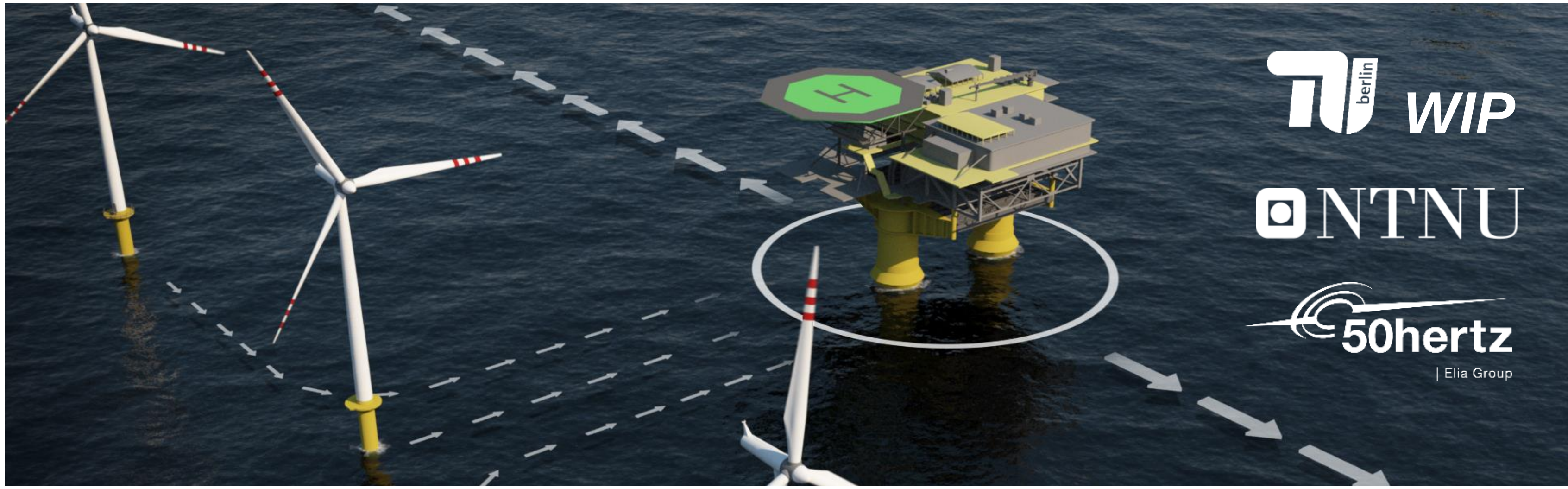
ERRA

DeepWind

Trondheim, Jan 2022

Felix Jakob Fliegner

System of the Future - 50Hertz

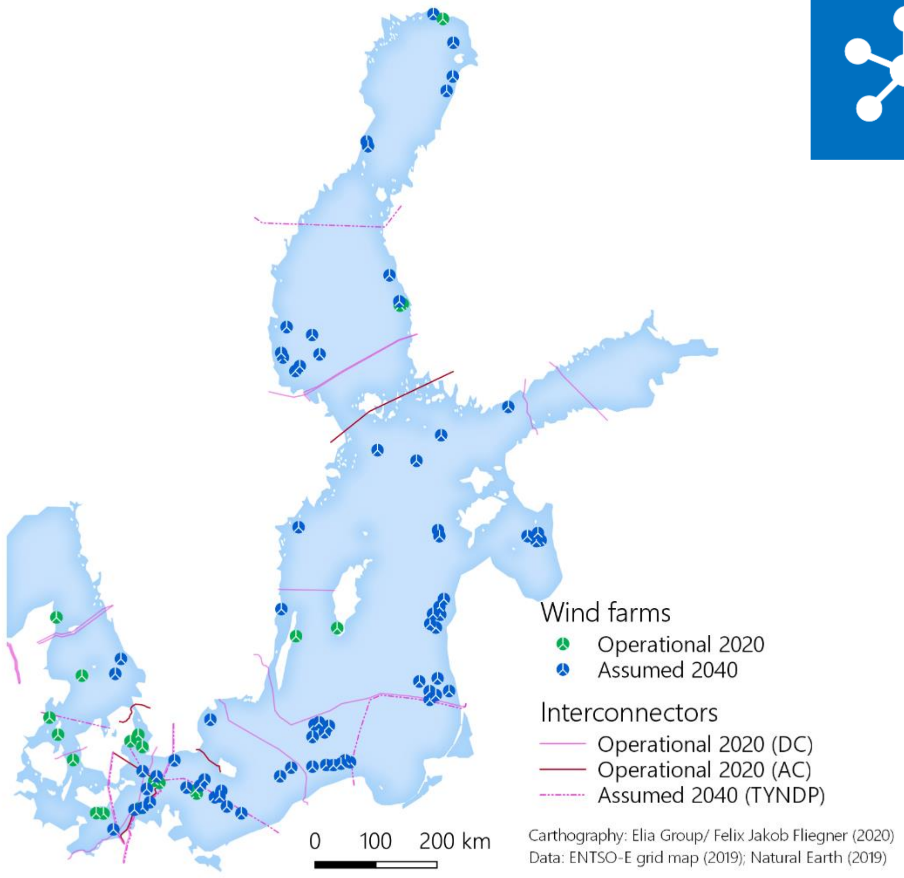


Offshore grid topology optimisation with a geographical information system

– Case of the Baltic Sea –

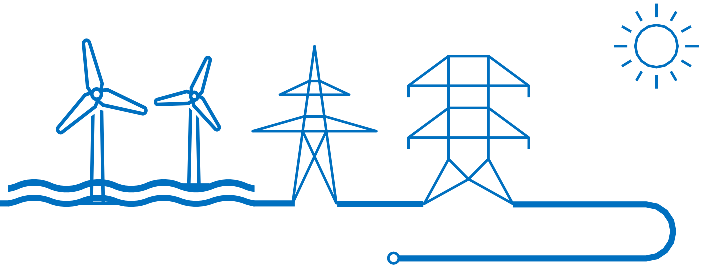
Picture: Kriegers Flak Combined Grid Solution
Worlds first Hybrid Interconnector between DK and DE
Picture: 50Hertz

