2019IDSSMITEI

Decision Support Models for Low-Carbon Electric Power Systems

Transmission Expansion Planning in Practice

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Transmission Expansion Planning (TEP)

- The **intermittent** nature of the output of most renewable energy sources (RES), its **non homogeneous distribution** and the deployment of a large share of this generation is expected to result in a significant **increase in the power flows among areas in large-scale systems**.
- As a result of this, the development of the network of the system should be planned in an integrated way and the number of **operation snapshots** to consider in the planning process should probably be high.
- **In this context,** it is important to identify the **main optimal transmission network corridors to reinforce**, the extent of reinforcements needed in them, and other operation variables affected by the existence of the grid:
  - Investment cost of grid additions
  - Fuel production costs
  - Production by technology
  - Network losses
  - RES curtailment
  - CO_2 emissions

Why coordination between generation and transmission expansion planning?

- Decisions are taken by independent entities
  - **Private generation** companies
  - **Publicly owned transmission** system operators

- With different time scopes
  - **Several years** for **generation investment**
  - A **decade** for **transmission investment**

Questions to address. Regarding coordination with generation expansion

- **What network reinforcements and how much investment** is required to integrate RES and emerging technologies (e.g., battery storage)?
- Is the network **neutral to the different RES** and emerging technologies used (CCS, CSP, Nuclear)? Which transmission network is needed for future generation storylines?
- How does the **decentralized or centralized location** of generation impact transmission network expansion (e.g., rooftop PV in Germany vs. large PV in Spain)?
- Does the network impact on the **location of the generation** (best spots), coordination between generation and transmission expansion?

Questions to address. Grid infrastructure/architecture options

- **How** the network should be developed (**AC vs. DC vs. supergrid**)?
  - Upgrade aerial lines, underground lines, submarine lines
  - Extensive use of FACTS
  - Reinforcements of high voltage 400 kV AC transmission network
  - Overlay at high voltage DC (HVDC) network
  - Overlay at ultra high voltage 750 kV AC (HVAC) network
- What is the impact of **new emerging network technologies** (PST, VSC, LCC) in the operation of the system?

Overlay at ultra high voltage 750 kV AC transmission network

Reinforcements of high voltage 400 kV AC transmission network

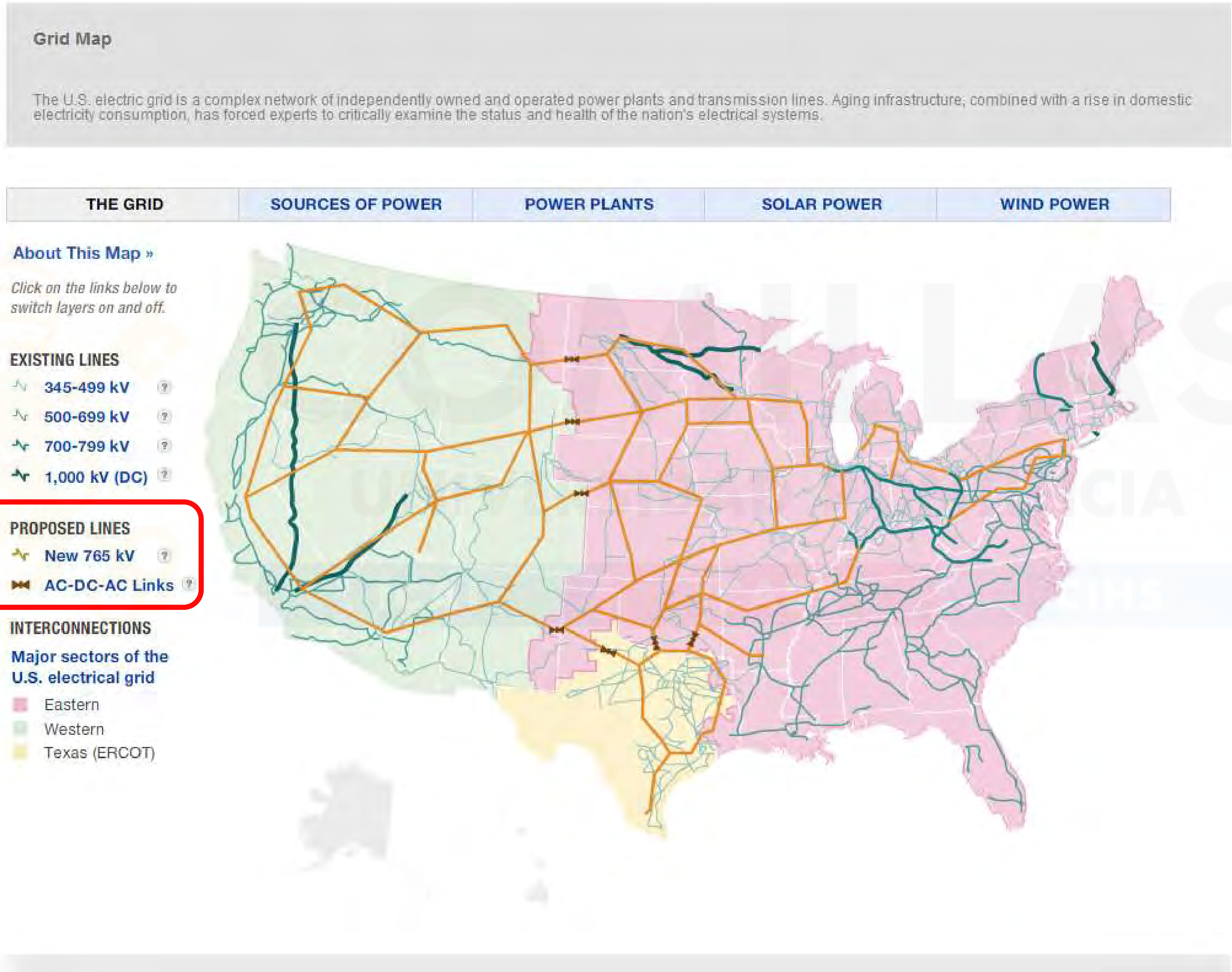
Overlay at high voltage DC transmission network

Extensive use of FACTS

Pan-European SuperGrid

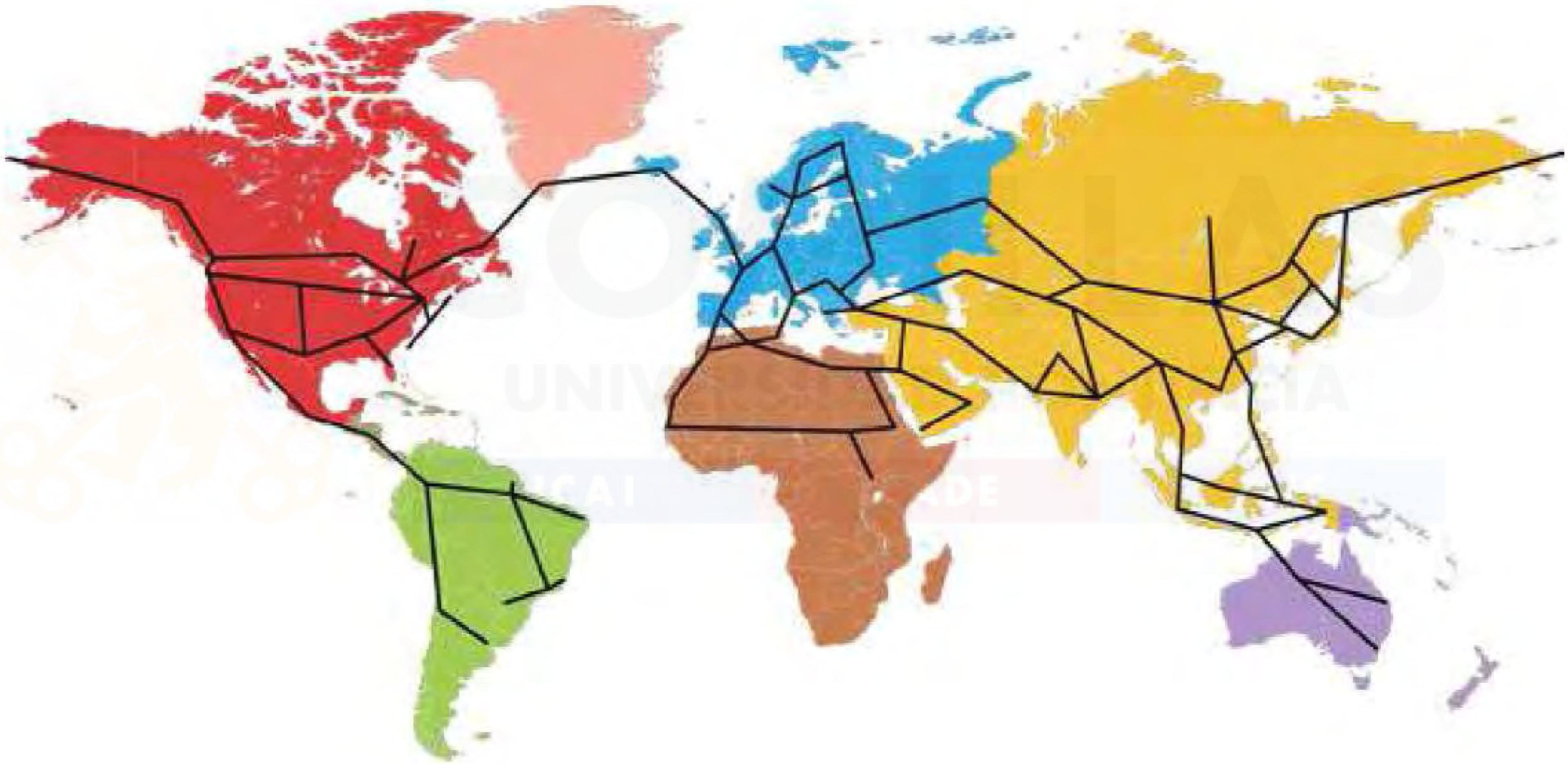
- Pan-European, inter-regional, cross-border projects
  - Project candidates: > 220 kV, > 500 MW of Network Transfer Capacity (NTC)
  - Project assessment based on clear indicators
- Transmission network that allows
  - Large-scale RES integration, decrease RES curtailment
    - North Sea wind generation + Norway/Alps hydro generation
    - South Europe/North Africa solar generation
  - Market integration

USA SuperGrid



First Steps to a Global SuperGrid

http://spectrum.ieee.org/energy/the-smarter-grid/lets-build-a-global-power-grid



Target electric systems

- Spain/Continental South West (CSW) Region (ES-FR-PT)
  - Nodes: 500
  - Existing Lines: 750
  - Candidate lines: 100
  - Scope: 10 years
  - Time periods: 100
- Europe
  - Nodes: 5000
  - Existing Lines: 7500
  - Candidate lines: 500
  - Scope: 1 year (static), 5 years (dynamic)
  - Time periods: 100

- Large-scale (Spanish) case can be currently solved but a very large-scale (European) case is not yet affordable

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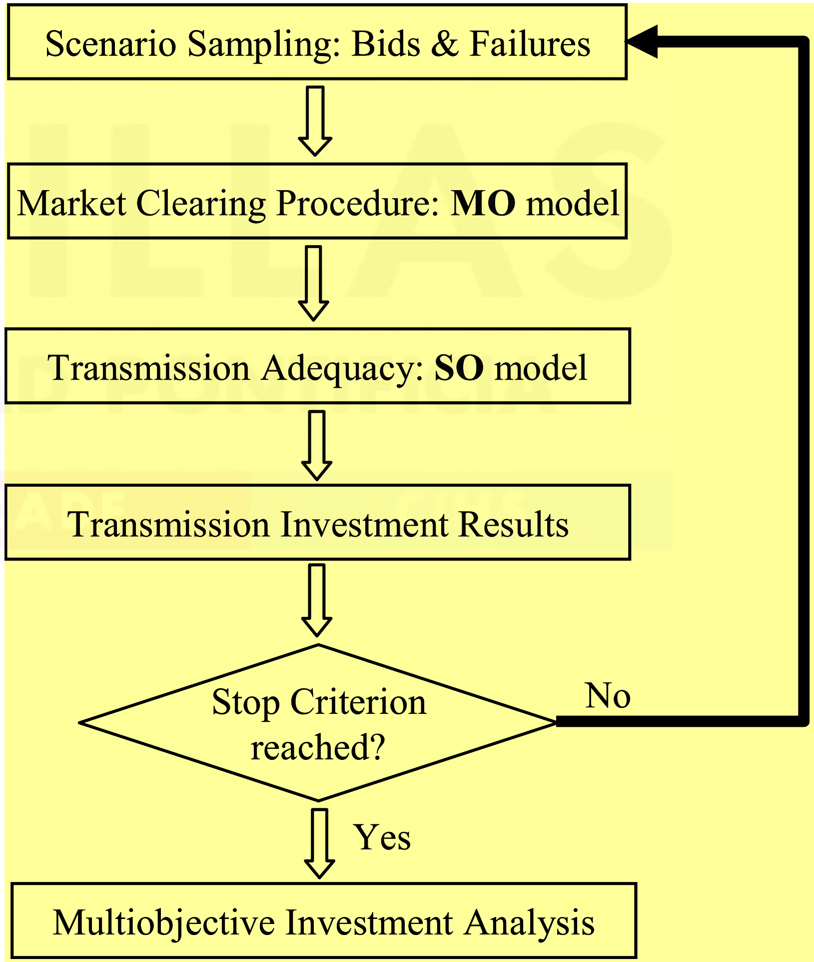
Some Real TEP Models

Comillas' experience on TEP models

- Short-term model
  - StarNet/RD developed by IIT for different companies in Dominican Republic (https://pascua.iit.comillas.edu/aramos/starnet.htm)
- Medium-term (operational) model
  - SIMUSIS/SIMUMER/SIMUPLUS developed by IIT for REE
- Long-term (tactical) models
  - PERLA (based on Benders decomposition) developed by IIT for REE
  - CHOPIN (based on heuristics) developed by IIT for REE
  - TEPES (based on Benders decomposition) (https://pascua.iit.comillas.edu/aramos/TEPES.htm)
- Very long-term (strategic) model
  - PLAER (trade-off analysis) developed by REE

SIMUPLUS (i)

- Operational transmission planning (medium term) (5-10 years)
- Determine incremental investment needs in transmission network in electricity markets
- Main assumption
  - Transmission expansion decisions shouldn't modify market clearing result
  - They must foster an effective competition within the power system



P. Sánchez-Martín, A. Ramos, J.F. Alonso *Probabilistic mid-term transmission planning in a liberalized market* IEEE Transactions on Power Systems 20 (4): 2135-2142 Nov 2005 10.1109/TPWRS.2005.856984

SIMUPLUS (ii)

1. Monte Carlo sampling
   - Demand bids and generation offers (market prices vs. variable costs)
   - Generation units and circuits availability (reliability assessment)
   - Hydro scheduling and wind/solar generation
2. Single node market clearing
   - Losses included as additional demand

   (Steps 1–2: Market Clearing)

3. Network constraint evaluation minimizing deviations w.r.t. market clearing
   - DC load flow, flow limits, ohmic losses
   - N-1 contingencies. Preventive or corrective dispatch

   (Step 3: Transmission Adequacy)

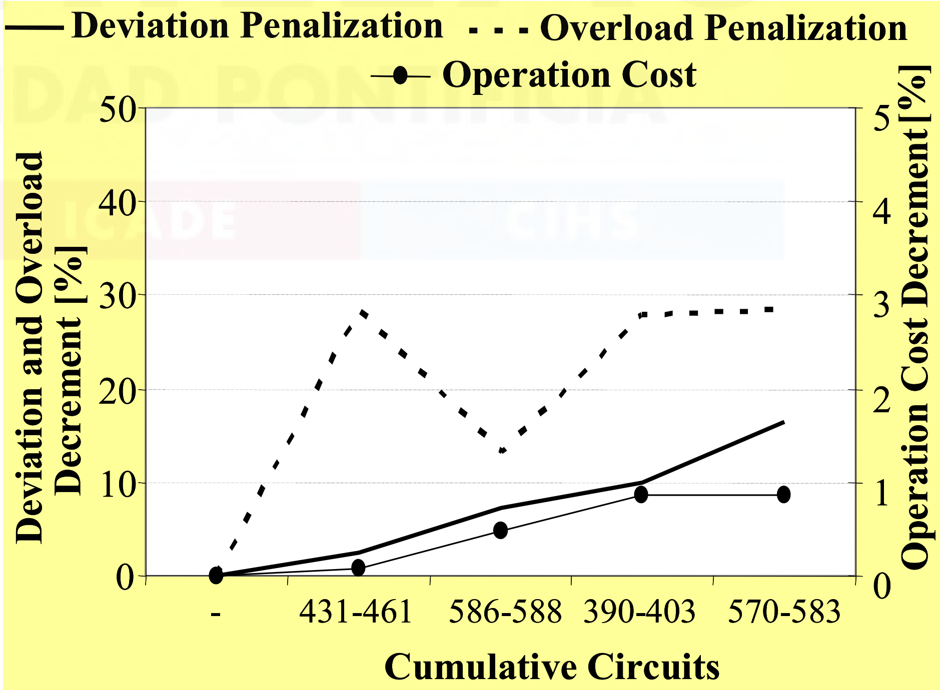
4. Determine sensitivities (derivative of the objective function w.r.t. investment)
   - Improvement in existing circuits
   - New circuit expansion
5. Multi-attribute investment analysis
   - Weigh sensitivities average, confidence interval, validity range, investment needs, environmental impact, etc.
   - Rank and select investment decisions
6. Repeat the process

SIMUPLUS (iii)

Spanish Iterative Investment Ranking

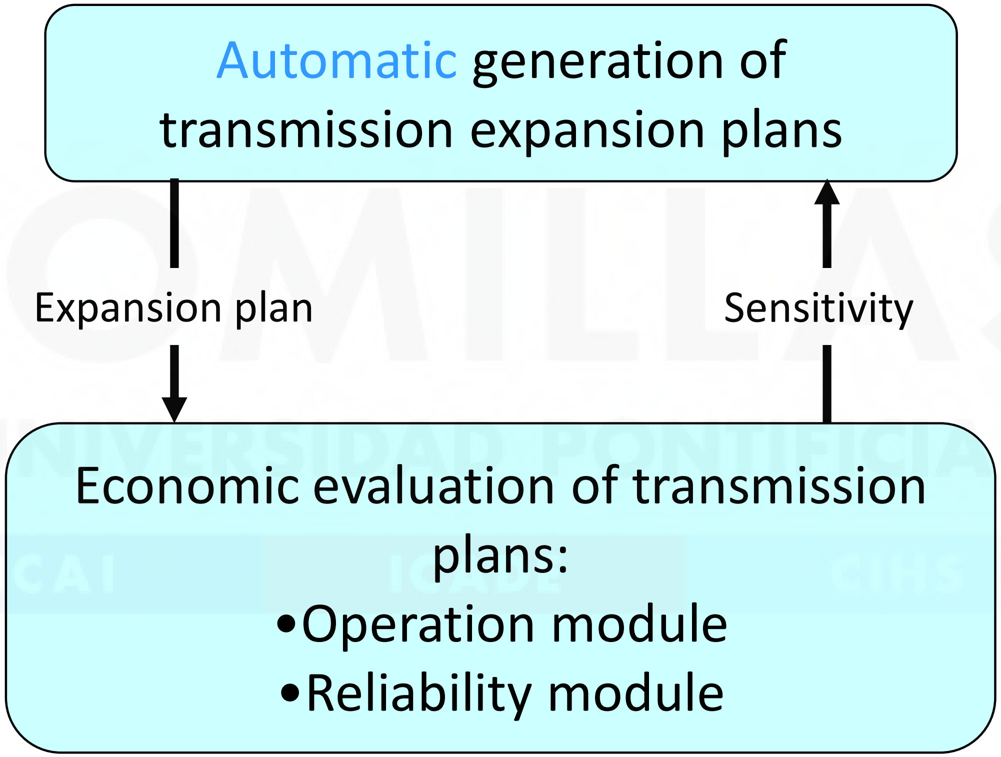
Stag e	Candidates	Sensitivity mean [M$/M$]	Confidence interval [%]	Validity range [MW]	Multi-attribute value
No circuit is added (initial stage)					
1	**431-461**	**-5.622**	**8.6**	**296**	**1.505**
	390-403	-3.365	7.9	119	0.767
	570-583	-1.254	63.4	131	0.727
Circuit 431-461 is added					
2	**586-588**	**-3.275**	**57.5**	**138**	**1.162**
	390-403	-3.352	7.9	107	0.941
	570-583	-1.849	56.8	128	0.897
Circuits 431-461 and 586-588 are added					
3	**390-403**	**-3.633**	**6.9**	**157**	**1.468**
	570-583	-0.289	39.1	138	0.894
	424-520	-2.841	7.9	6	0.638
Circuits 431-461, 586-588 and 390-403 are added					
4	**570-583**	**-0.587**	**51.4**	**129**	**1.434**
	424-520	-2.930	7.8	5	0.821
	500-567	-1.784	10.1	30	0.745
Circuits 431-461, 586-588, 390-403 and 570-583 are added					
5	**457-498**	**-0.495**	**19.8**	**83**	**1.293**
	424-520	-3.027	7.6	7	0.933
	500-567	-1.665	10.9	21	0.774
No more circuits are added					

- 623 nodes and 1021 circuits, 165 thermal units and 76 hydro units. 12 network expansion alternatives. Sampling of 100 scenarios in each stage and obtain the three best alternatives.



