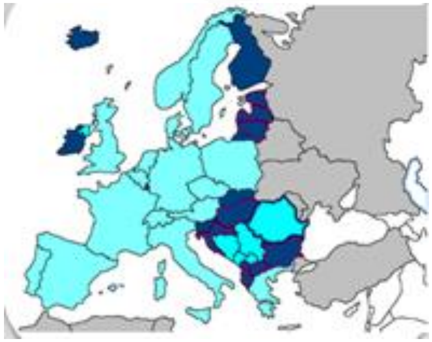
Goal: to develop methods and tools to support supergrid planning, based on future power system scenarios, with options for a pan-European grid planning between now and 2050, taking into account benefits, costs and risks



Clusterization of the pan-European system

e-Highway2050 partnership

28 partners coordinated by RTE



🟦 28 Direct Partners

amprion
Brunel UNIVERSITY LONDON
čeps, a.s.
Collingwood Environmental Planning
Universidad Pontificia ICAI ICADE COMILLAS MADRID
dena

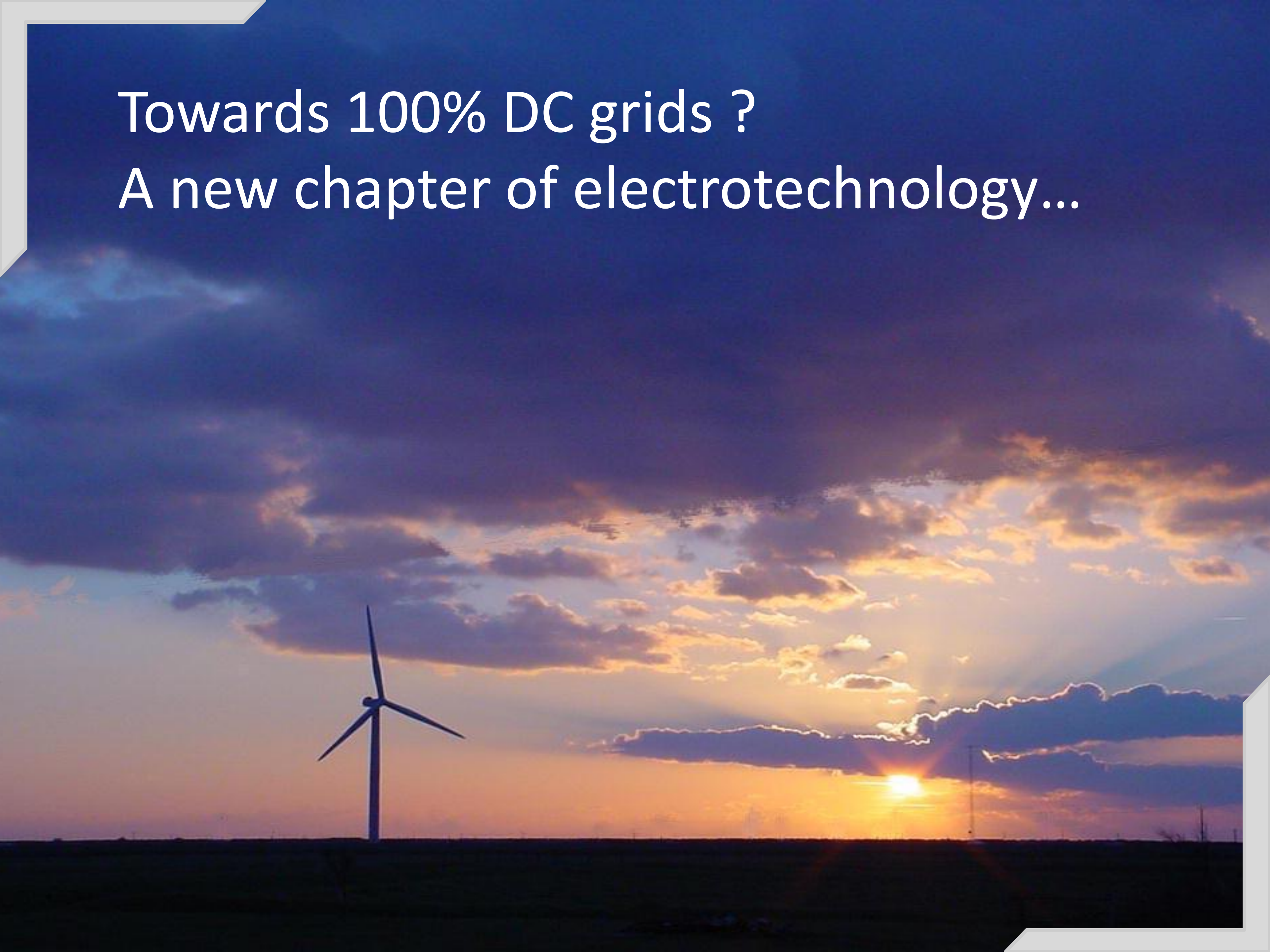
E3G
ECN
elia group
ensiel ENERGIA E SISTEMI ELETTRICI
entsoe Reliable Sustainable Connected
eurelectric ELECTRICITY FOR EUROPE