Setting the Scene

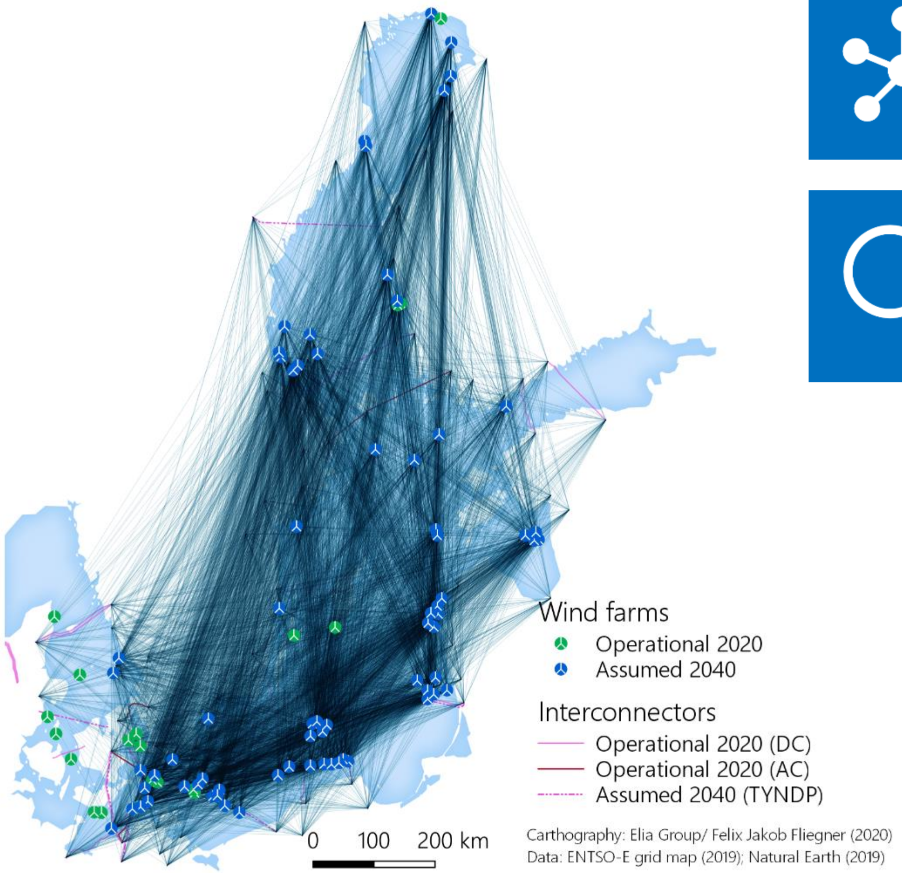


The future is offshore

90+ GW offshore wind potential in Baltic Sea alone
More power grid interconnection foreseeable



Setting the Scene



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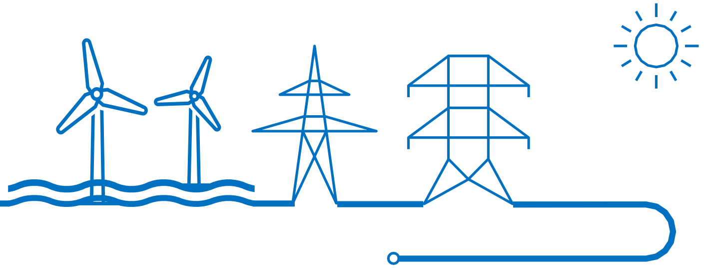
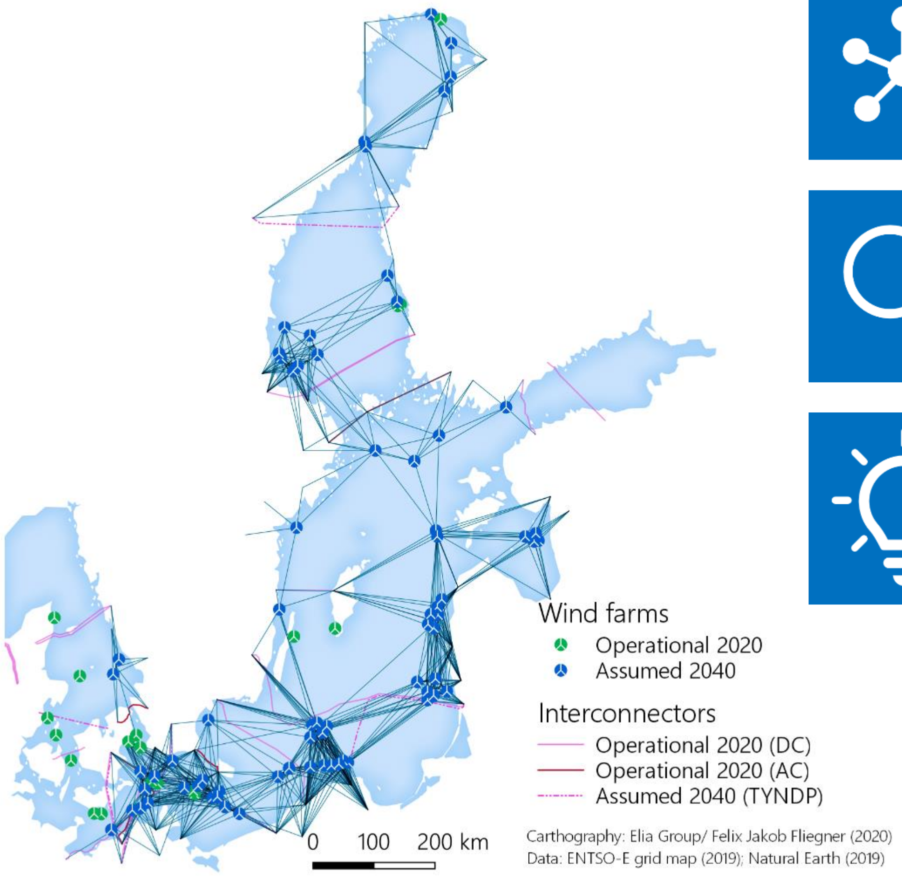
The challenge ahead