PERLA (Planificación Estática de la Red a LArgo plazo)

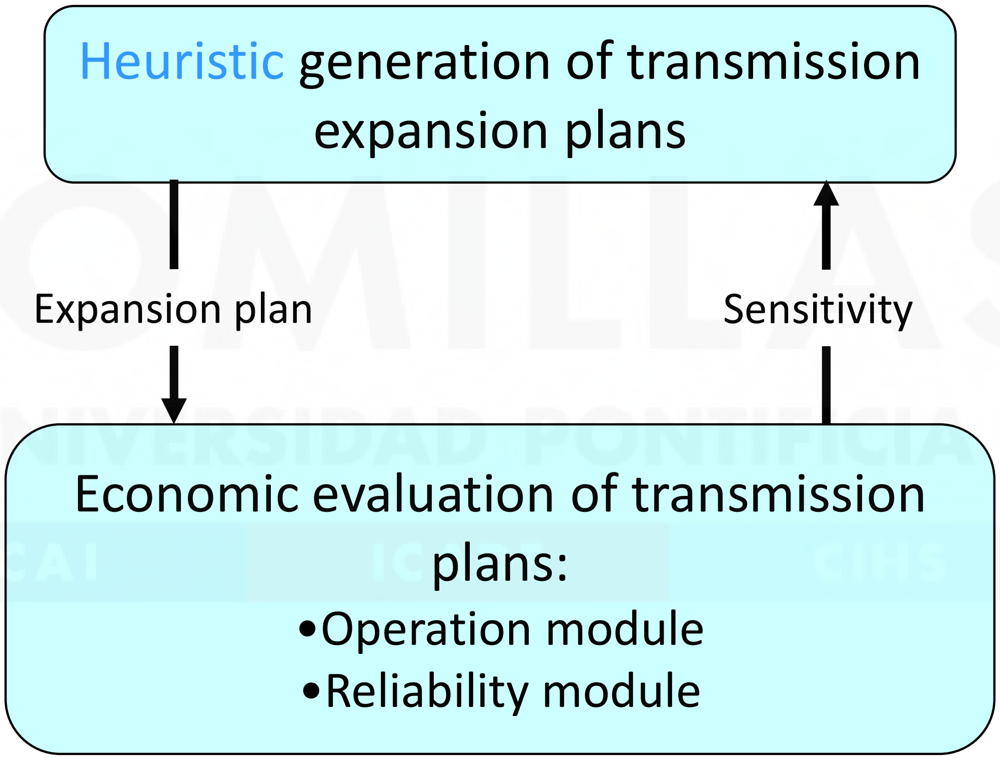
- Static tactical transmission planning (long term) (10-20 years)



J.F. Alonso, A. Sáiz, L. Martín G. Latorre, A. Ramos, I.J. Pérez-Arriaga *PERLA: An Optimization Model for Long Term Expansion Planning of Electric Power Transmission Networks* IIT-91-009 January 1991 (https://pascua.iit.comillas.edu/aramos/papers/PERLA.pdf)

CHOPIN (Código Heurístico Orientado a la Planificación INteractiva)

- Static tactical transmission planning (long term) (10-20 years)



G. Latorre, J.I. Perez-Arriaga *CHOPIN, A Heuristic Model for Long Term Transmission Expansion Planning* IEEE Transactions on Power System, 9 (4): 1886-1894 , Nov 1994 10.1109/59.331446

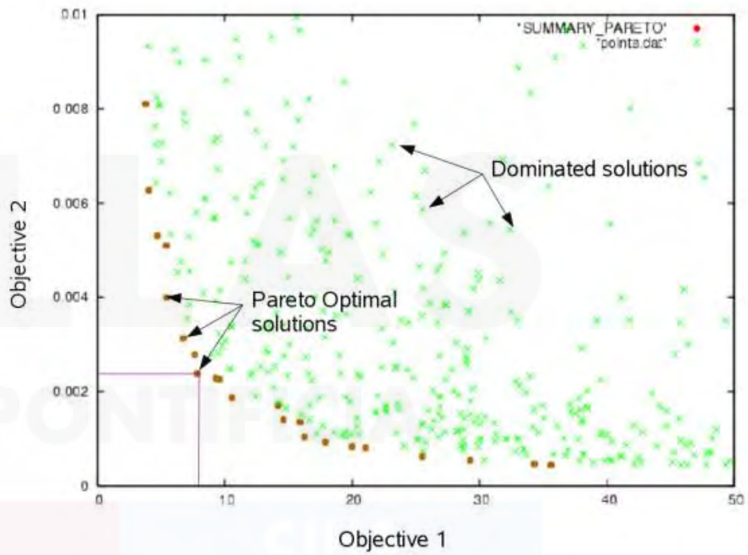
CHOPIN (Código Heurístico Orientado a la Planificación INteractiva)

- Starts from a user-given transmission plan
- **Local search** guided by **sensitivities** extending the **depth-first search**
- **Heuristic truncated enumeration** of the complete solution space

$$Sensitivity = \frac{operation\ cost\ decrement}{per\ unit\ investment\ cost}$$

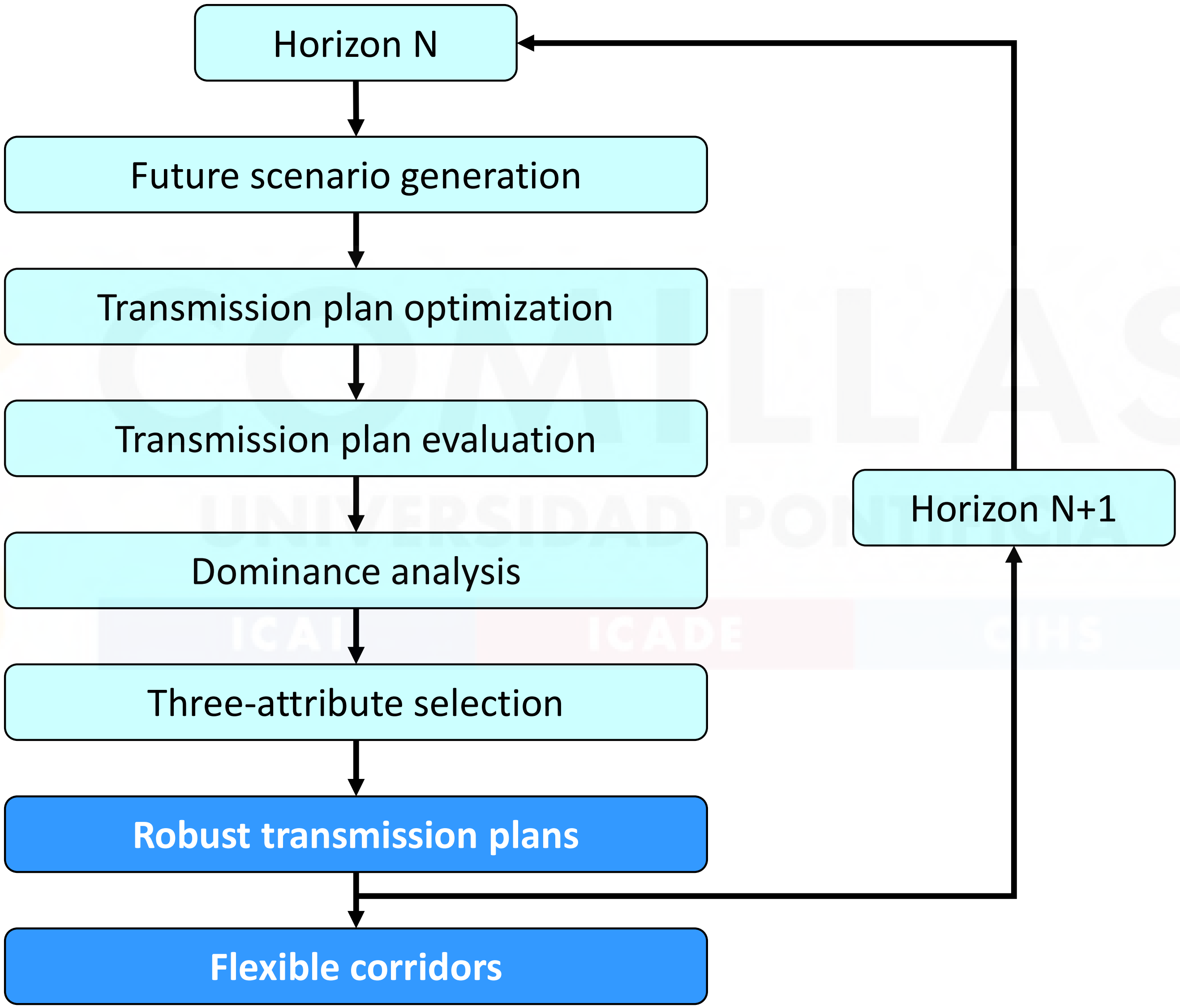
PLAER (PLAnificación Estratégica de la Red de transporte)

- Strategic transmission planning (very long term) (20+ years)
- Trade-off analysis between conflicting objective functions
  - Investment and operation costs
  - Environmental impact (e.g., length)
  - Risk (e.g., administrative permits and delays)
- **PERLA** is used internally as the automatic transmission plan generator



de Dios, R., Sáiz, A., Melsión, J.L. and Bassy, A. *PLAER. Strategic Transmission Network Planning* 11th Power System Computation Conference, Avignon, France, August 1993

PLAER (PLAnificación Estratégica de la Red de transporte)



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TEPES

Long-Term Transmission Expansion Planning Model for an Electric System

TEPES (Long-Term Transmission Expansion Planning Model for an Electric System) https://pascua.iit.comillas.edu/aramos/TEPES.htm

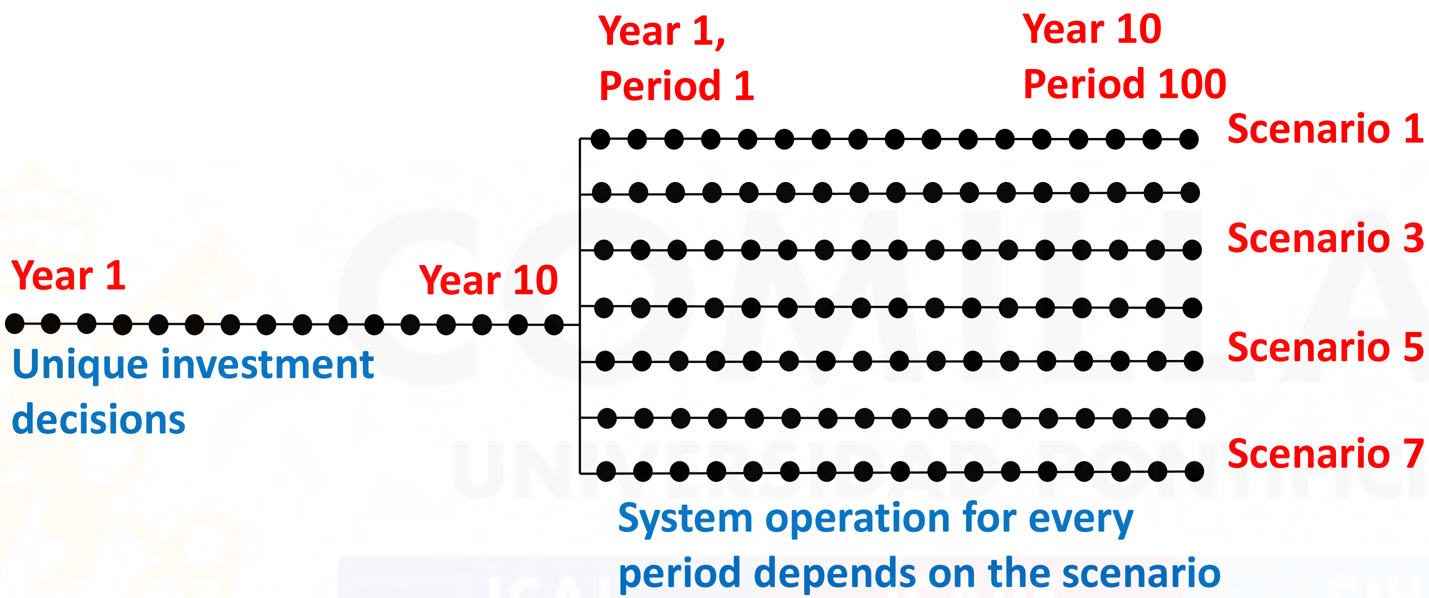
TEPES finds the **optimal transmission expansion plan** for a system, given a set of stochastic scenarios and a definition of the problem objectives. It can be used to guide expansion decisions or analyze the impact of RES on network needs.

- **Detailed system modeling** (system sizes of the order of 1000's of nodes)
  - Hybrid modeling is also possible (different areas have different levels of detail).
  - TEPES can take the output of another model as flows or a rough expansion and carry out a detailed expansion (e.g., Enertile, Empire).
  - This allows to model power plants individually (vs. technology aggregates).
- **Kirchhoff's Laws** are considered:
  - **Loop flows**
  - **Piecewise linear approximation of losses**
- Represents the impact of **different transmission technologies**
  - Voltage levels
  - HVDC
  - PSTs

Key features (i)

- **Dynamic:** The model can deal with a range of horizons, **from the short-term (i.e., 2020 horizon) to the long-term (i.e., 2050 horizon)** planning problem. In the latter case, several planning horizons can be established.
  - The model represents hierarchically the different time scopes to make decisions in an electric system: Year, Period, Sub-period and Load level.
  - This time division allows a flexible representation of the periods where to evaluate the system operation, e.g., using representative snapshots.
- **Stochastic** (random) demand, hydro inputs, fuel costs, renewable energy production, contingencies in generation and transmission assets.
- **Multicriteria**
  - Transmission investment cost,
  - Variable operation costs (including generation emission cost),
  - Reliability cost associated to N-1 generation and transmission contingencies.
- Solved with **Stochastic Mixed-Integer Programming** using
  - **Direct solution**
  - **An efficient version of Benders decomposition**

Stochastic optimization problem



- Operation scenarios: demand, RES generation, hydro inflows, fuel and emission costs
- Generation and network contingency scenarios

All the scenarios are evaluated

Key features (ii)

- Decides the **optimal investments** from an initial list of **pre-defined candidates** (including new lines, reinforcements and transformers) or **candidates automatically generated by the model**
  - Fractional investments can be allowed in some cases
  - Centralized, cost-based operation
- Implemented in GAMS, solved with CPLEX or GUROBI, exchanges data with Microsoft Excel and shows outputs in Google Earth.
- Outputs include:
  - **Operation**:
    - Output of different units and technologies (thermal, storage hydro, pumped storage hydro, RES)
    - Fuel consumption
    - Emissions
    - RES curtailment, hydro spillage
    - Hydro reservoir scheduling
    - Line flows, line ohmic losses, node voltage angles
    - Consider existing and candidate HVDC lines and converting stations into the model
  - **Marginal**:
    - Long-Run Marginal Costs
    - Transmission Load Factors (TLF)

Publications

- S. Lumbreras, F. Banez-Chicharro, A. Ramos *Optimal Transmission Expansion Planning in Real-Sized Power Systems with High Renewable Penetration* Electric Power Systems Research 49, 76-88, Aug 2017 10.1016/j.epsr.2017.04.020
- F. Banez-Chicharro *Methodology for Benefit Analysis of Transmission Expansion Projects* PhD Thesis. Universidad Pontificia Comillas. June 2017 (Summary).
- F. Banez-Chicharro, L. Olmos, A. Ramos and J.M. Latorre *Estimating the benefits of transmission expansion projects: an Aumann-Shapley approach* Energy 10.1016/j.energy.2016.10.135
- Q. Ploussard, L. Olmos and A. Ramos *An operational state aggregation technique for transmission expansion planning based on line benefits* IEEE Transactions on Power Systems 10.1109/TPWRS.2016.2614368
- S. Lumbreras, A. Ramos *How to Solve the Transmission Expansion Planning (TEP) Problem Faster: Acceleration Techniques Applied to Benders Decomposition* IET Generation, Transmission & Distribution 10: 2351-2359, Jul 2016 10.1049/iet-gtd.2015.1075
- S. Lumbreras, A. Ramos *The new challenges to transmission expansion planning. Survey of recent practice and literature review* Electric Power Systems Research 134: 19-29, May 2016 10.1016/j.epsr.2015.10.013
- S. Lumbreras, D.W. Bunn, A. Ramos, M. Chronopoulos *Real Options Valuation Applied to Transmission Expansion Planning* Quantitative Finance 16(2): 231-246 February 2016 10.1080/14697688.2015.1114362
- F. Bañez, L. Olmos, A. Ramos, J.M. Latorre *Benefit allocation of transmission expansion plans based on Aumann-Shapley* IIT-14-050A, October 2014
- S. Lumbreras *Decision Support Methods for Large-Scale Flexible Transmission Expansion Planning* PhD Thesis. Universidad Pontificia Comillas. June 2014 .
- C. Duro *Transmission Expansion Planning using a Genetic Algorithm*. Final project of Engineering Degree. Universidad Pontificia Comillas. June 2014
- S. Lumbreras, A. Ramos, P. Sánchez *Automatic Selection of Candidate Investments for Transmission Expansion Planning* International Journal of Electrical Power and Energy Systems 59: 130-140, July 2014 10.1016/j.ijepes.2014.02.016
- S. Lumbreras, A. Ramos *Transmission Expansion Planning using an Efficient Version of Benders' Decomposition. A Case Study* IEEE PowerTech. Grenoble, France. June 2013 10.1109/PTC.2013.6652091
- S. Lumbreras, A. Ramos and S. Cerisola *A Progressive Contingency Incorporation Approach for Stochastic Optimization Problems* IEEE Transactions on Power Systems 28 (2): 1452-1460, May 2013 10.1109/TPWRS.2012.2225077

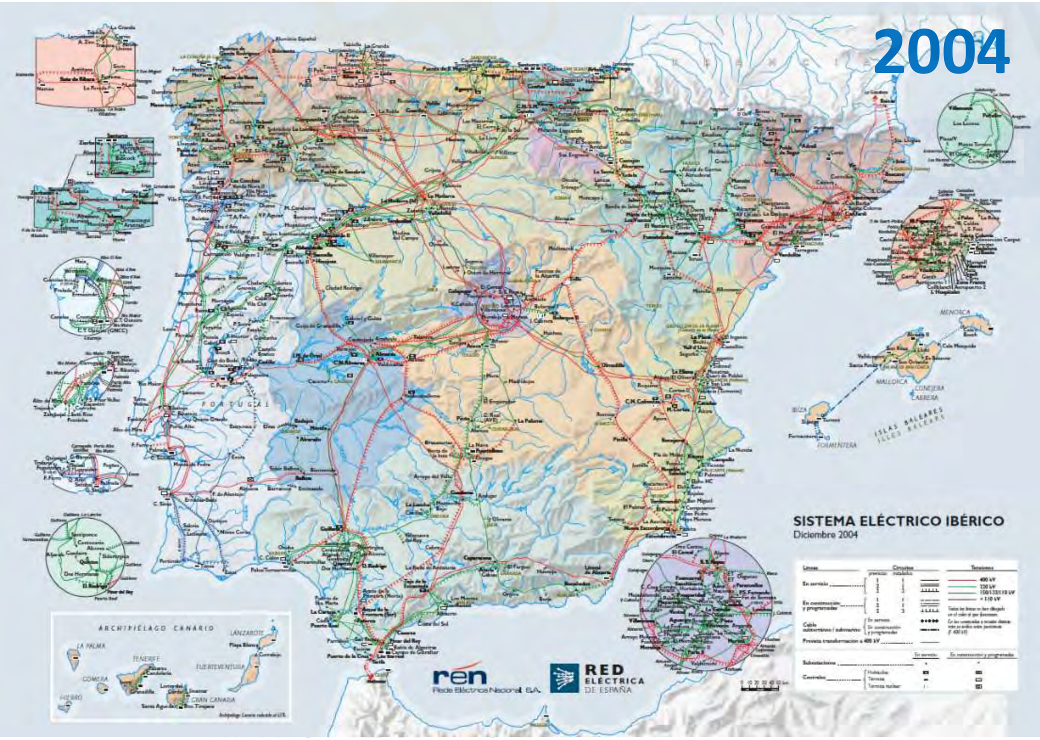
3

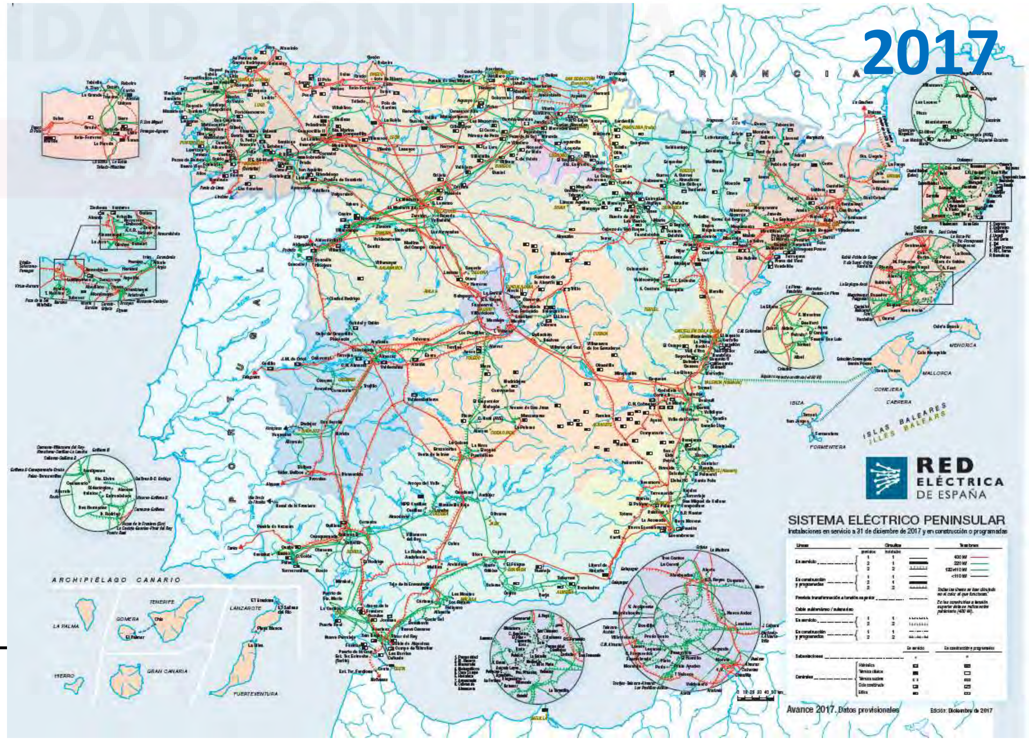
Spain Case Study

Transmission network development

http://www.minetad.gob.es/ENERGIA/PLANIFICACION/PLANIFICACIONELECTRICIDADYGAS/Paginas/desarrollo-redes.aspx

- Reports on network expansion planning
  - Desarrollo de la red de transporte de la electricidad 2015-2020.
  - Desarrollo de la red de transporte de la electricidad 2008-2016.
  - Desarrollo de la red de transporte de la electricidad 2002-2011.