europacable
EWEA THE EUROPEAN WIND ENERGY ASSOCIATION
IEN
KU LEUVEN
PÖYRY

PSE Operator S.A.
REN
RSE Ricerca Sistema Energetico
Rte Réseau de transport d'électricité
SINTEF

swissgrid
T&D europe
TÉCNICO LISBOA
TECHNOFI
Terna
TU berlin

Towards 100% DC grids ?
A new chapter of electrotechnology…



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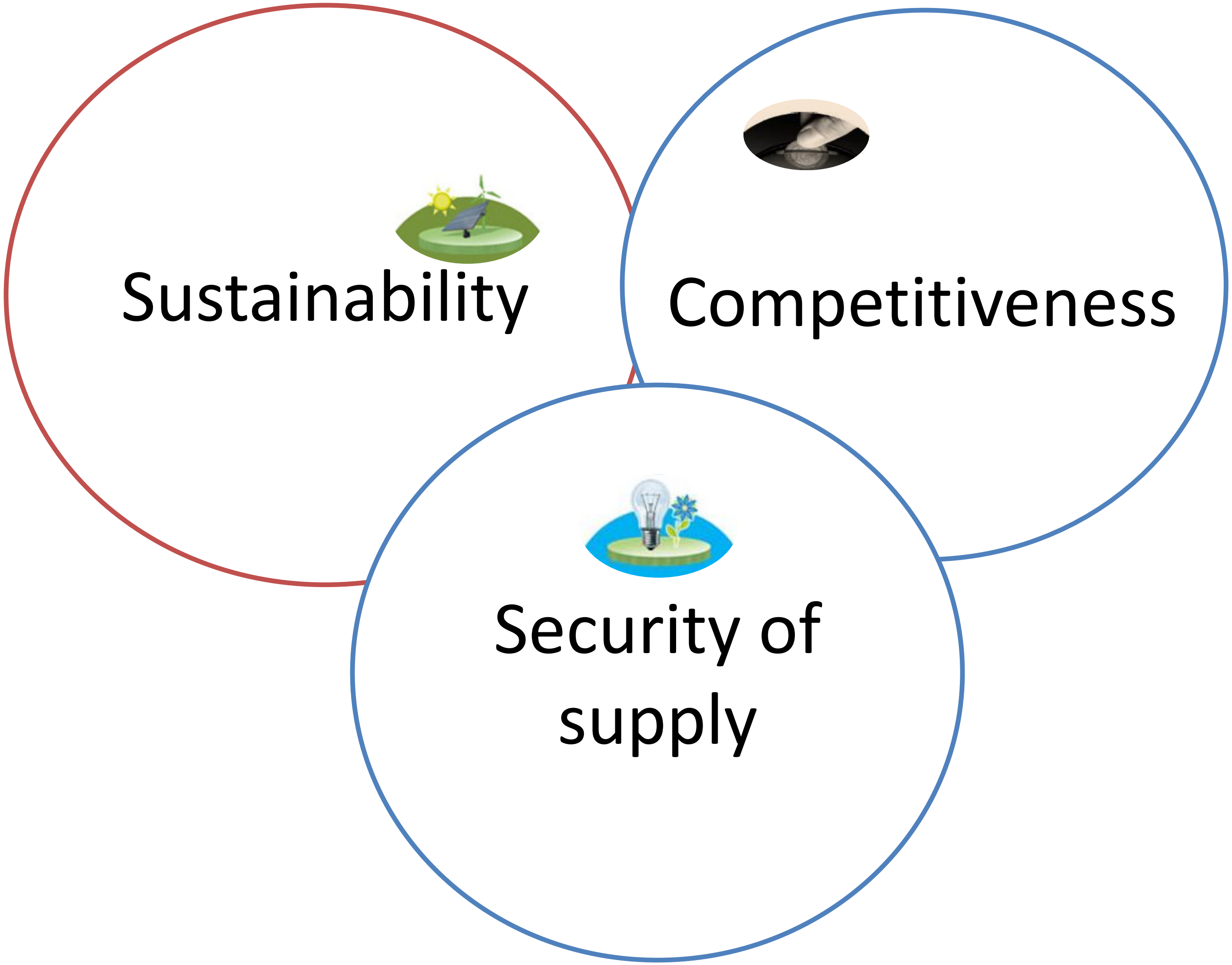
CONCLUSION

In order to ensure...