How to integrate offshore wind optimally while using synergies with interconnectors?



Setting the Scene



The future is offshore

90+ GW offshore wind potential in Baltic Sea alone
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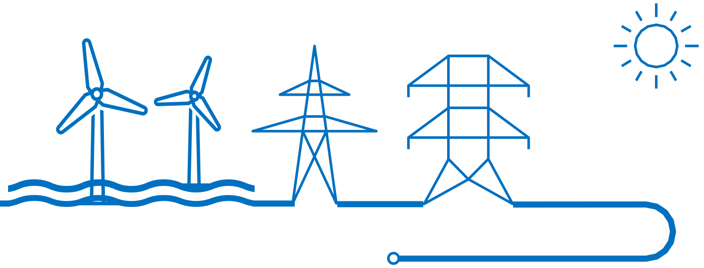
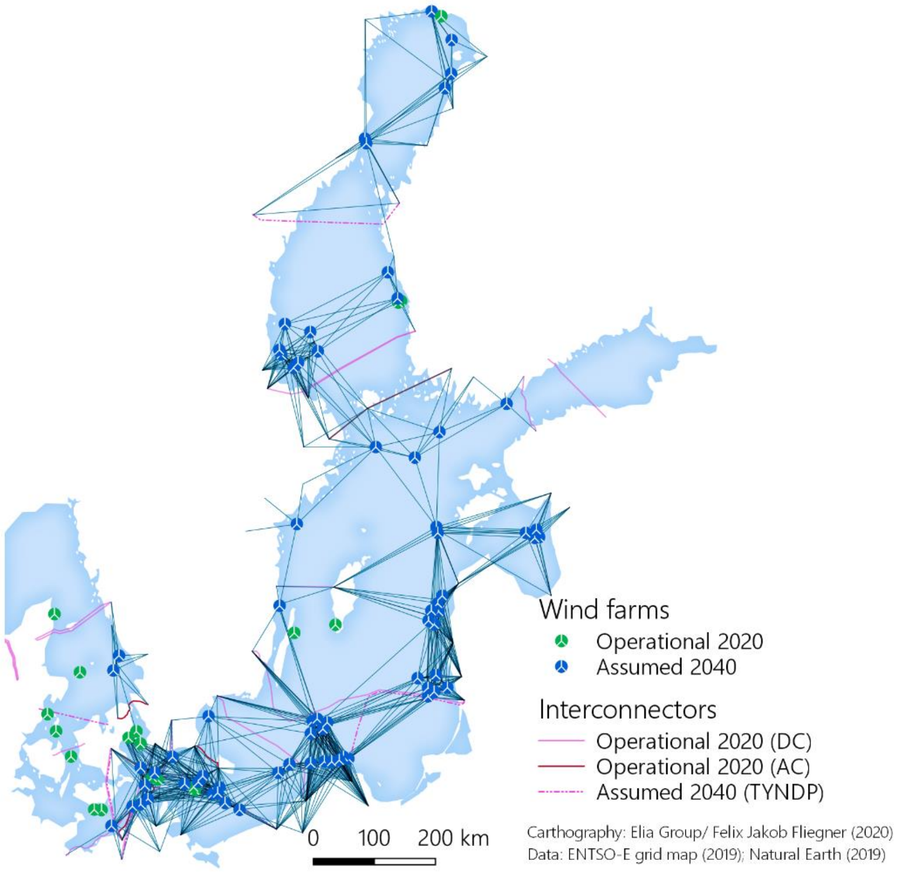
How to integrate offshore wind optimally while using synergies with interconnectors?