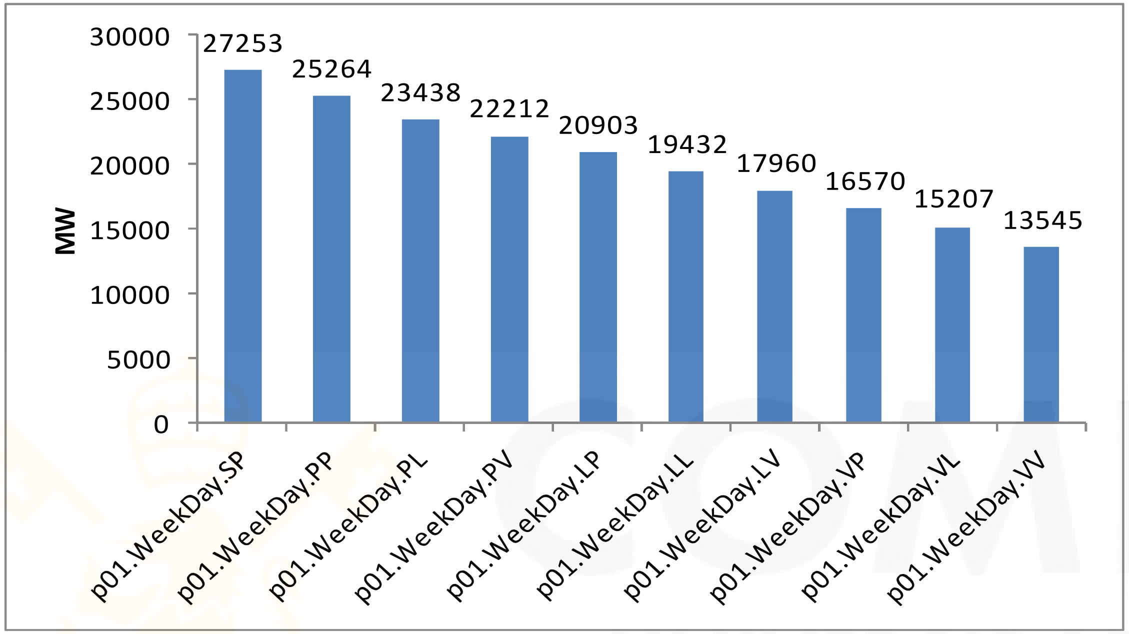
Spain-France underground interconnection

http://ree.es/en/activities/unique-projects/new-interconnection-with-france

- Line of 400 kV in DC that will increase the exchange capacity up to 2,800 MW.
- 65 km length, totally buried by means of a trench system and will use other already existing linear infrastructures when possible.
- Two converter substations: Santa Llogaia (Spain) y Baixas (France).
- Tunnel of 8.5 km and 3.5 m of diameter will house the cables in the section crossing the Pyrenees

Fuente: REE

Mainland Spain 2025



Energy	[GWh]	169291	
Max Load	[MW]	27253	
Min Load	[MW]	13545	
Peak/OffPeak Ratio	[p.u.]	2.0	
Nuclear	[MW]	5770	21%
Domestic Coal	[MW]	2769	10%
Imported Coal	[MW]	1456	5%
CCGT	[MW]	4044	15%
Oil	[MW]	115	0%
RES + run of the river hydro	[MW]	5417	20%
Storage hydro	[MW]	7927	29%
Installed Capacity	[MW]	27496	100%
Thermal generation	[MW]	14153	51%
Natural Hydro Inflows (W)	[GWh]	37909	
Natural Hydro Inflows (D)	[GWh]	19883	
Energy cost			
Nuclear	[€/MWh]	15	
Domestic Coal	[€/MWh]	27	
Imported Coal	[€/MWh]	22	
CCGT	[€/MWh]	31	
Oil	[€/MWh]	46	
CO2 emission cost	[€/t CO2]	0	

Years	1
Periods	1
Sub-periods	1
Load levels	10
Operation scenarios	2
Gen contingency scenarios	0
Net contingency scenarios	0
Nodes	428
Existing lines	625
Candidate lines	93
Thermal units	50
Hydro plants	122
Intermittent generators	41

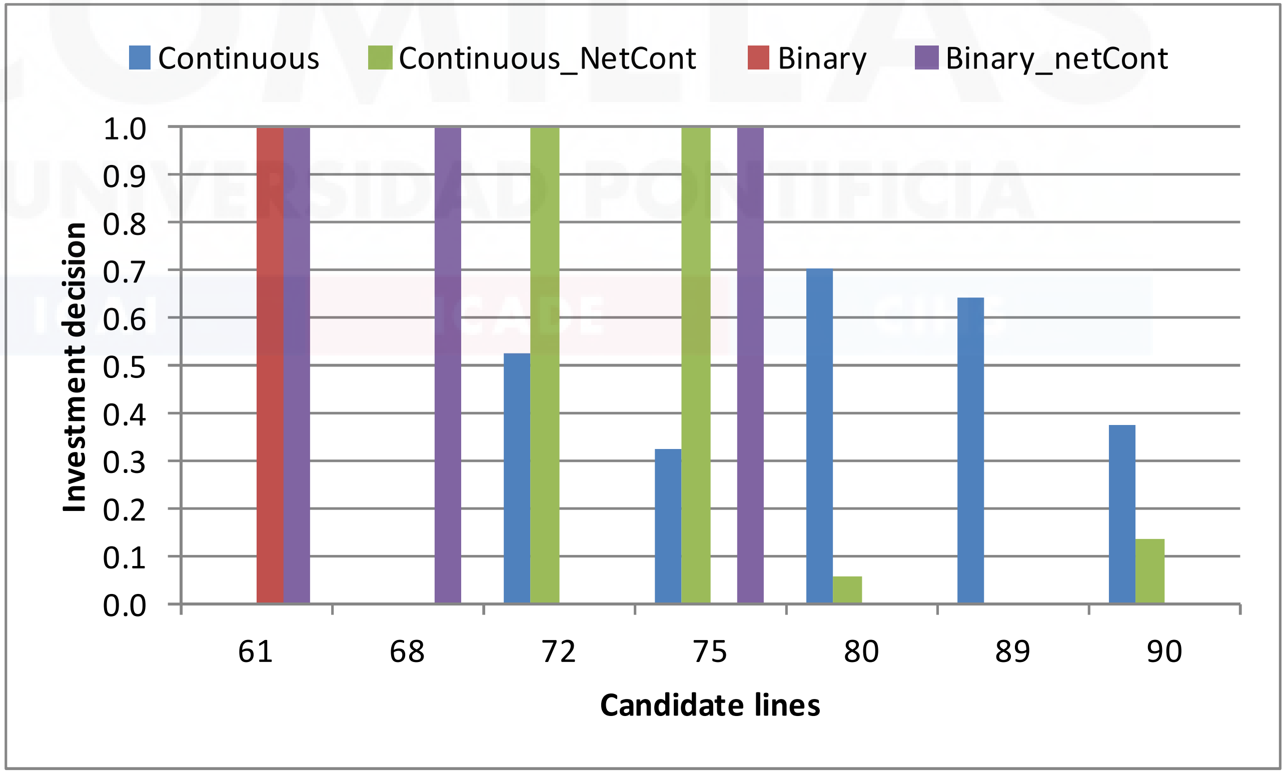
Mainland Spain. 400 kV Nodes. Demand and Generation

Mainland Spain. 400 kV existing and candidate lines

Summary of cases

- Introducing network contingencies with the continuous variables approaches them to binary ones
- Introducing network contingencies with the binary variables increases the total investment

Linear relaxation of binary variables is not the solution to focus the candidate lines



Mainland Spain. Installed lines. Iteration 1

Mainland Spain. Installed lines. Iteration 2

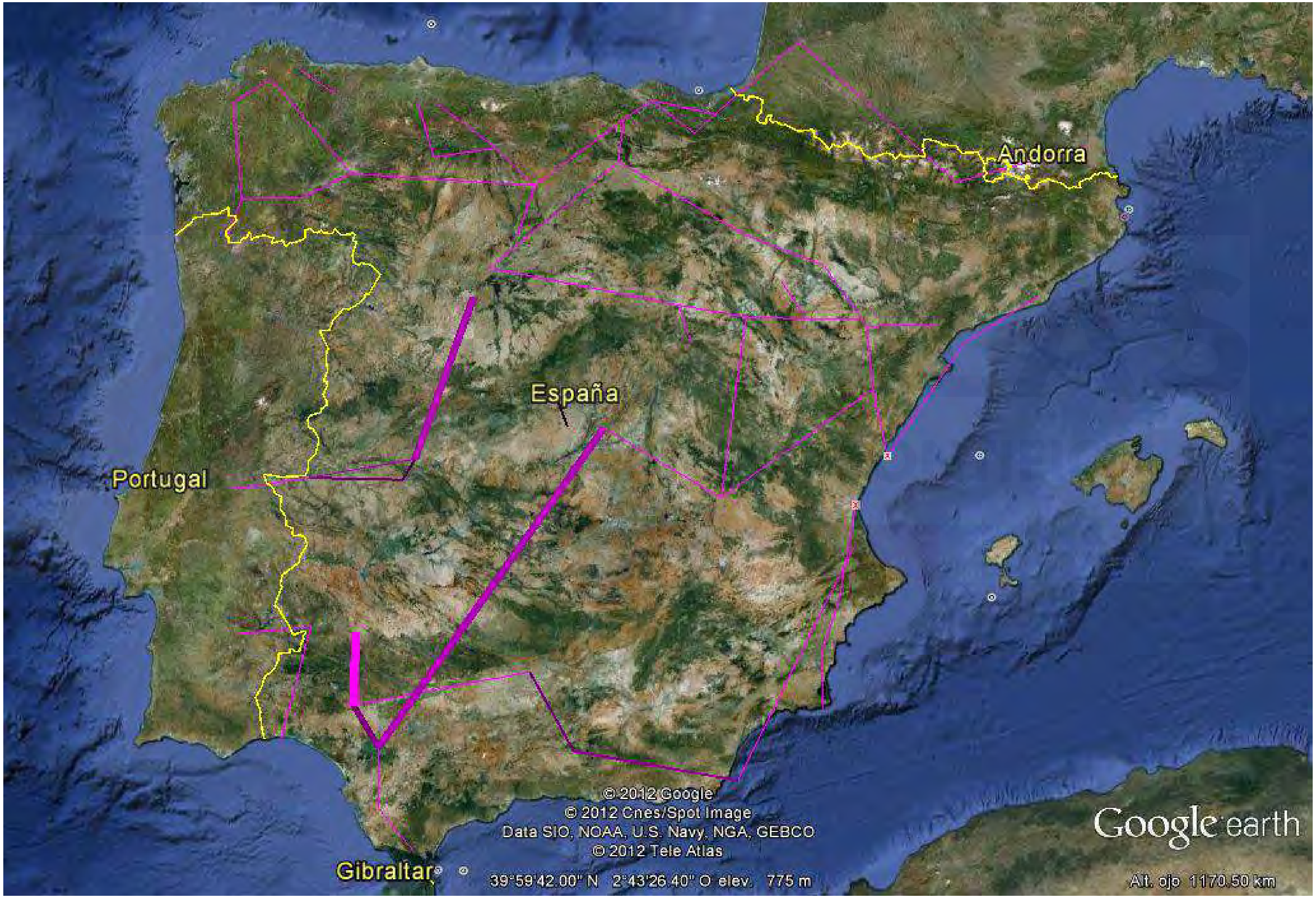
Mainland Spain. Installed lines. Iteration 3

Mainland Spain. Installed lines. Iteration 4

Mainland Spain. Installed lines. Iteration 5

Mainland Spain. Installed lines. Iteration 6

Mainland Spain. Installed lines. Iteration 7



Mainland Spain. Installed lines. Iteration 8

Mainland Spain. Installed lines. Iteration 9

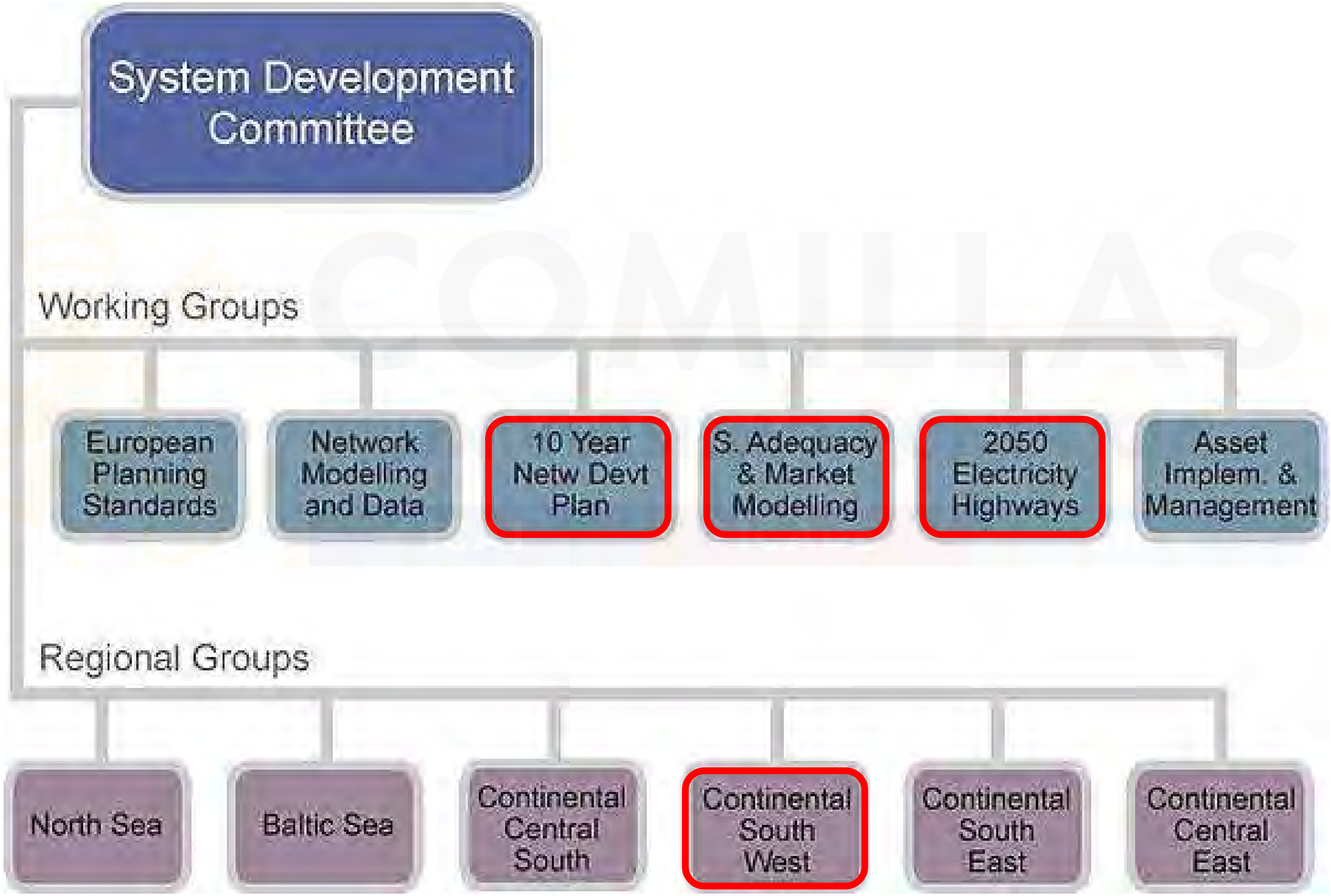
Mainland Spain. Installed lines. Iteration 10

4

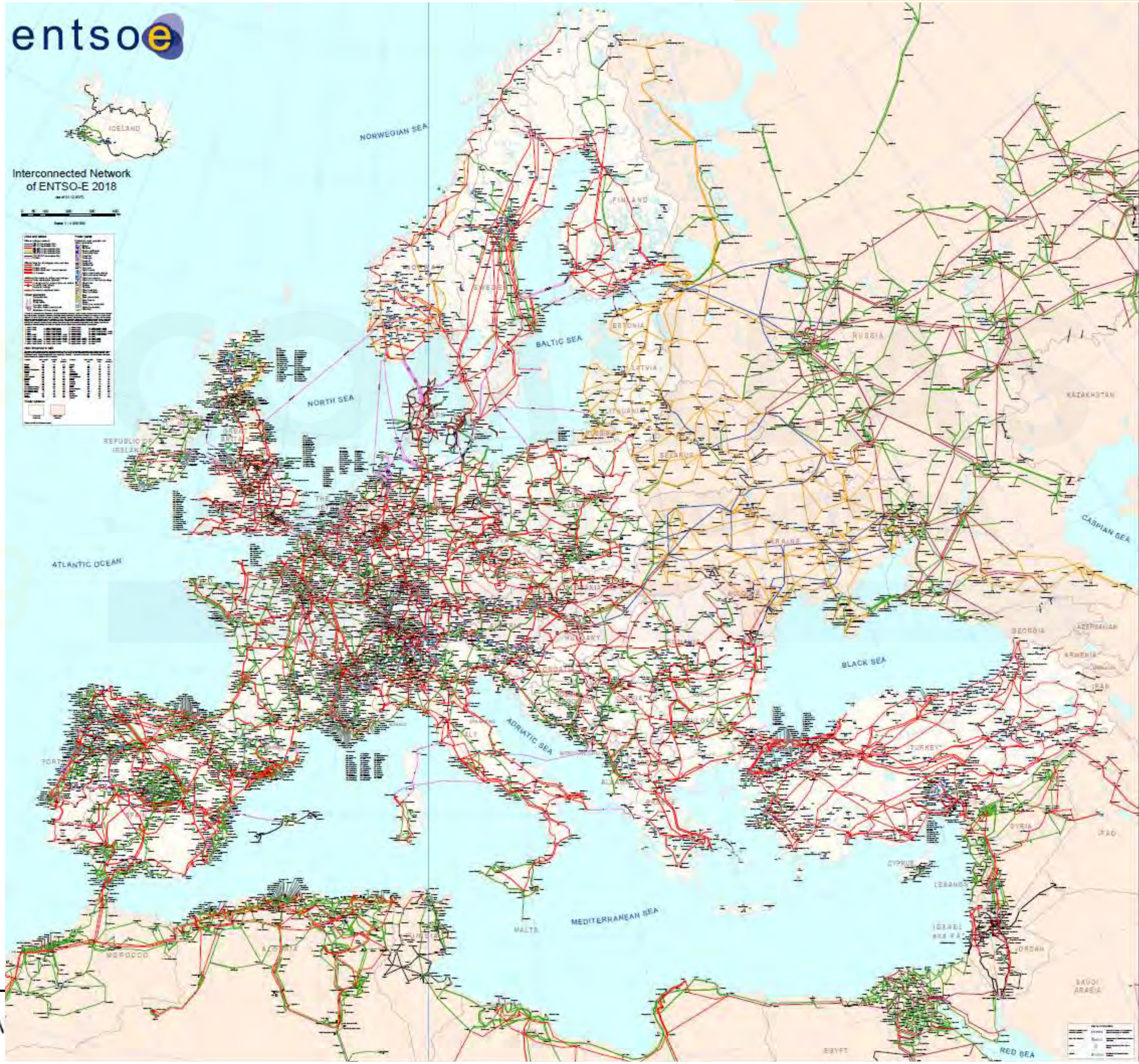
European Case Studies

ENTSO-E's System Development Team

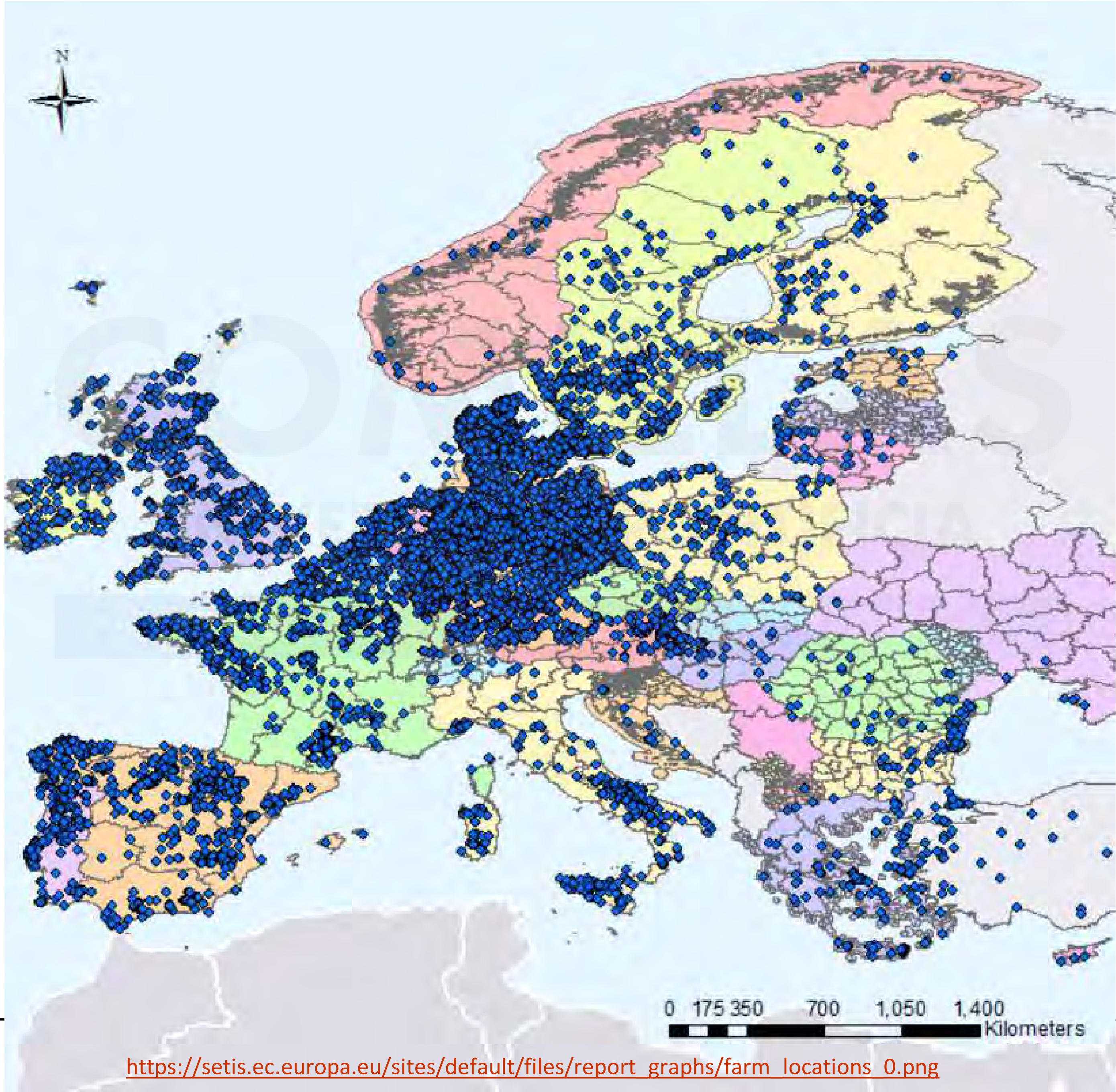
https://www.entsoe.eu/about-entso-e/system-development/system-development-team/Pages/default.aspx