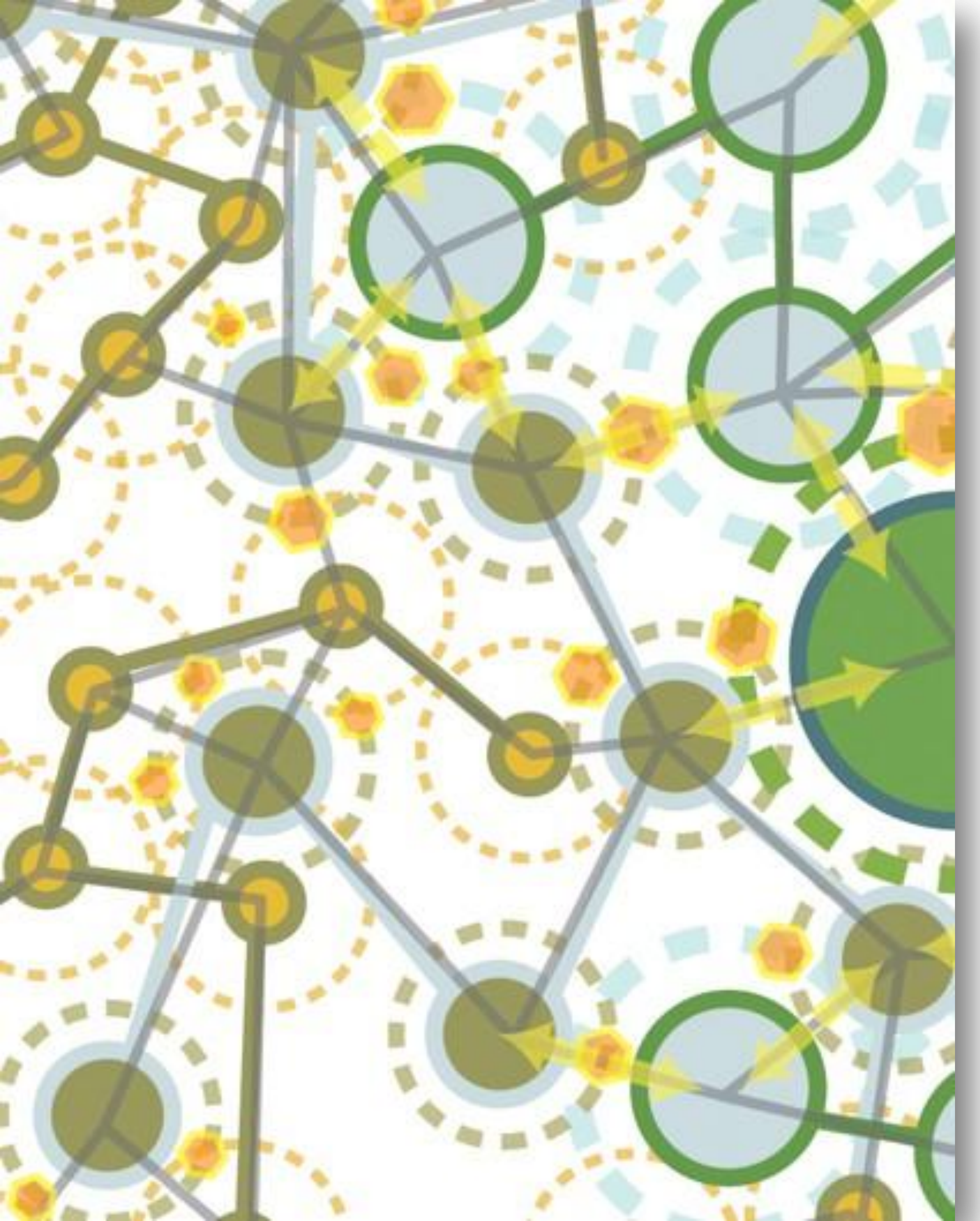
Sustainability

Competitiveness

Security of supply

… we need:

- A real thrust in infrastructure development
- A market redesign
- More R&D and innovation



Thank you for your attention