Contribution

Demonstrate coupling of GIS analysis with market modelling to facilitate the analysis.
No power grid outlook!



Content



1. The core problem

- Bundling of transmission paths
- Rationale for graph topology setup

2. Framework development

- Clustering of wind farms in QGIS
- Assumptions + Market Model in Julia

3. Illustration of results

- Base Case topology
- Sensitivity Analysis

4. Concluding remarks

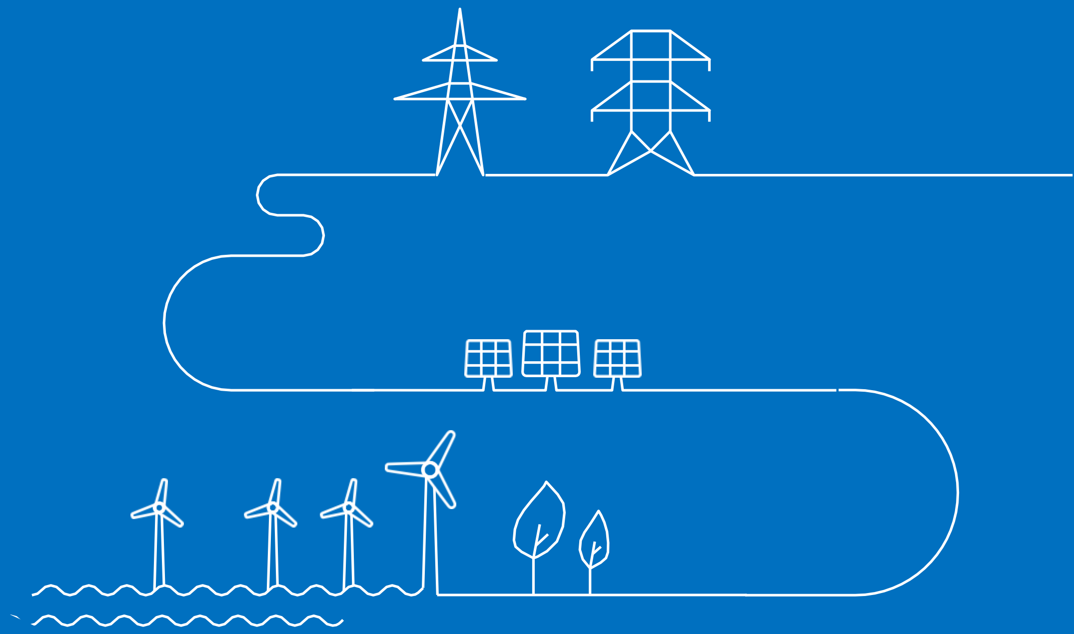
- Contribution & Limits of the proposed framework
- Rescope & Further Research