ENTSO-E Grid Map 2018



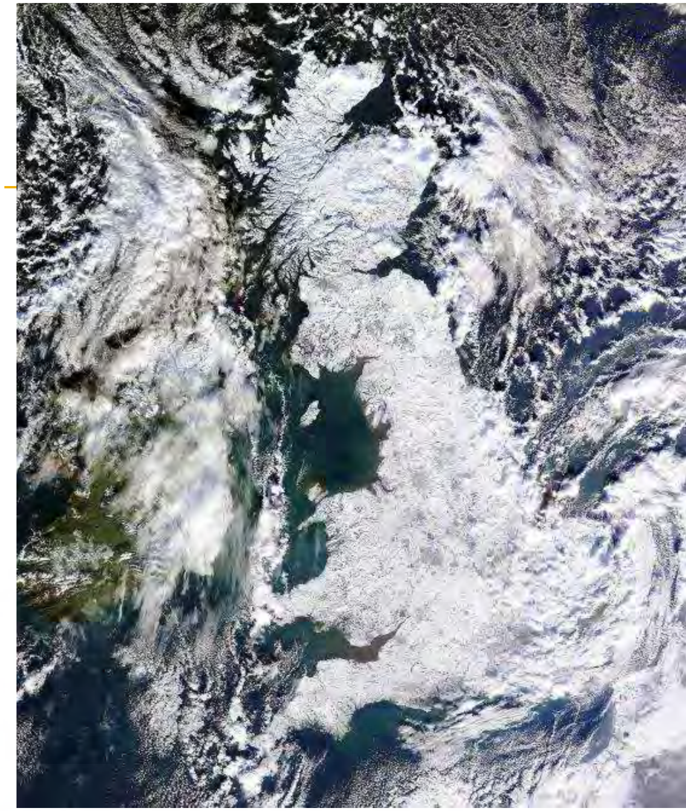
Map of European wind farms



https://setis.ec.europa.eu/sites/default/files/report_graphs/farm_locations_0.png

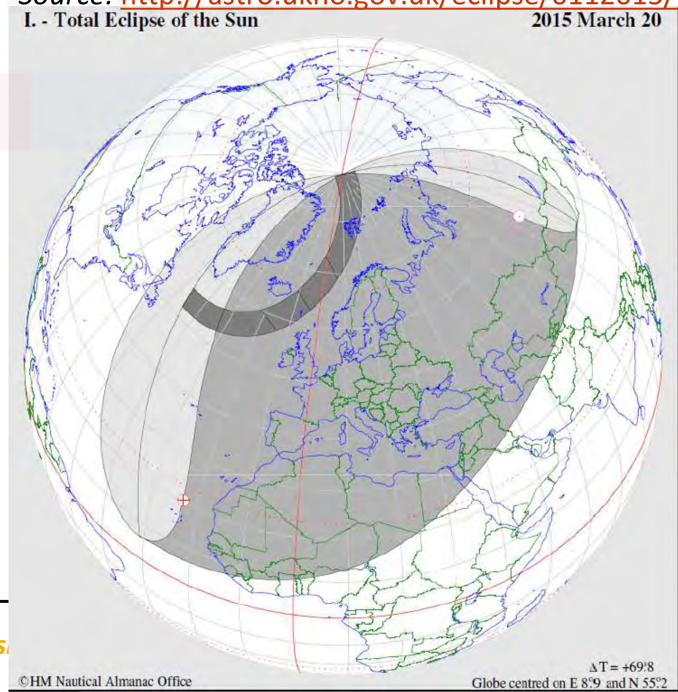
Mid-term Adequacy Forecast

- Pan-European probabilistic assessment of adequacy (long term) (5-15 years)
- Definition: System adequacy of a power system is a measure of the ability of a power system to supply the load in all the steady states in which the power system may exist considering standard conditions. [ENTSO-e]
  - Every two years. Non-binding
  - Overview of national or regional generation adequacy for the summer and winter period and highlight possibilities for neighboring countries to contribute to the generation/demand balance in critical situations
  - Technical resilience: withstand with extreme system situations (rare contingencies, meteorological events)



UK, January 7, 2010

Source: http://astro.ukho.gov.uk/eclipse/0112015/



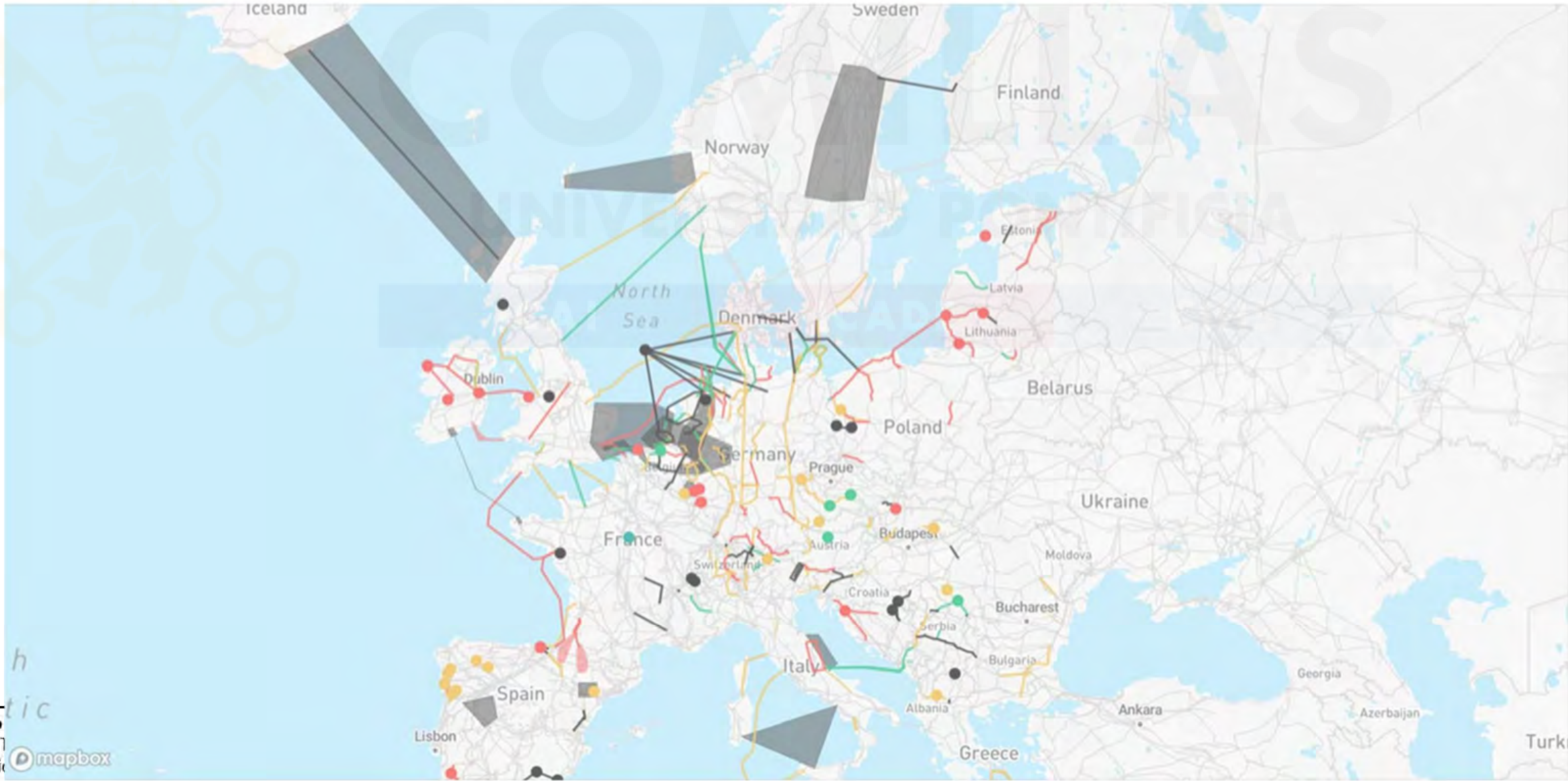
Ten-Year Network Development Plan (TYNDP) (http://tyndp.entsoe.eu/)

- **Biannual**, **non-binding**. TYNDPs published in 2010, 2012 , 2014, 2016 and recently released 2018
- **Increase information and transparency** regarding the investments in electricity transmission systems which are required on a pan-European basis and to support decision-making processes at regional and European level.
- **Six regional groups**, designed to address the challenges for grid development and the integration of new generation, especially RES, at a regional level through a structure which reflects the regions' particularities and needs.

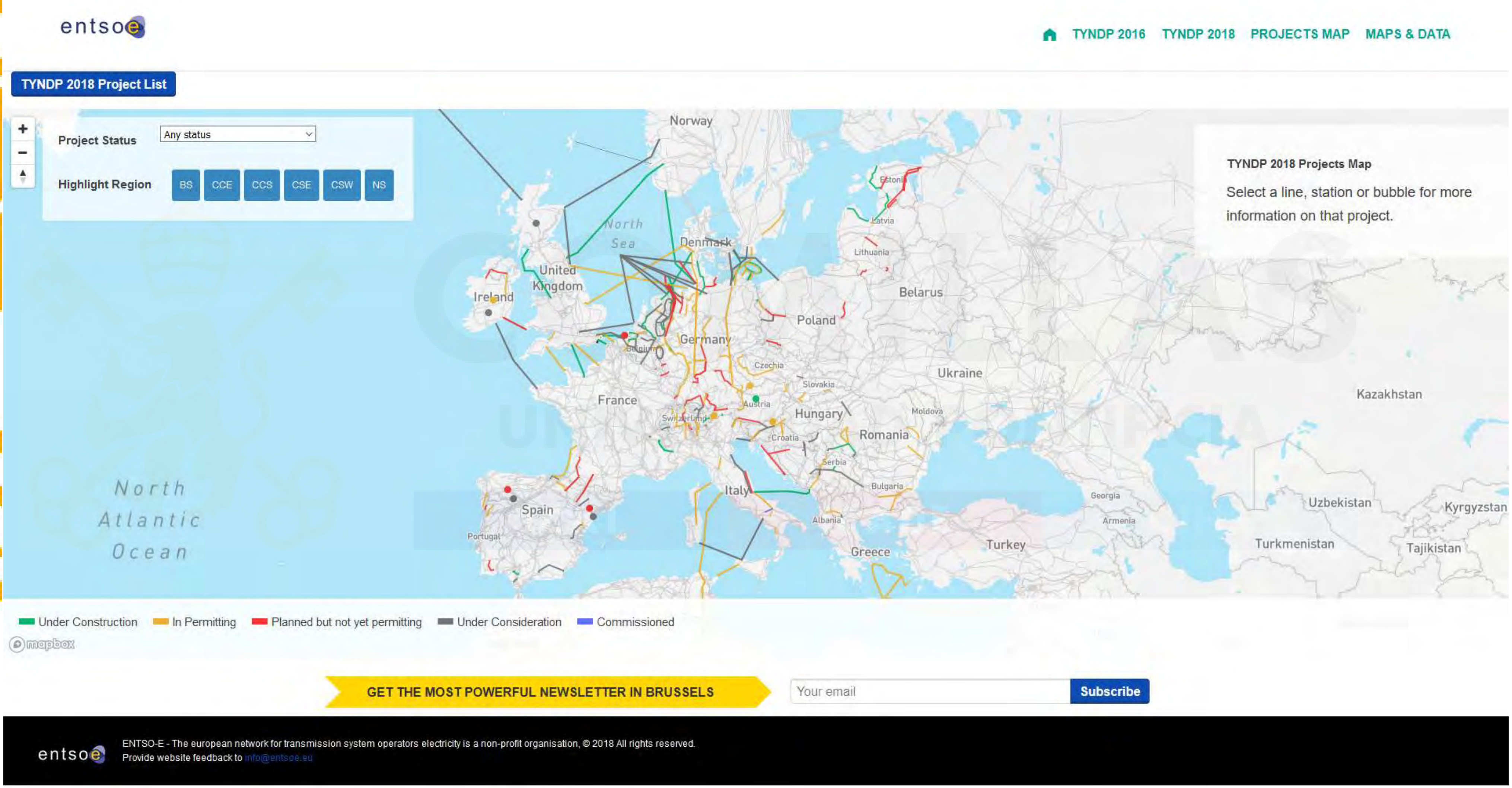
Bottom-Up Approach

TYNDP 2018 Outcomes

- **48-58%** of demand in 2030 will be covered by **renewable energy**.
- A **65-75% reduction of CO2 emissions** in 2030 versus 1990 levels.
- A **€2-5 billion reduction in annual generation variable costs**.