The core problem

Framework development

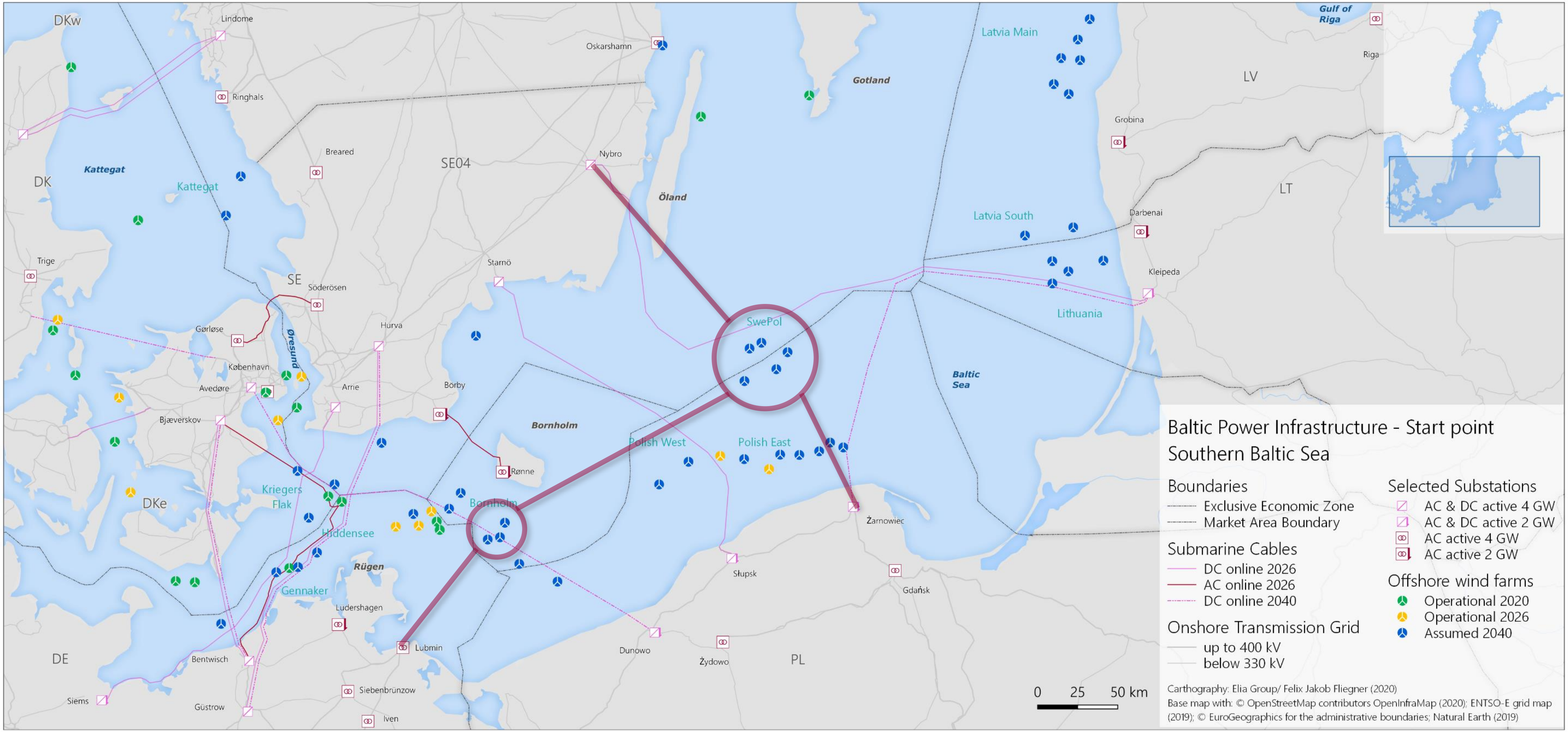
Results

Discussion



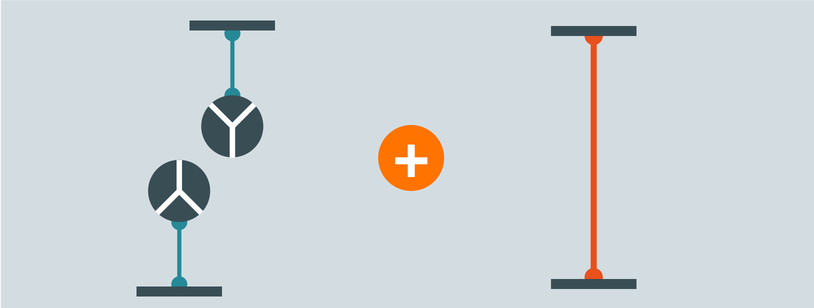
The core problem

How to connect the blue wind farms?