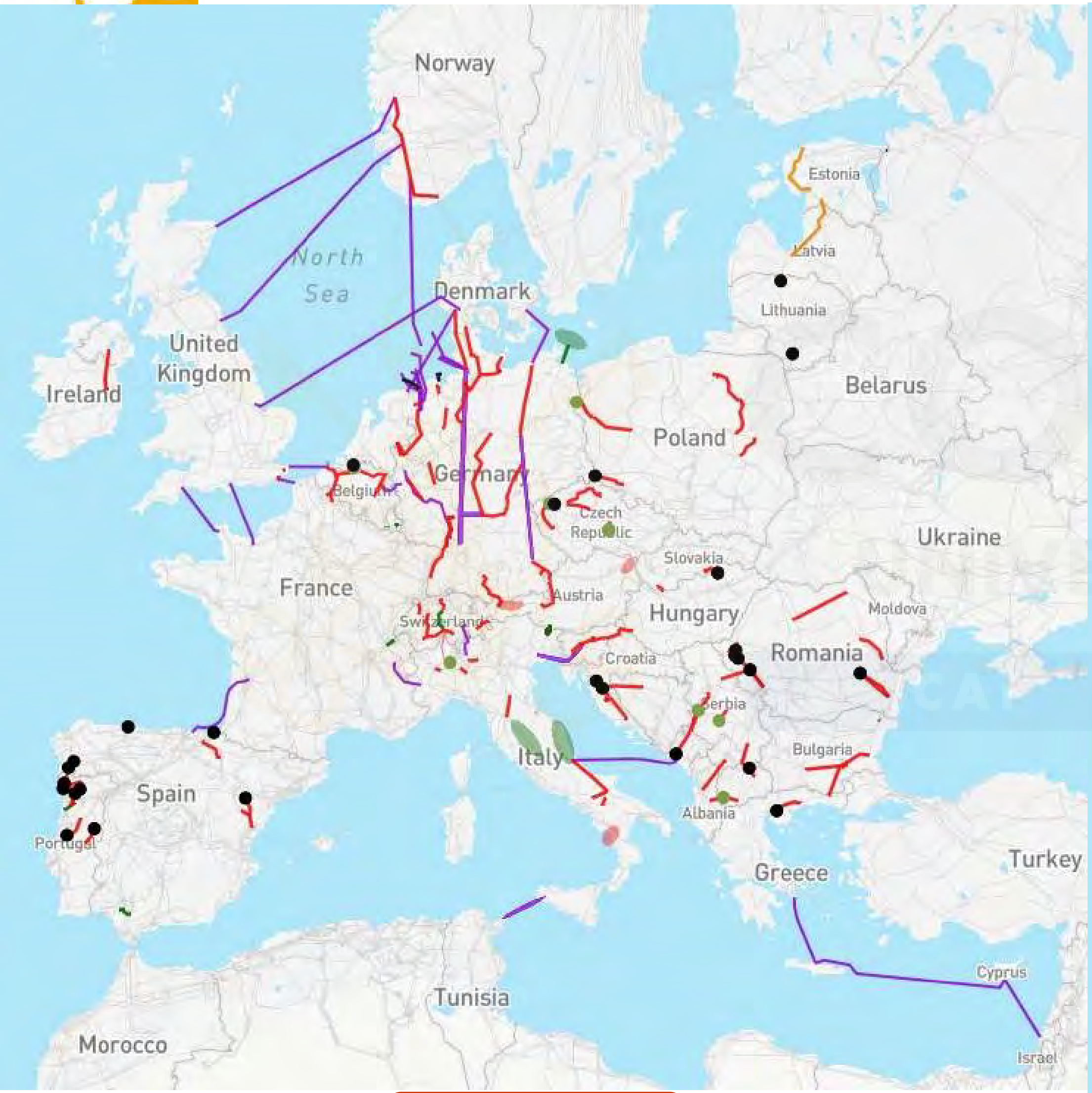


TYNDP 2018 Map

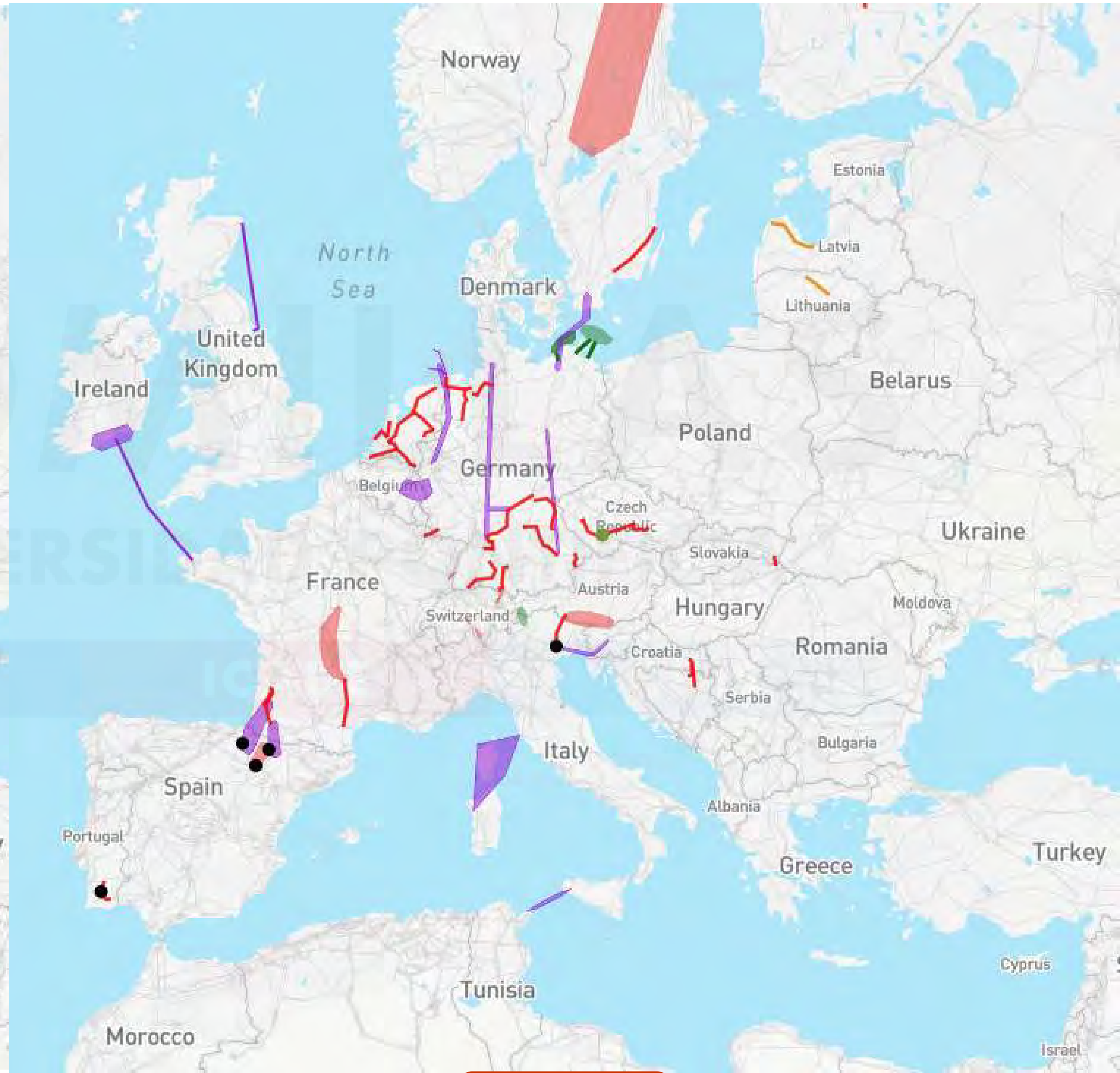


https://tyndp.entsoe.eu/tyndp2018/

TYNDP 2016 Maps



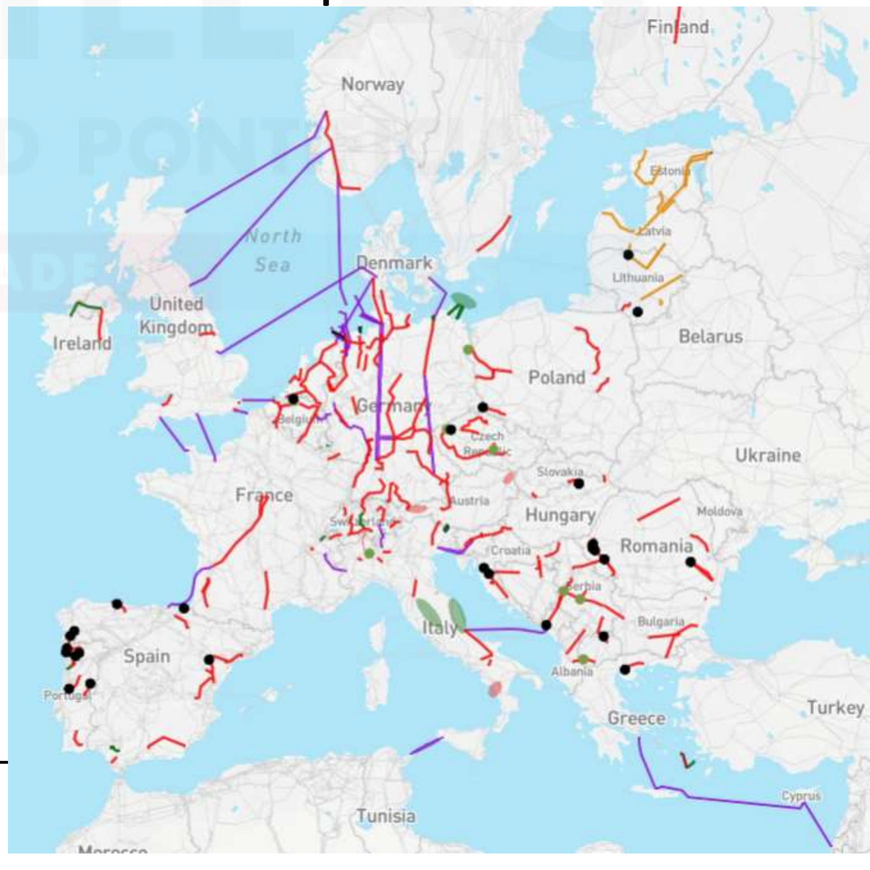
Medium term



Long term

TYNDP 2016 Outcomes

- **€150bn investments**, of which 70-80 by 2030
- **1 to 2 €/MWh** impact on bills due to transmission investment
- **45 to 60% RES** across 4 visions for 2030
- **50% to 80% emissions cut** depending on the vision
- **1.5 to 5 €/MWh potential reduction** in wholesale prices
- **40% reduction in congestion** hours



Projects of Common Interest (PCI). Overview

- Provide a high-value to the **Internal Electricity Market** (IEM) of the EU
- Facilitated **permit granting process** and improved **regulatory treatment** to ensure their deployment
- Identified based on the results of a **Cost-Benefit Analysis** (CBA) using the **beneficiaries pay principle**

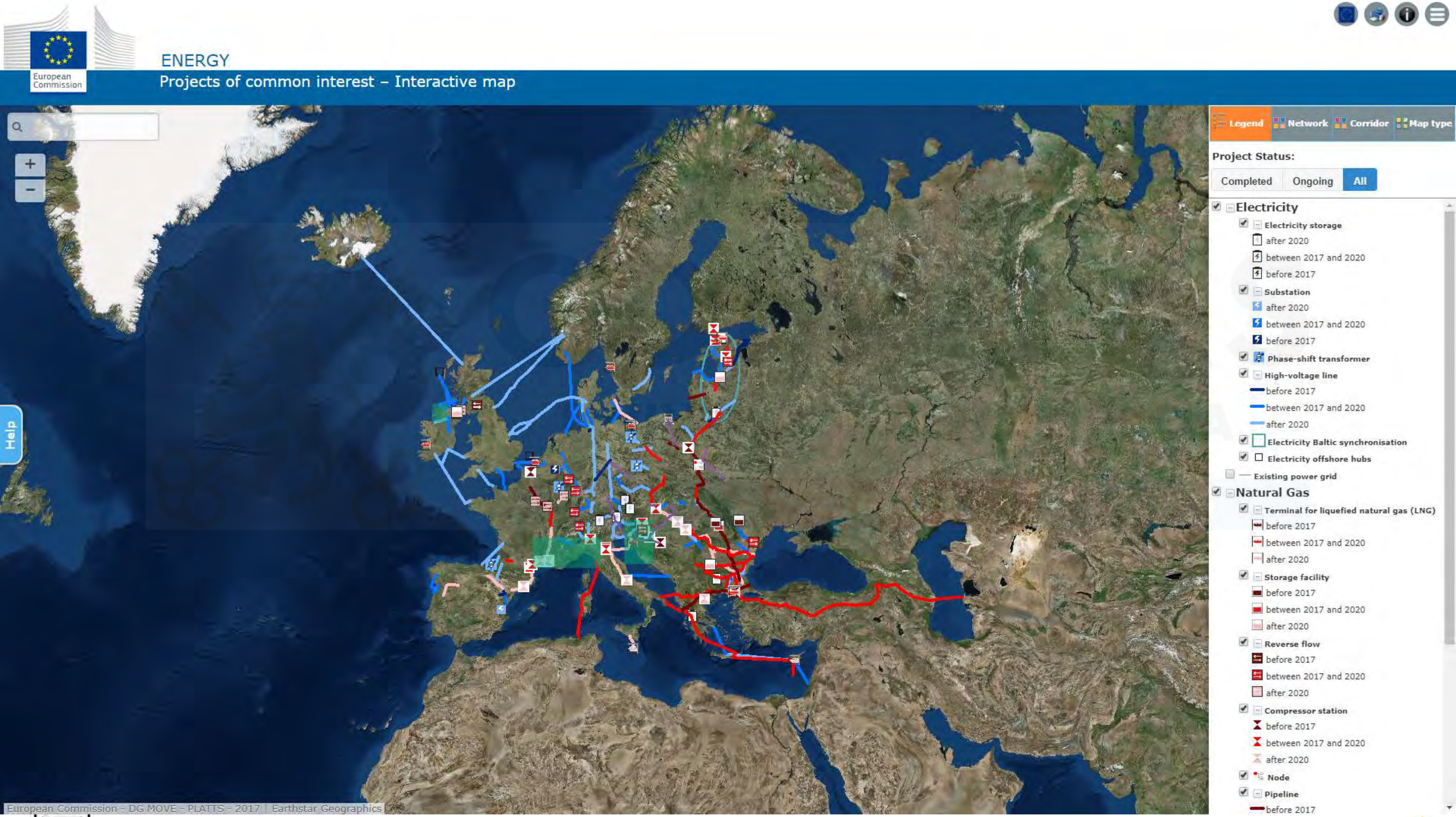
Projects of Common Interest (PCI). Selection process

Selected on the basis of five criteria:

1. have a **significant impact on at least two EU countries**
2. **enhance market integration** and contribute to the integration of EU countries' networks
3. **increase competition on energy markets** by offering alternatives to consumers
4. **enhance security of supply**
5. **contribute to the EU's energy and climate goals**. They should facilitate the integration of an increasing share of energy from variable renewable energy sources.

https://ec.europa.eu/energy/en/topics/infrastructure/projects-common-interest

PCI list for electricity interconnectors in Member States below 10%



http://ec.europa.eu/energy/infrastructure/transparency_platform/map-viewer/main.html

Electricity Transmission Expansion Planning

Integrated methodology for large-scale planning

- **SET-Nav (2050)**
- Navigating the Roadmap for Clean, Secure and Efficient Energy Innovation developed for the European Union
- http://www.set-nav.eu/

Advanced methods for large-scale TEP

- **eHighWay2050 (2030)**
- Modular development plan of the pan-European transmission system 2050 developed for the European Commission.
- http://www.e-highway2050.eu/e-highway2050/

Network investment needs associated to large-scale integration of RES in Europe from MENA countries in 2030 and 2050

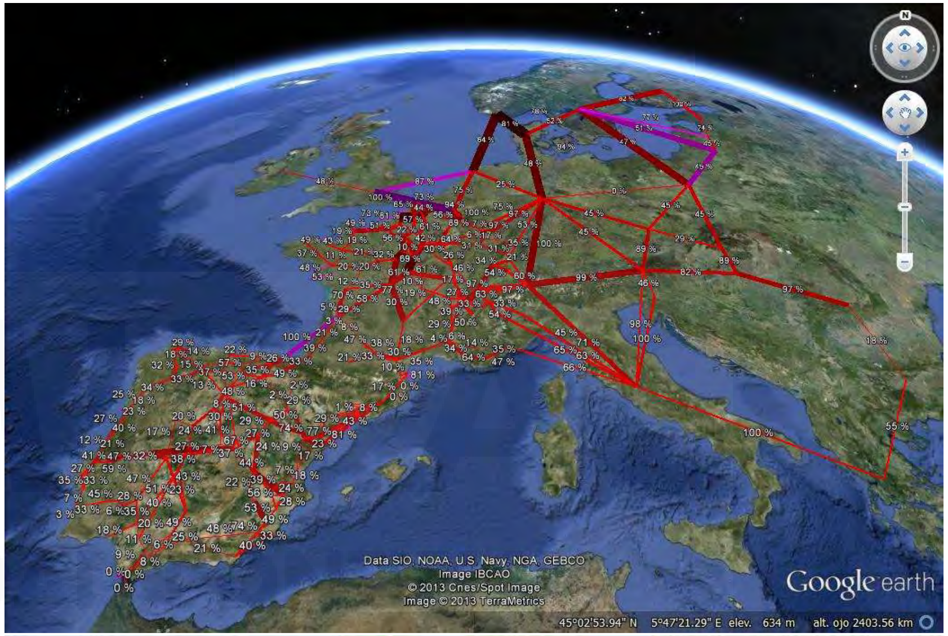
- **DESERTEC (2030 and 2050)**
- Pre-feasibility analysis on power highways for the Europe-MENA region integration in the framework of the Dii Rollout Plan 2050 developed for Desertec Industrial Initiative (Dii).
- http://desertenergy.org/getting-connected/

Network developments associated to different European RES policies

- **RESCost (2030 and 2050)**
- Estimating costs of renewable energies compared to conventional energy sources up to 2030 and beyond developed for Fraunhofer ISI.
- http://www.isi.fraunhofer.de/isi-de/x/projekte/targets-2030_331333.php

Impact on transmission network due to RES integration

- **Beyond2020**
- Design and impact of a harmonized policy for renewable electricity in Europe (Beyond 2020) developed for the European Commission.
- http://www.res-policy-beyond2020.eu/



e-HighWay 2050

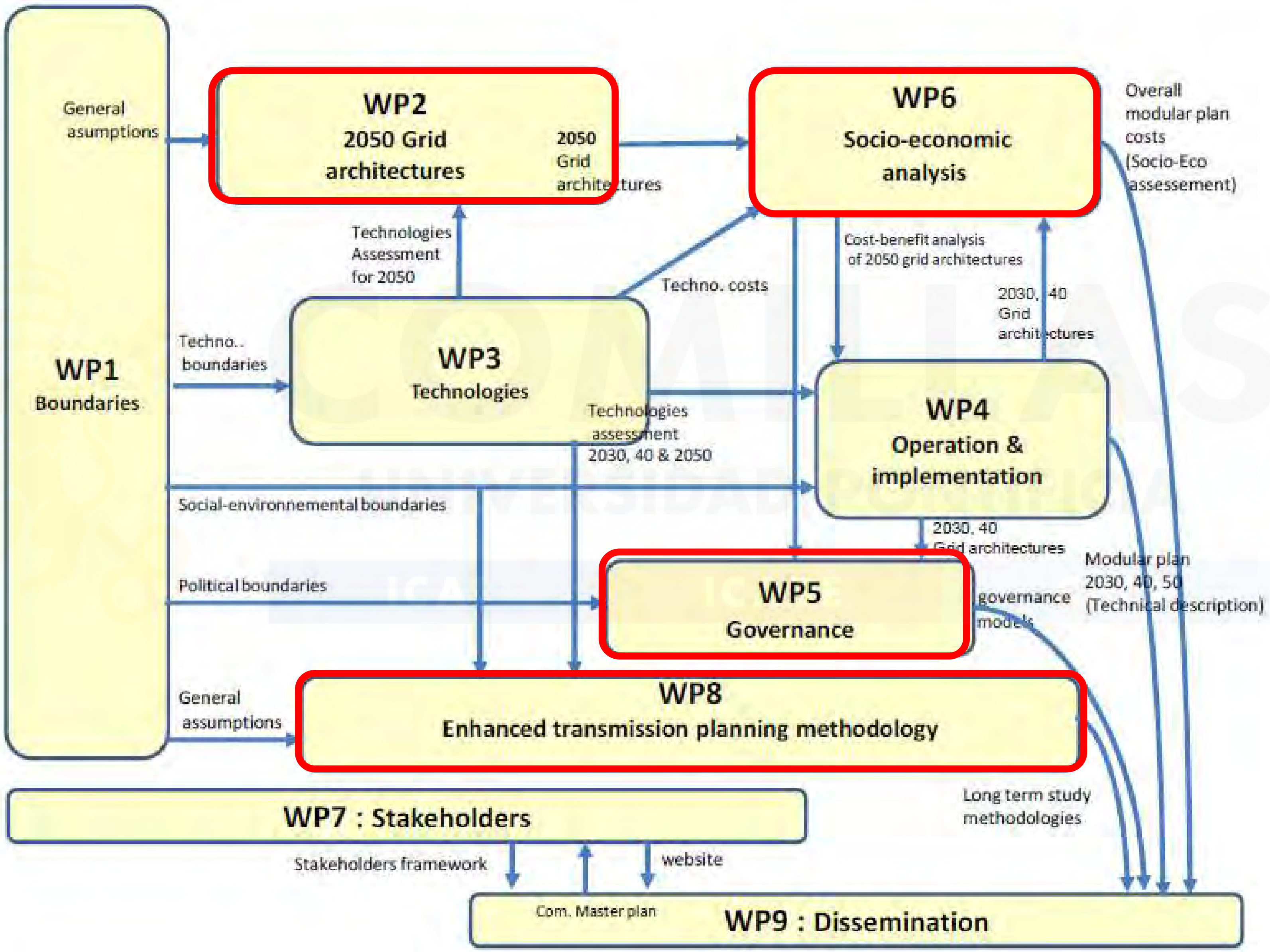
https://youtu.be/fBcwJmZ6qK0?list=PLXEY7WtH7KEXw3Mre9OJwNABY09fwVIk8

e-HighWay 2050 (http://www.e-highway2050.eu/e-highway2050/)

- ENTSO-E Position Paper on a Framework Regarding Electricity Highways (https://www.entsoe.eu/fileadmin/user_upload/_library/position_papers/111209-ENTSO-E_Position_Paper_Framework_EH_FINAL.pdf)
  - Analyzing and justifying bulk power transmission needs taking into account future generation and its spread throughout the whole transcontinental region,
  - Proposing concrete implementation, operation and governance principles for needed grid investments throughout Europe and to neighboring areas,
  - In the interest of security, efficiency, feasibility and sustainability, consider the whole energy supply chain including relevant technical/technological, economical/financial, ecological, political/sociopolitical and geopolitical/security issues,
  - Following a modular approach: 2030, 2035, 2040, 2045 and 2050,
  - Proposing general strategic Electricity Highways architectures including technology options.

Top-Down Approach

e-HighWay 2050. Work packages



e-HighWay 2050. WP2. Grid architectures for 2050

- Scenario development
  - Assessment of existing scenarios for 2030 and beyond (EC Roadmap 2050, PRIMES forecast)
- Pan-European model of the Transmission System
  - Regionalization of the European network
- Market simulation
- Grid architecture development
- Sanity check of the architectures proposed

e-HighWay 2050. WP2. Grid architecture development

- Automatic computation of transmission expansion plans
  - Classical optimization of the expansion of the grid
    - Results in optimal expansion plans according to criteria considered in WP2
    - An optimization problem is solved for this
  - Intelligent search for a suitable plan based on the application of heuristic rules
    - Does not guarantee that the optimality of the plan that is computed
    - Suitable to be applied to large and complex systems
- Iterative search for a suitable expansion plan
  - Planning module proposes (a set of) network investments based on techno-economic information produced in other modules
  - Operation including the set of reinforcements proposed is computed and new information is sent to the planning module

e-HighWay 2050.
WP2. Classical optimization of the expansion of the grid (i)

- Adapted to both long and medium term expansion planning of both large and small systems
- Dedicated tool maximizing social welfare with limited modeling detail
- Involves representing the operation of the system in a simplified way
  - Not very large number of nodes (granularity considered in e-highways may be appropriate)
  - Part of existing technical constraints are not represented: voltage constraints, dynamic stability ones, maximum short circuit currents

e-HighWay 2050.
WP2. Classical optimization of the expansion of the grid (ii)

- Requires separately assessing the technical feasibility of the expansion plan proposed → using a separate grid analysis tool
  - If infeasibilities detected by grid analysis tool are local and not many, changes to the expansion plan can be proposed using this same tool
  - Otherwise, grid tool is used to identify new boundary conditions considered in the optimal expansion planning problem

e-HighWay 2050. WP2. Automatic search for a plan based on the application of heuristic rules

- Adapted to both long and medium term expansion planning of both large and small systems
- Use of a dedicated planning tool for this
- Economic impact of network investments considered endogenously
- Able to work with larger systems and with a higher level of technical modeling detail than the optimization approach
  - → May consider the most relevant technical constraints within the search process

  … However, given the size and complexity of the problem to solve, the solution computed may be far from optimal
- Carrying out a grid (technical) analysis of the solution provided by the planning module may or may not be necessary
  - – This will depend on the level of complexity of the grid model used in the planning algorithm

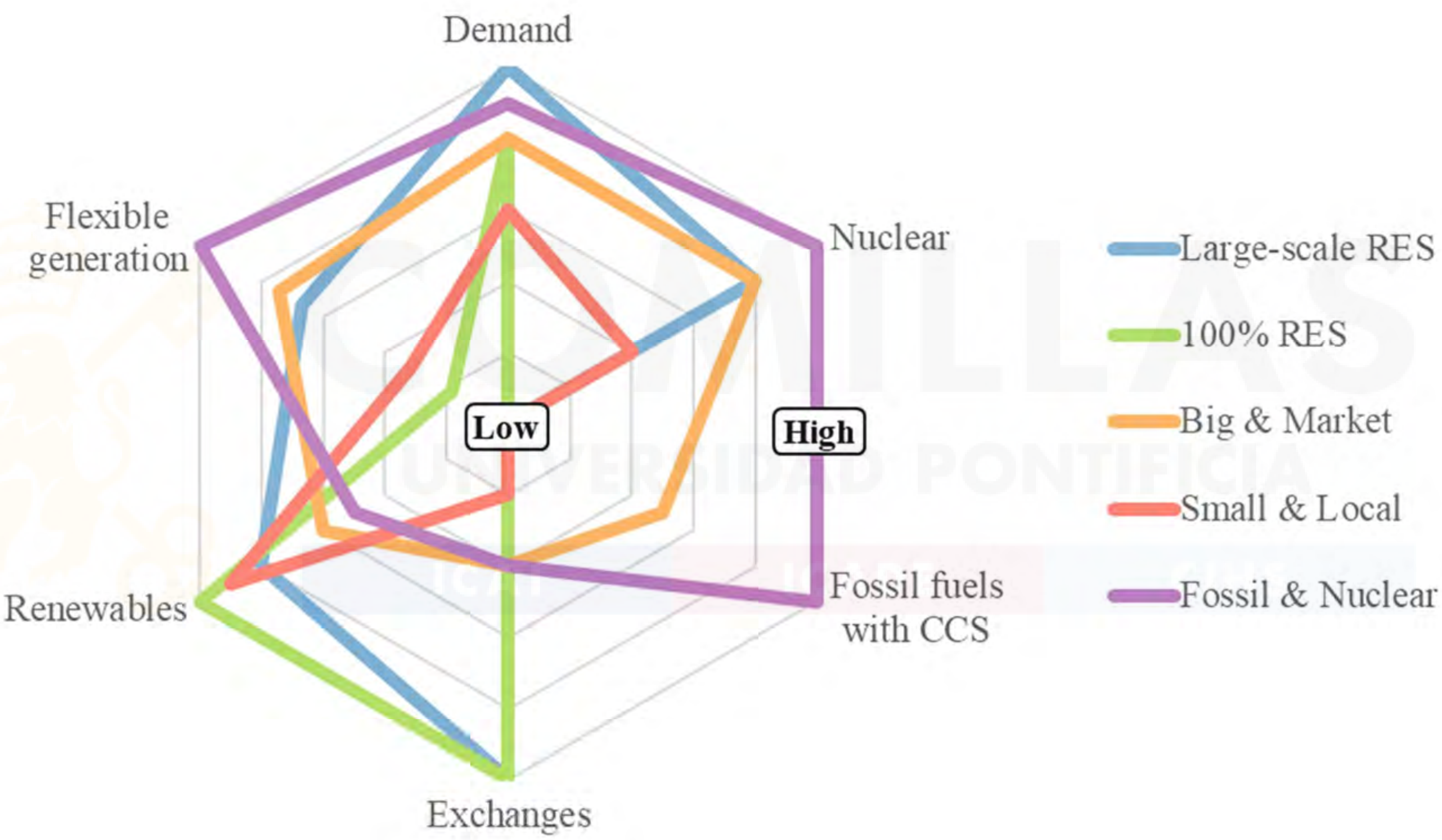
e-HighWay 2050.
WP2. Iterative search for a suitable expansion plan (i)

- Best adapted to medium term planning of not very large systems
- Requires iteration between planning module and grid analysis module
  - For any given network architecture, the network analysis module computes the economic dispatch subject to relevant technical constraints, producing:
    - Relevant information on the economic impact of reinforcements
    - Set of non-satisfied technical constraints
  - Planning module proposes changes to the set of network reinforcements based on information produced in the grid analysis module
    - Aimed at maximizing social welfare
    - While addressing technical infeasibilities previously detected

e-HighWay 2050.
WP2. Iterative search for a suitable expansion plan (i)

- Appropriate indicators of the economic impact of network reinforcements must be defined previously
  - Maybe based on marginal impact

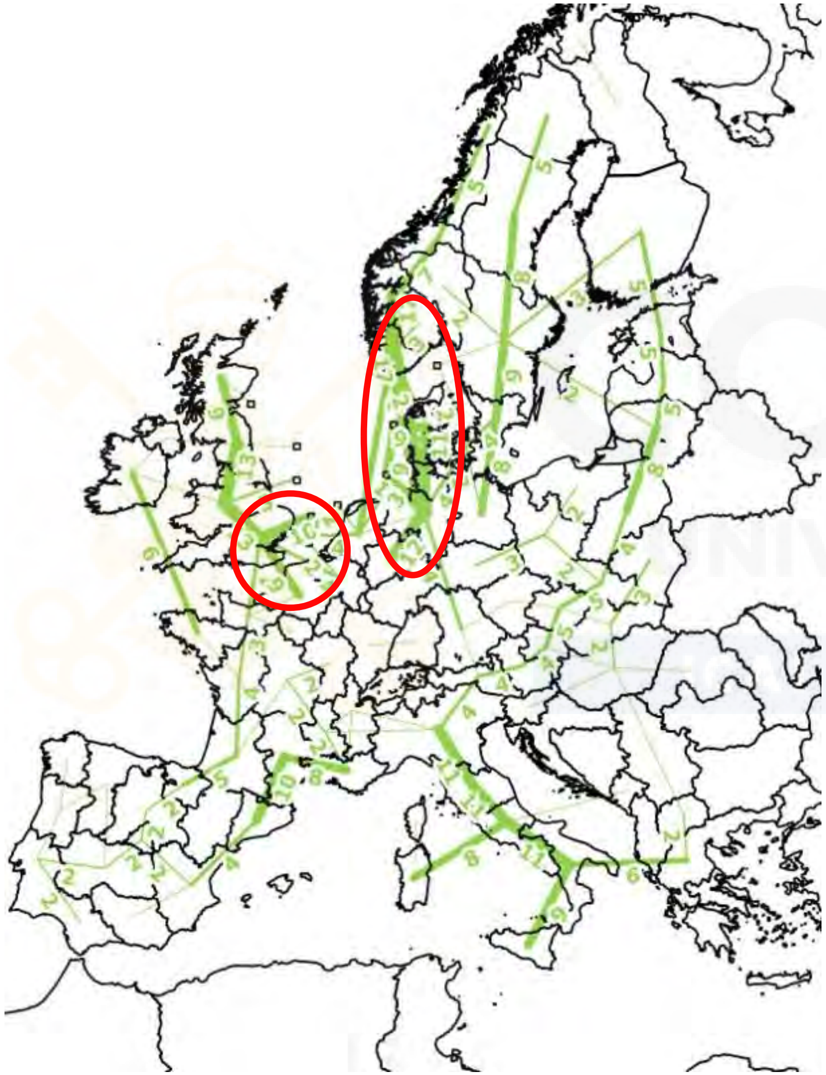
e-HighWay 2050.
Long-Term TEP Scenarios



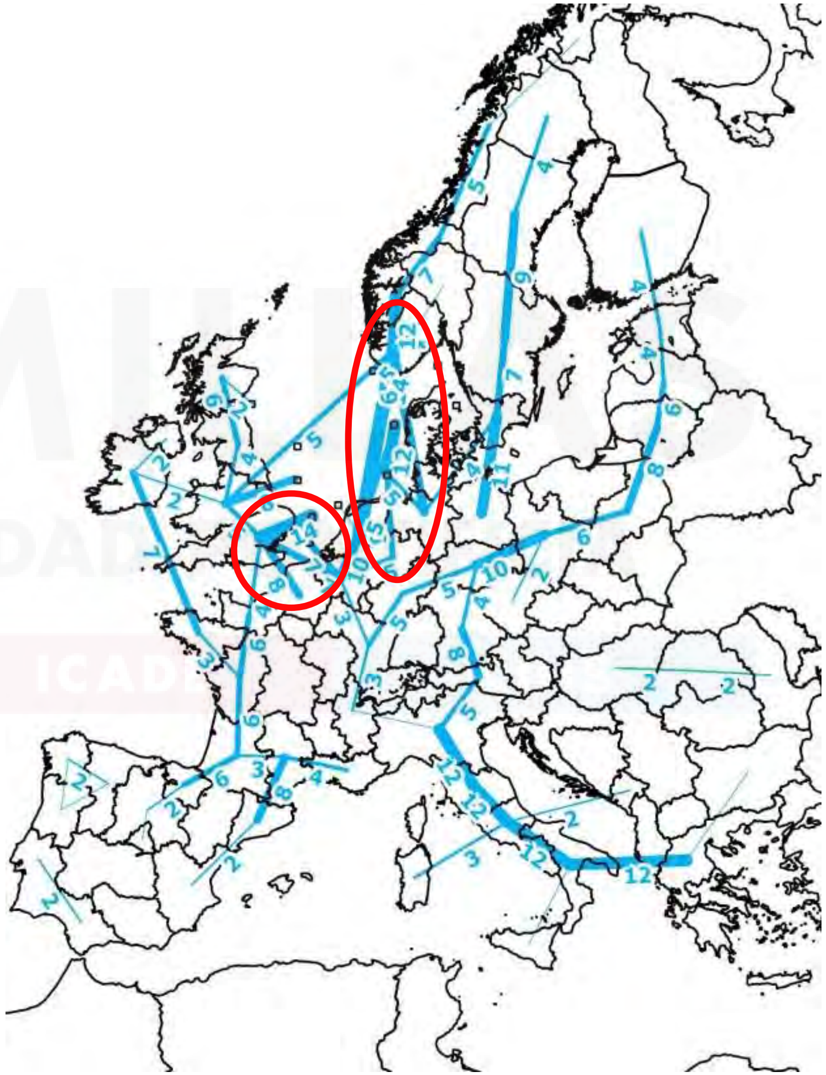
Source: João G. Dedecca et al. *Governance of the Integrated North Sea Offshore Grid: Simulation of Expansion Planning Constraints*

e-HighWay 2050.

Large-scale RES

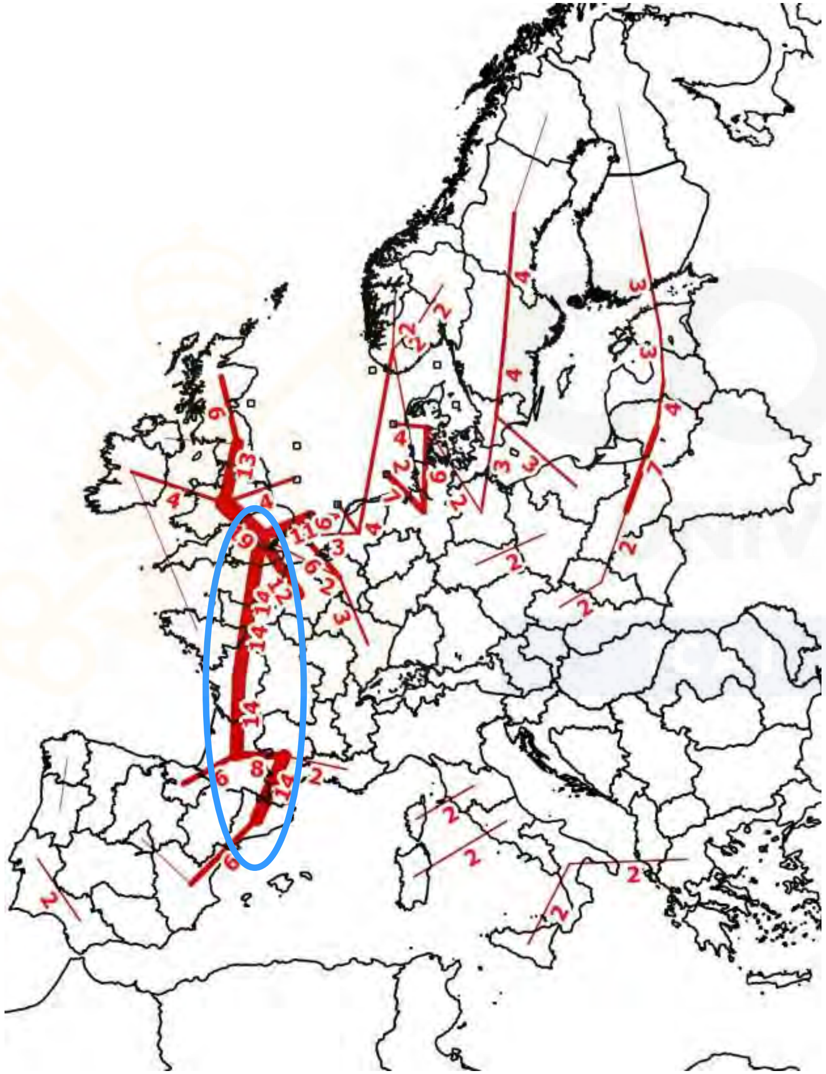


100 % RES



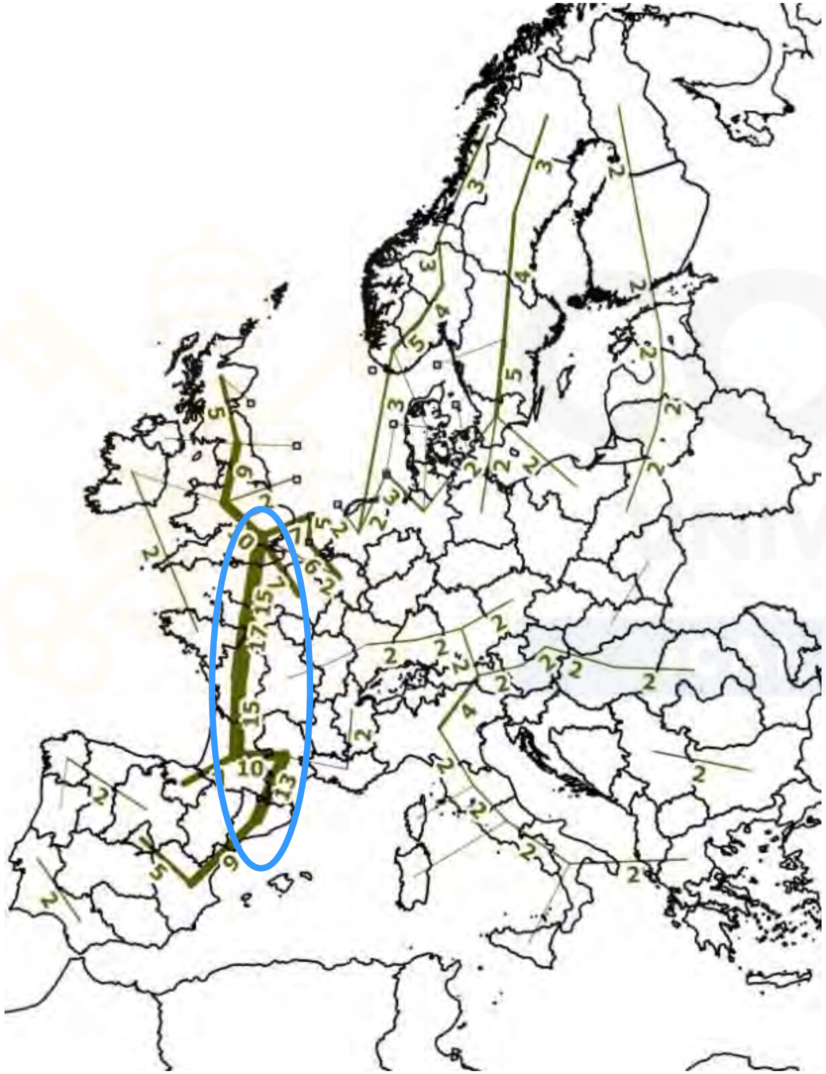
e-HighWay 2050.

Big & Market



Small & Local

e-HighWay 2050.
Fossil & Nuclear



e-HighWay 2050.
WP6. Socio-economic analysis

- Multi-criteria methodology for comparing transmission investments by assessing socio-economic impact on the basis of costs, risks and benefits for society and stakeholders
- And incorporating the impact of the governance models

e-HighWay 2050.
WP8. Enhanced transmission planning methodology

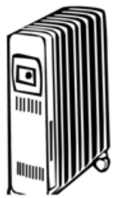
- Define a new methodology able to address challenges in long-term grid planning
- Elaboration of test cases
- Definition of generation and demand scenarios
- Enhanced modular development plan
- Robustness of the grid architecture proposed
- Enhanced methodology for long-term planning and specification of the associated tools

e-HighWay 2050. Challenges for TEP

Spatial complexity: *Europe to smart cities*

Temporal complexity: *msec. to decades*

Stochastic complexity: *weather conditions and human behaviors*

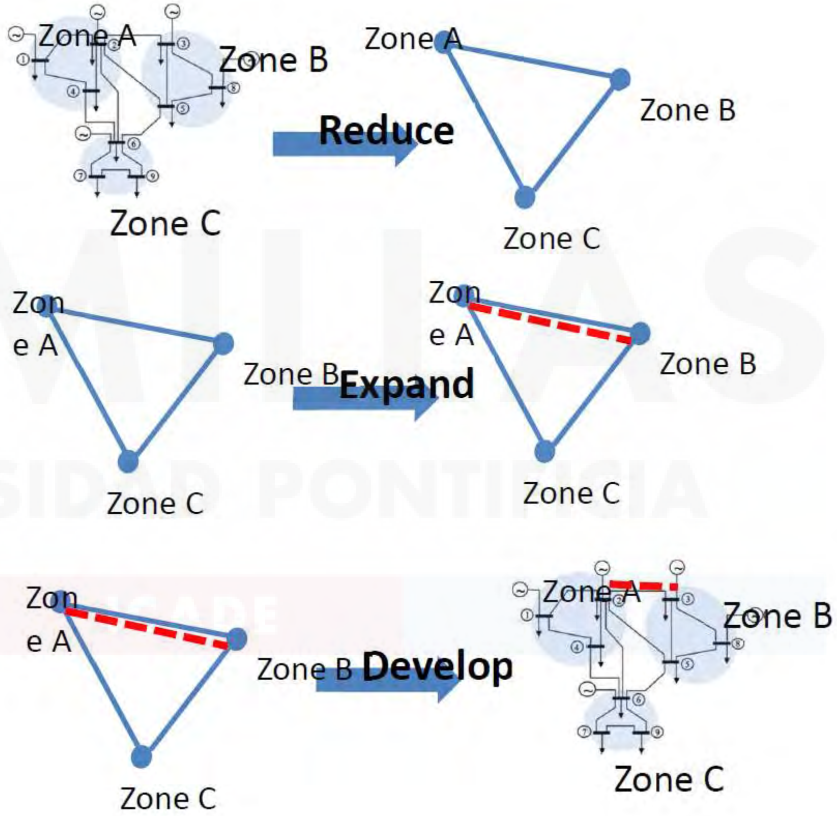


e-HighWay 2050.
Overview of the WP8 methodology (i)

1. Network reduction
Reduce
(from nodal to zonal grid)

2. Optimal grid expansion at zonal level
Expand
(dynamic transmission expansion planning at zonal level)

3. Optimal grid expansion at nodal level
Develop
(static transmission expansion planning at nodal level)



- S. Lumbreras, A. Ramos, F. Banez-Chicharro, L. Olmos, P. Panciatici, C. Pache, J. Maeght *Large-scale Transmission Expansion Planning: from zonal results to a nodal expansion plan* IET Generation, Transmission & Distribution 11 (11), 2778-2786, Aug 2017 10.1049/iet-gtd.2016.1441
- S. Lumbreras, A. Ramos, L. Olmos, F. Echavarren, F. Banez-Chicharro, M. Rivier, P. Panciatici, J. Maeght, C. Pache *Network Partition Based on Critical Branches for Large-Scale Transmission Expansion Planning* IEEE PowerTech. Eindhoven, The Netherlands. June 2015 10.1109/PTC.2015.7232344

e-HighWay 2050.
Overview of the WP8 methodology (ii)

All time horizons and scenarios

STEP 1 – ADEQUACY WITHOUT GRID

STEP 2 – DETECTION OF OVERLOAD PROBLEMS

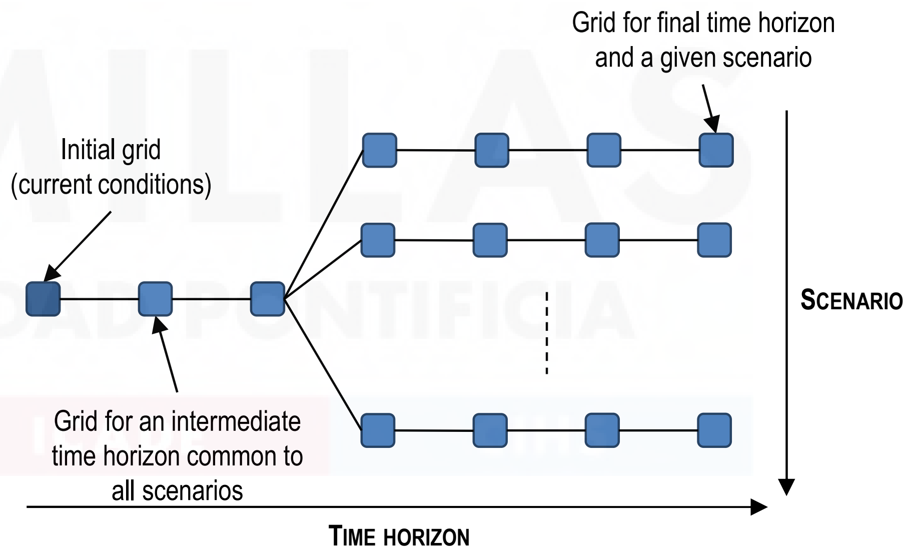
STEP 3 – NETWORK REDUCTION ACCORDING TO CRITICAL BRANCHES (≈100 NODES)

STEP 4 – OPTIMAL GRID EXPANSION AT ZONAL LEVEL FROM TODAY TO 2050

First two time horizons

STEP 5 – GRID EXPANSION AT NODAL LEVEL

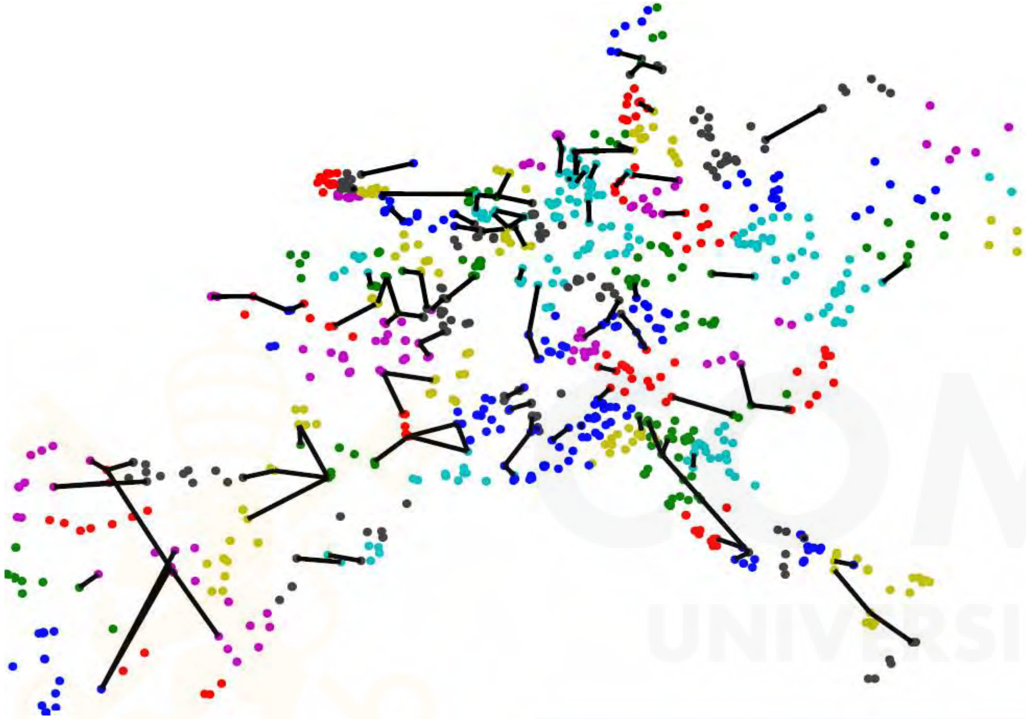
STEP 6 – ROBUSTNESS OF THE PROPOSED GRID ARCHITECTURES

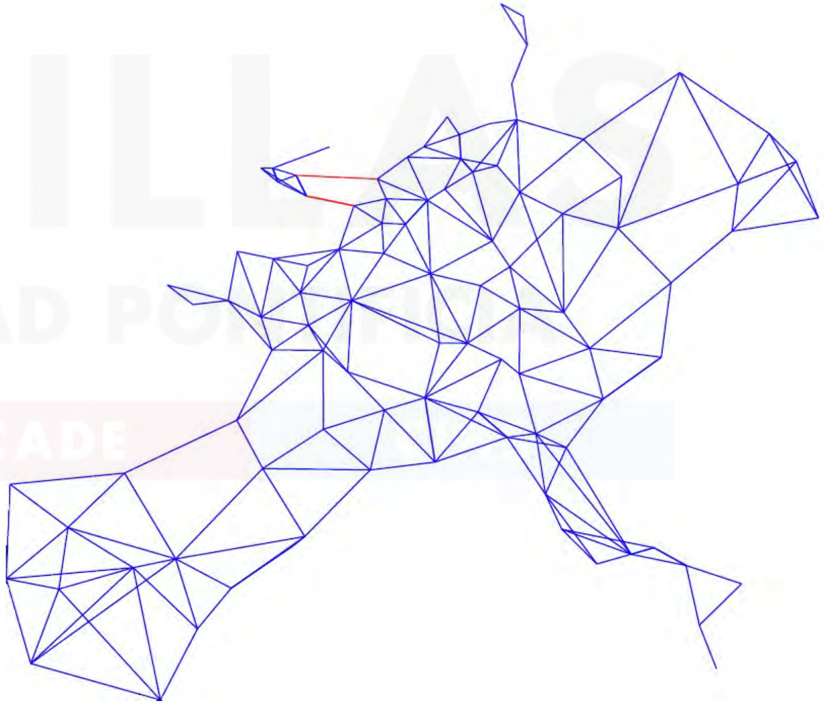


e-HighWay 2050. European original network

Number of nodes	**5155**
Number of 400kV nodes	1385
Number of lines	**10209**
Number of 400kV PST	17
Number of 400kV interconnection lines	69
Number of HVDC links	3
Number of generating units with $P_{min} > 0$	418
Number of hydro units with reservoir	348

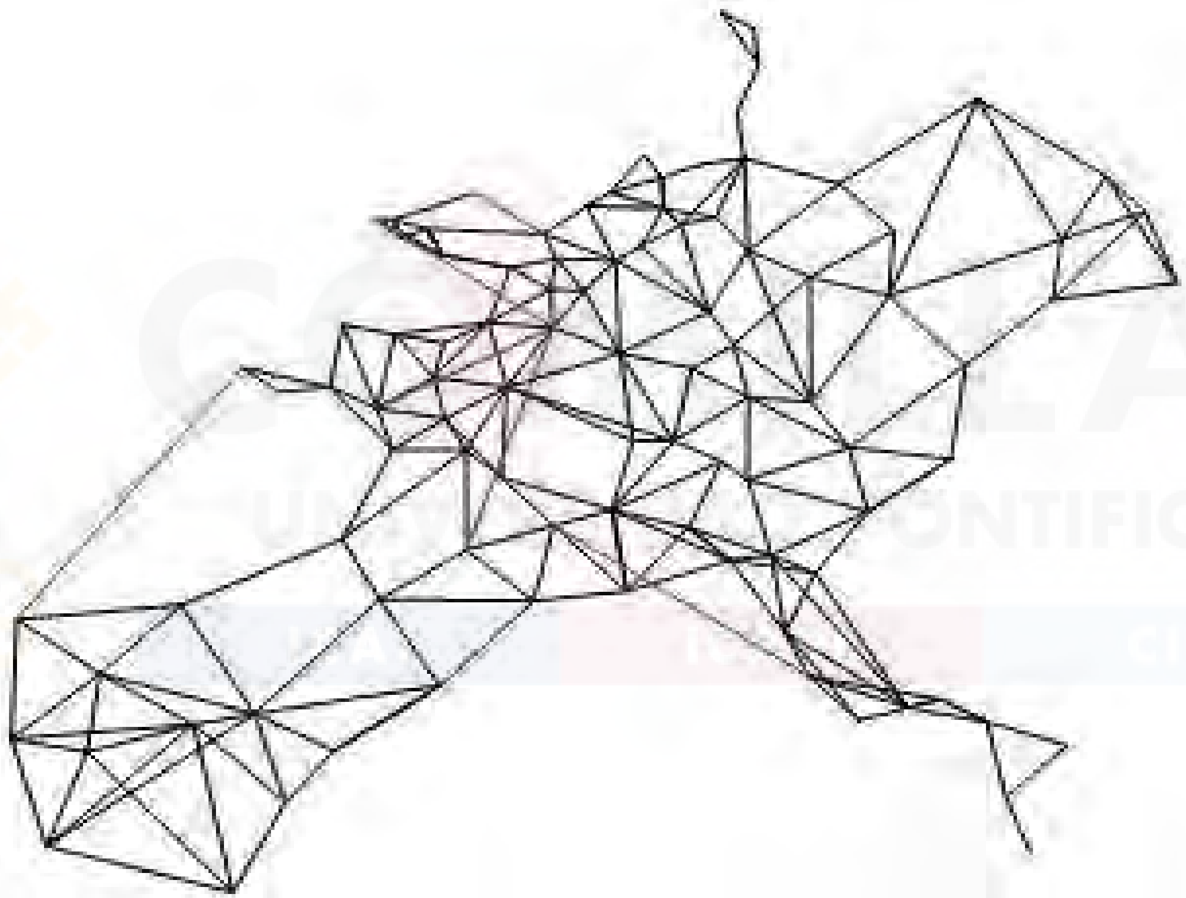
e-HighWay 2050.
European network reduction





Number of zones	100
Number of 400kV corridors	243
Number of PST	17
Number of HVDC links	3

e-HighWay 2050
Zonal expansion



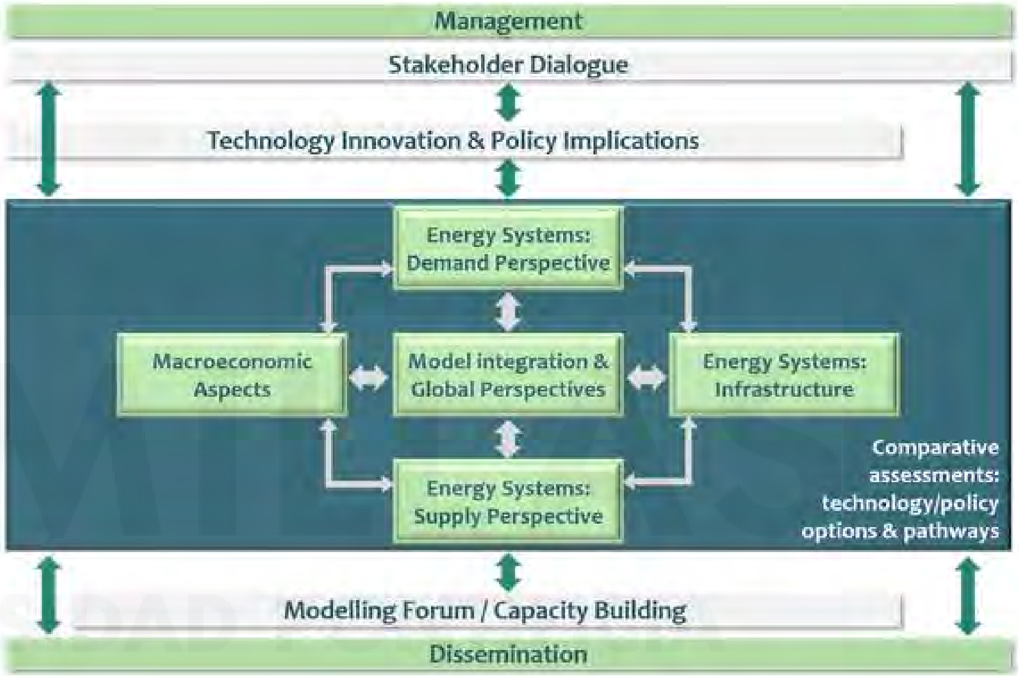
e-HighWay 2050. Nodal expansion

Overall method for TEP studies

- Definition of main assumptions
  - 2050 towards a low carbon economy
  - Up to 17% of Europe's demand for power in 2050 from the deserts of North Africa and the Middle East
  - Generation storylines
- Determine localized long-term European/regional generation expansion plans
  - Localize future generation and demand in nodes
  - Hourly time periods
- Determine snapshots (~80) to evaluate transmission expansion plans
- Determine cross-border interconnections
  - Save (flexible, no regret) decisions
  - Dynamic decisions are more important that final “optimal” decisions. Alternatively, sequential static decisions for some target years (2030, 2050, etc.)
  - Modular development
- Determine specific national reinforcement studies

SET-Nav. Overview

Stakeholder dialogue and Dissemination are the central elements of the dissemination part, including the organisation of topical stakeholder workshops and a broad set of complementary dissemination activities (regional workshops, final conference, web, policy briefs etc.).



Technology innovation and Policy Implications will integrate insights on innovation system policies into SET-Plan scenarios and modelling to develop novel empirical relationships between innovation systems and key innovation processes relevant to the SET-Plan.

Model integration and Global Perspectives will provide key parameters regarding the potential development of global fossil fuel markets and other parameters ("global perspectives") to the EU-centered modelling works in SET-Nav.

Energy Systems: Demand Perspective will provide and apply the modelling framework for the demand side of energy systems including buildings, industrial processes and transport.

Energy Systems: Infrastructure will assess the needs for electricity infrastructure brought by the transformation of the energy system. Complementarily, the needs for gas infrastructure and for Carbon Capture and Storage (CCS) infrastructure that will accompany the anticipated developments will be addressed considering the interrelationships between the three different infrastructure systems.

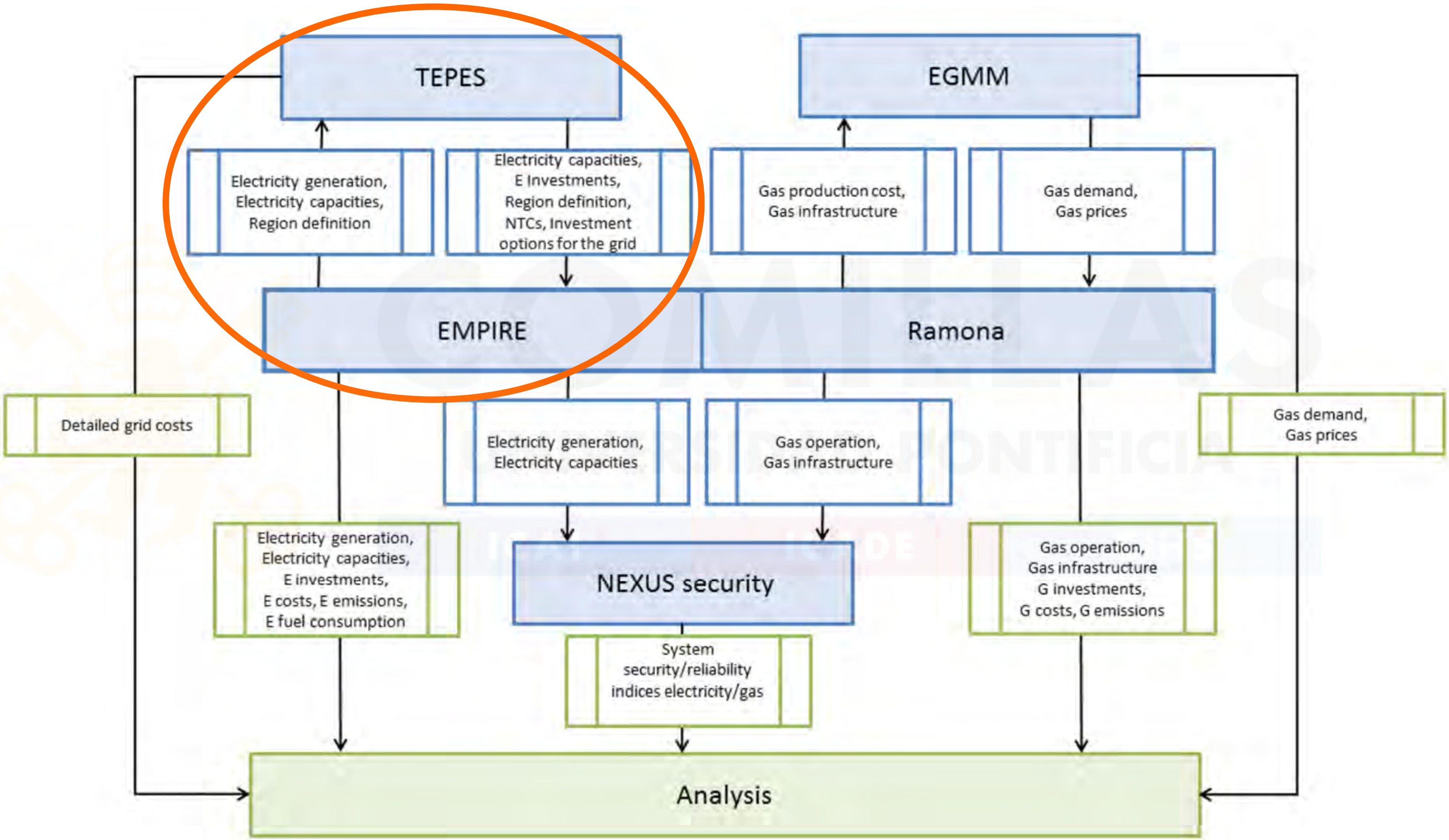
Energy Systems: Supply Perspective will develop a strong modelling framework regarding energy supply with a particular focus on electricity. In this context enabling and improving interaction between the different models with complementary strengths (system optimisation, policy representation, etc.) is a strong focus.

Macroeconomic Aspects will analyse the interrelationship between energy transformation and the economy, evaluating the macro-economic impacts of the distinct energy transformation pathways.

Comparative assessments: Technology/Policy Options and Pathways carries out a coordinating function in two ways: On the one hand it manages the process that defines transformation pathways that are run by all modelling groups and that ensures consistent implementation of the pathway iterations across models. On the other hand the results from all the case studies, pathway analyses and other complementary assessments are consolidated here.

Modelling forum / Capacity building is in charge of the development of new approaches for building advanced, more holistic energy-economy-environment models. Cross-fertilisation of ideas across distinct modelling methodologies is a central pillar thereby, as is capacity-building and sharing of "best-practice examples" in applied energy system modelling.

SET-Nav. Interlinkages for all supply models



RESCost. Objective

- EC proposal for 2030
  - 40 % reduction target of emissions from 1990
  - 27 % for RES in final energy consumption
  - 30 % energy efficiency target from 2007
- Germany Ministry of Economics wanted to study 3 future generation storylines

RESCost. Generation storylines

- **GHG40**
  - 40% GHG emission reductions by 2030
  - **ETS main driver** for low-carbon technology support
  - **Energy efficiency** measures in place
  - Achievement of 2020 RES targets
  - **No dedicated support** for RES beyond 2020
  - 26.4% RES share by 2030
- **30Quo**
  - 40% GHG emission reductions by 2030
  - ETS one driver for low-carbon technology support
  - Energy efficiency measures in place
  - Achievement of 2020 RES targets
  - After 2020 continuation of **RES support by means of an EU green certificate scheme**
  - 30% RES-Share by 2030
  - **Technology-uniform quota obligation** across all EU members
- **30SNP**
  - 40% GHG emission reductions by 2030
  - ETS one driver for low-carbon technology support
  - Energy efficiency measures in place
  - Achievement of 2020 RES targets
  - Continuation of. **RES support with balanced RES support across countries in terms of a feed-in premium**
  - 30% RES-Share by 2030

RESCost. TEP modeling summary

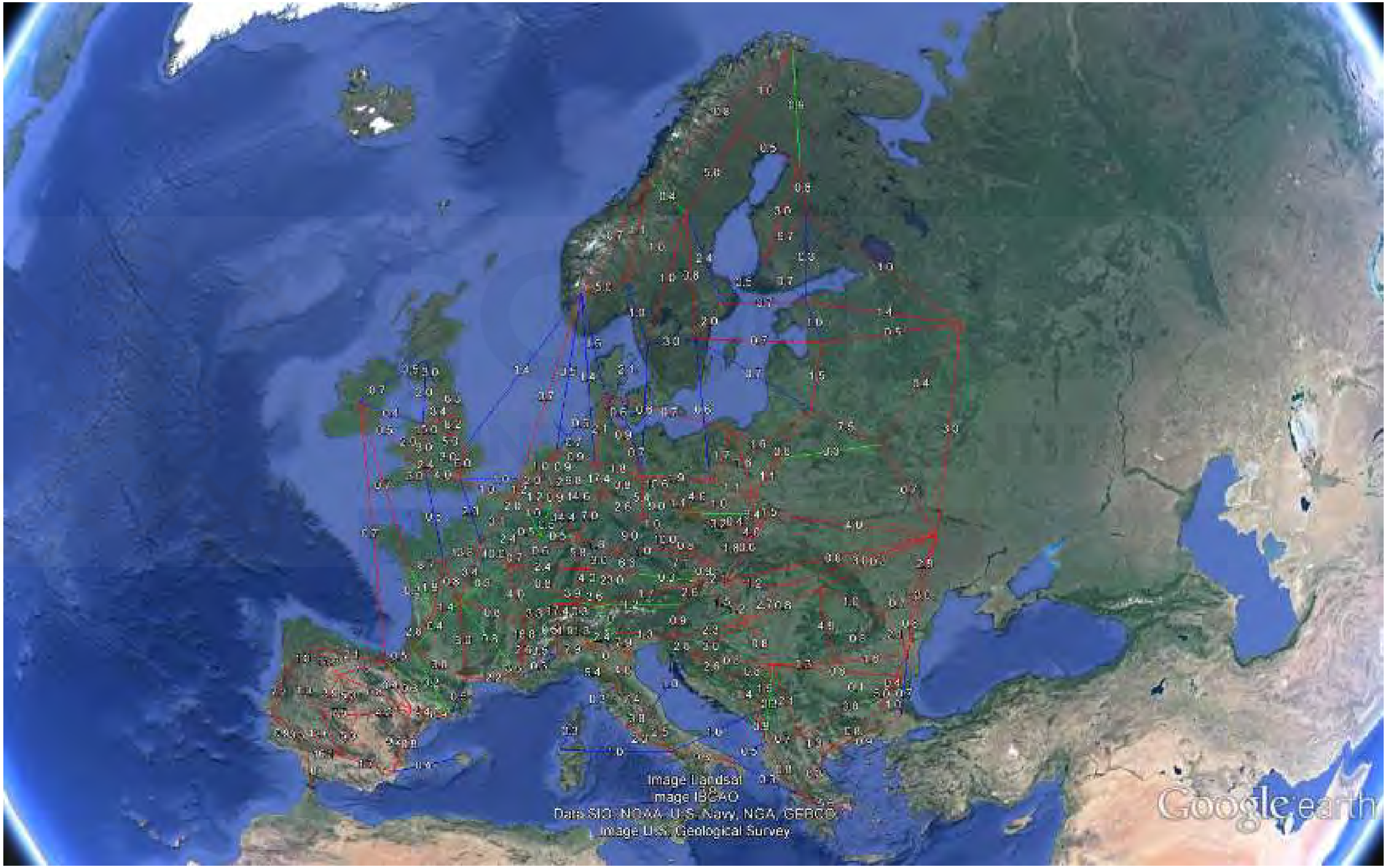
- Base case is ENTSO-e 2012
- Area division in each country
- Allocation of demand and generation to areas
- Losses proportional to the corridor flow
- Capacity of each corridor
- Transportation model load flow
- Expansion up to 2030 and 2050 directly from 2020

A. Held, M. Ragwitz, F. Sensfuß, G. Resch, L. Olmos, A. Ramos, M. Rivier *How can the renewables targets be reached cost effectively? Policy options for the development of renewables and electricity networks* Energy Policy 116, 112-126, 2018 10.1016/j.enpol.2018.01.025

RESCost. Results

	GHG40	30QUO	30SNP
System costs in 2030	65 €/MWh	64 €/MWh	68 €/MWh
Transmission Network Costs in 2030	0.16 €/MWh	0.19 €/MWh	0.30 €/MWh
Generation investment	26.5 % share of RES	a lot of WG-onshore and half of 30SNP PV	a lot PV and WG-offshore

RESCost. Existing extended network in 2020 with TEPES



RESCost. New investments in 2030 GHG40 with TEPES

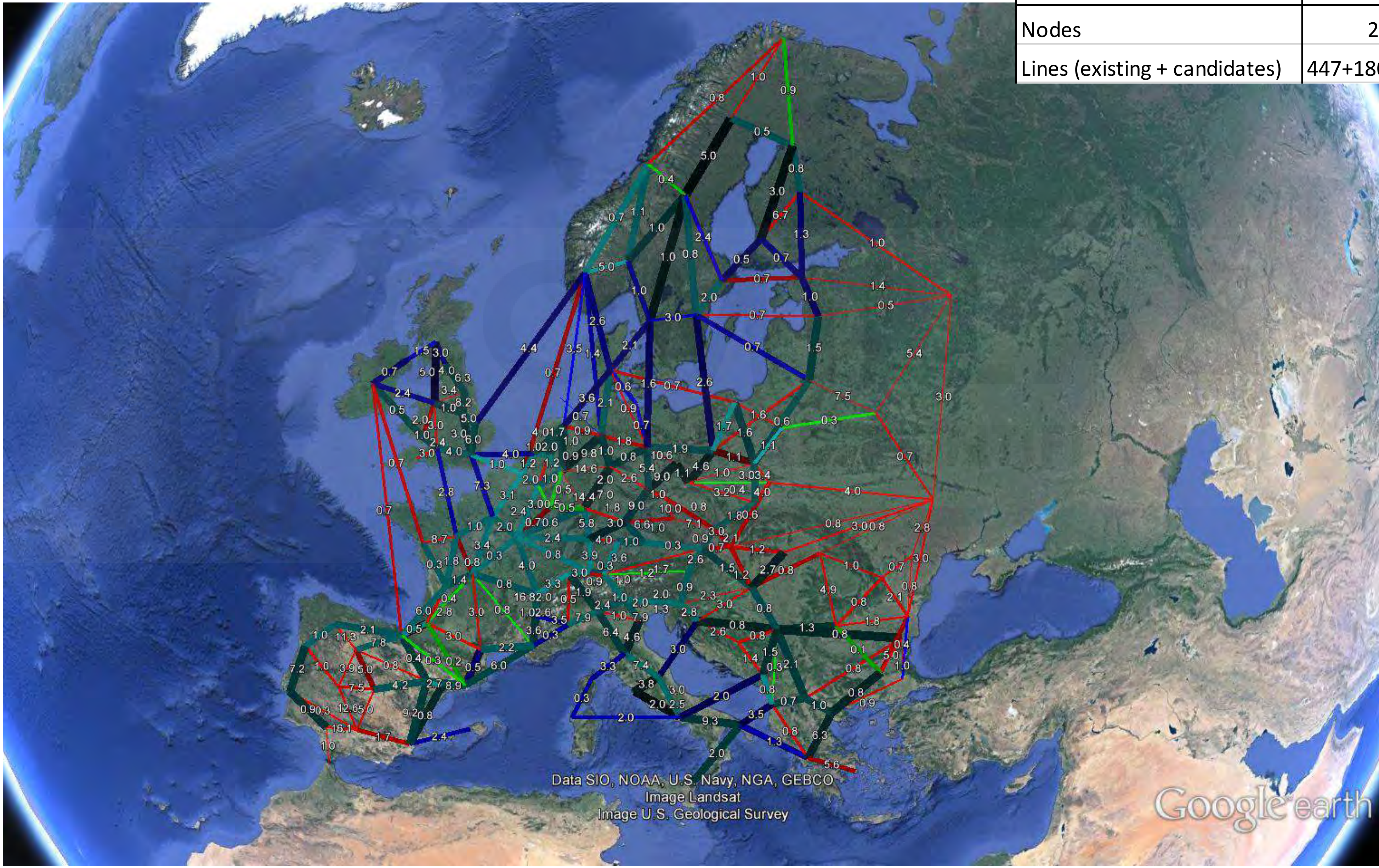
RESCost. New investments in 2030 30Quo with TEPES

Fraunhofer ISI

RESCost. New investments in 2030 30SNP with TEPES

RESCost 2050

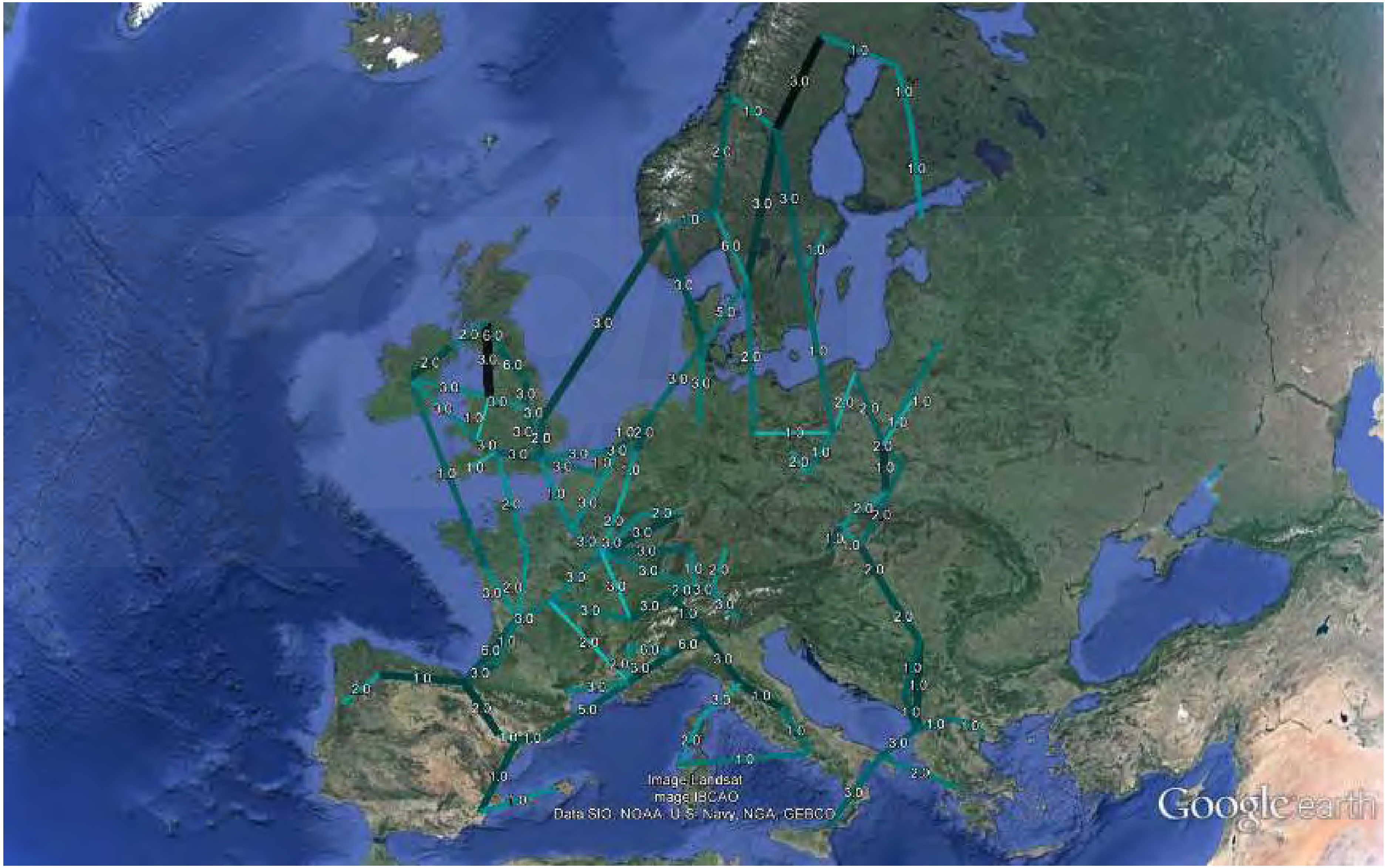
Years	1
Periods	1
Sub-periods	1
Load levels	80
Nodes	254
Lines (existing + candidates)	447+1807



RESCost. New investments in 2050 GHG40 with TEPES

RESCost. New investments in 2050 30Quo with TEPES

RESCost. New investments in 2050 30SNP with TEPES

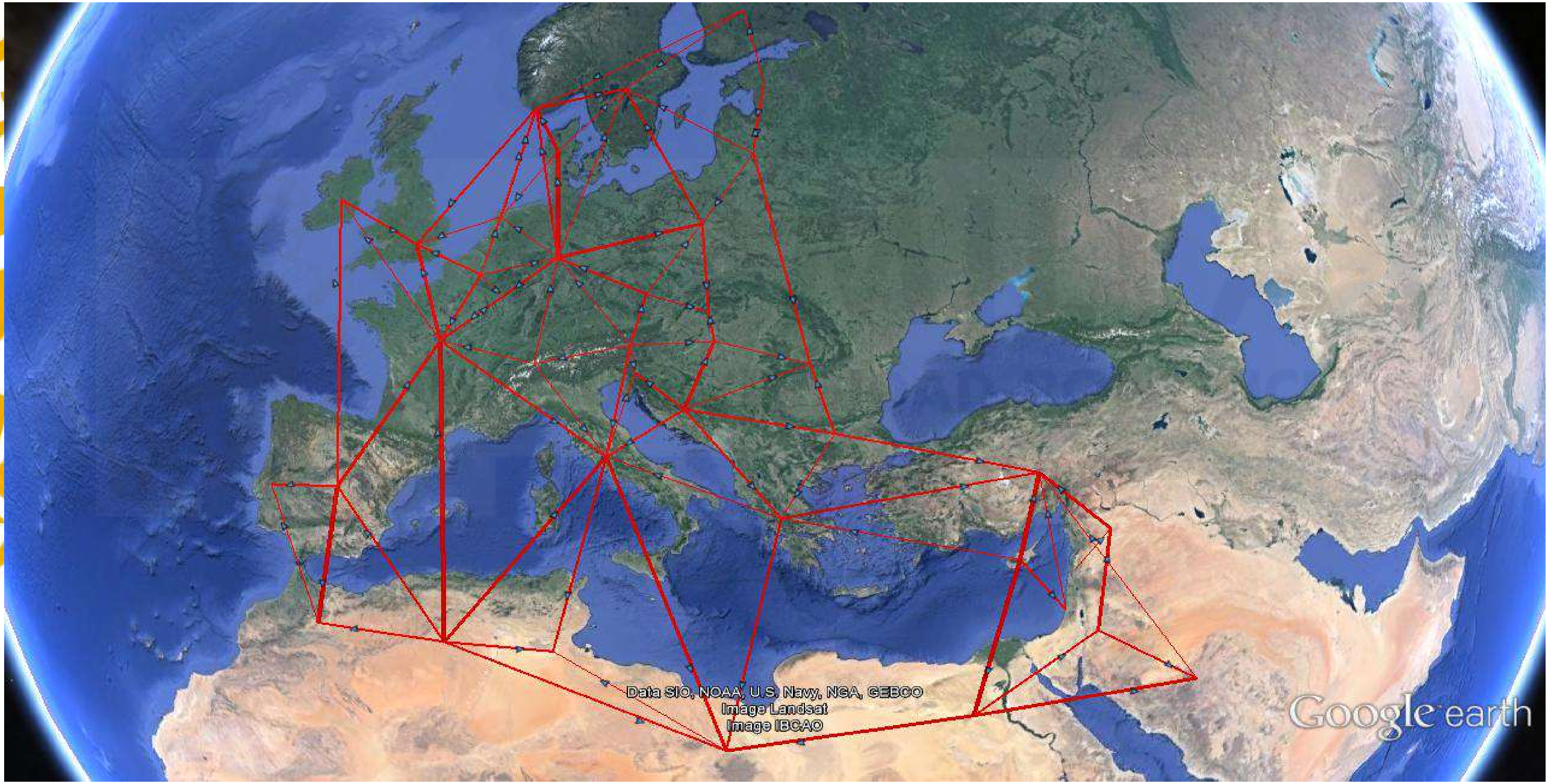


Desertec Industrial Initiative (Dii) (http://desertenergy.org/)

- Private industry consortium working towards enabling this vision in Europe, the Middle East and North Africa (EUMENA).
- The power generated from sun and wind is intended primarily to meet the local demand of the producer countries, but could also be exported to Europe. The overall objective of Dii is to create a market for RES from the deserts.
- Development of numerous individual projects in the field of power generation and transmission and a suitable regulatory framework which will evolve over the coming years and decades
- Desert Power 2050: Perspectives on a Sustainable Power System for EUMENA
- Desertec Power: Getting Connected (2030)

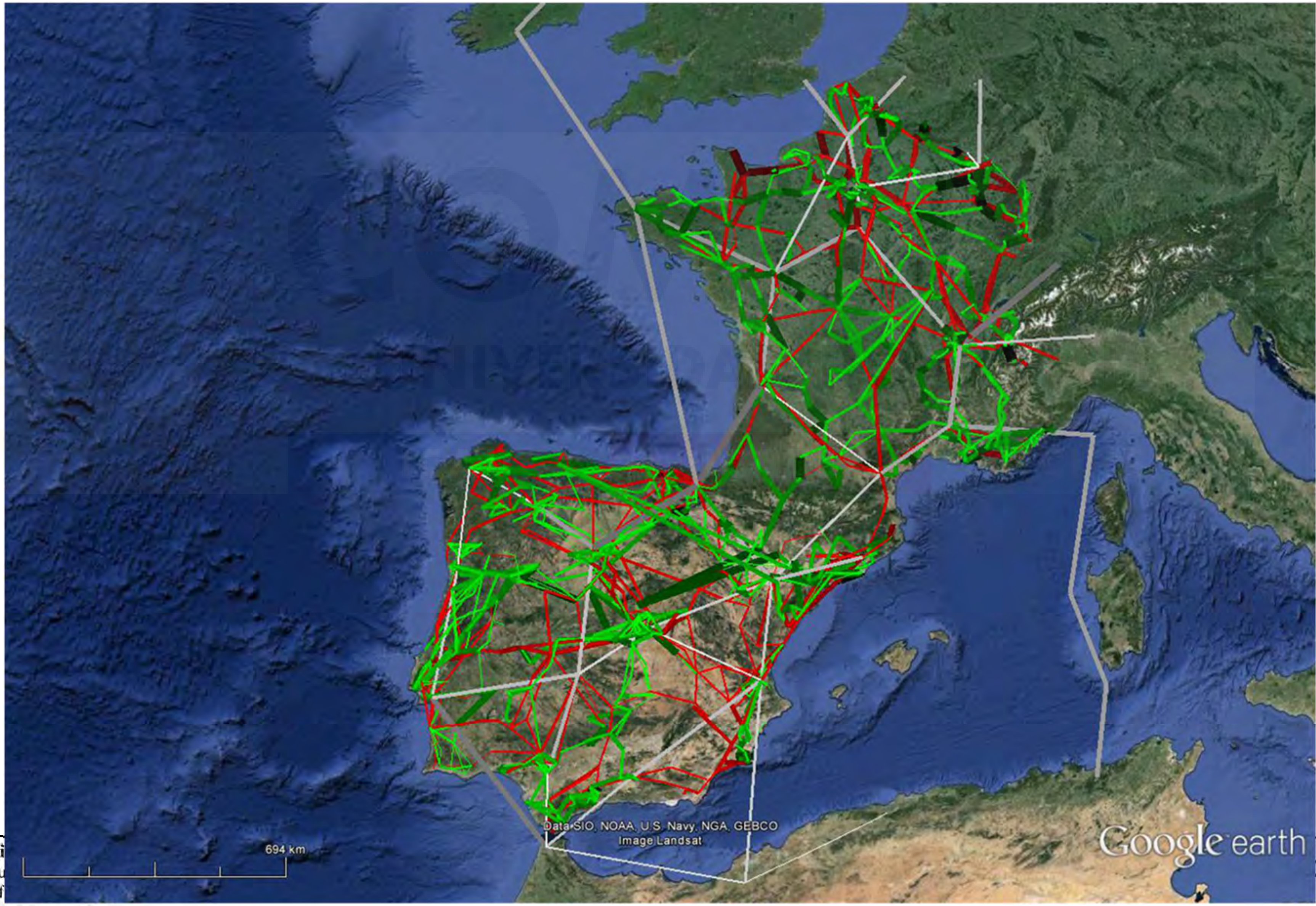
Desertec 2050

Year	1
Period	1
Subperiod	1
Load Level	80
Thermal units	468
Hydro plants	0
Nodes	79
Lines (existing + candidates)	127+183



Desertec 2030

Year	1
Period	1
Subperiod	1
Load Level	70
Thermal units	169
Hydro plants	94
RES	1649
Nodes	1667
Lines (existing + candidates)	3560+252



MedGrid (http://www.medgrid-psm.com/en/project/)

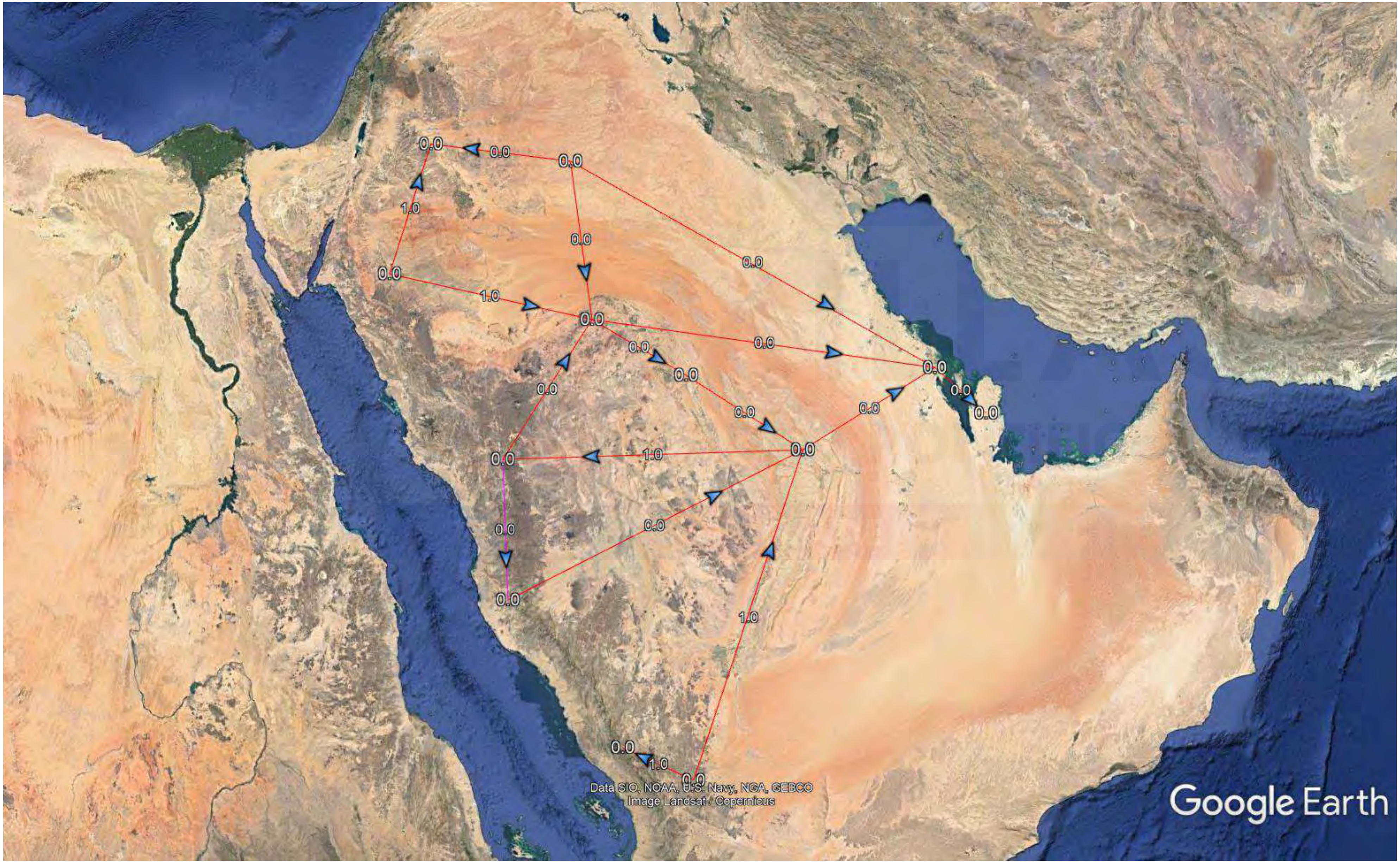
- Ensure energy security, reduce greenhouse gases and boost economic development through a range of ambitious co-development projects around the Mediterranean.
- Transmit electricity from solar or wind power plants to load centers on either rim of the Mediterranean
- Requires new infrastructure in the shape of submarine High-Voltage Direct Current (HVDC) cables.
- Better interconnection will strengthen the reliability of power systems and create a large electricity market in the South, to satisfy energy demands at the best possible price.

MedGrid Objectives

- Identify some alternative reinforcement plans of the Western corridor's transmission network
  - to increase the NTC values in +1GW, +2GW, +3GW
  - between North Africa and France (crossing Spain and Portugal)
  - taking as reference the network already foreseen for 2020-2022

- Comparison and selection of the best alternatives

Saudi Arabia



Nigeria


SKT_1
KTN_1
BRN_6
KBI_2
JGW_2
ZMF_2
KN_2
YBE_1
BRN_1
KBI_1
KD_3
BUC_1
GMB_2
NIGR_5
NIGR_8
PLT_3
BRN_4
NIGR_3
NIGR_1
ADM_1
NIGR_4
FCT_1
FCT_2
NSRW_2
TRB_1
FCT_3
OY_2
OGN_2
KG_6
OSN_4
KG_2
BEN_2
TRB_3
OY_3
TRB_2
KG_4
LAG_4
ED_4
ENG_2
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LAG_5
ED_2
ENG_1
AB_2
ANB_1
DLT_1
RV_3
IM_2
AKB_2
RV_1
AB_4
CRV_2
AKB_3

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