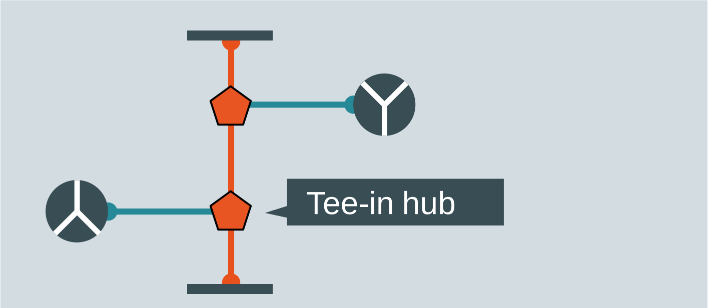
Hybrid assets are the enablers for the future offshore grid

Connecting wind farms and countries…



Radial *Interconnector*

…merged in one system: hybrid asset



Hybrid Asset

Added Value

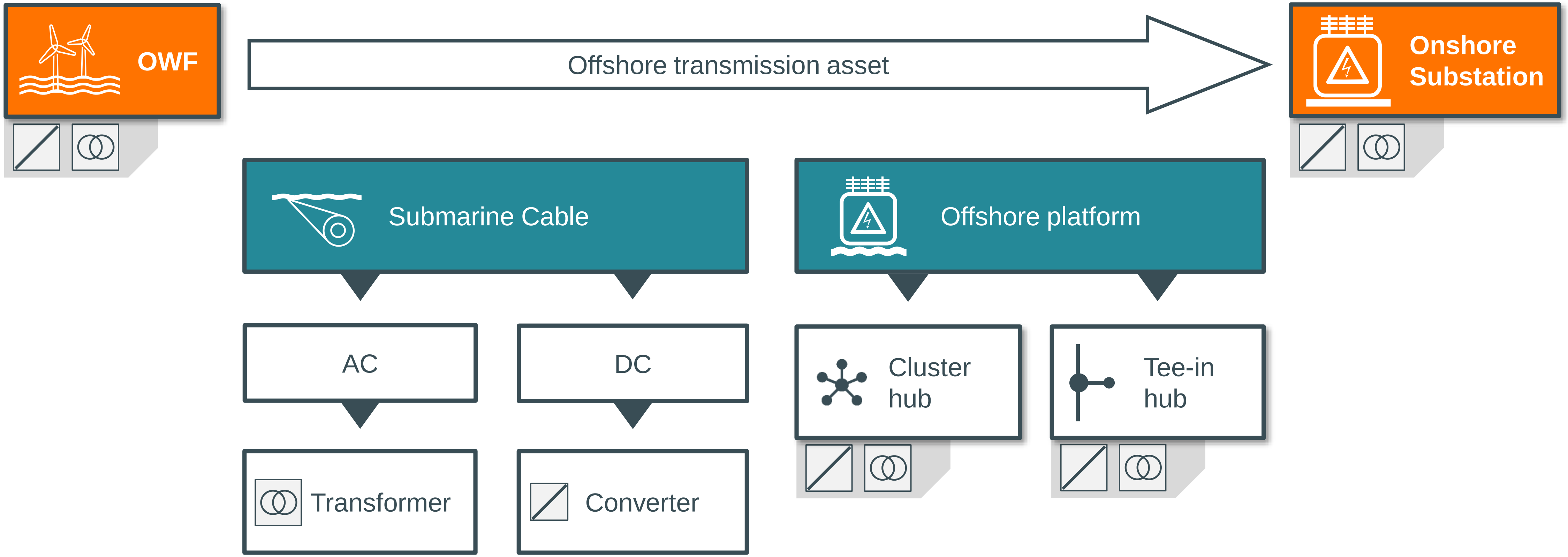
- ✓ *Reduced investment **cost***
- ✓ *Multiple **trade opportunities** for OWF*
- ✓ *Higher cable **utilisation***

Challenge

- × *Distributional effects*
- × *Regulatory framework*
- × *Technical interoperability*

Source: OffshoreGrid 2011, Baltic InteGrid 2019, PROMOTiON project 2015-2020

Centre of analysis is the combinatorial analysis of offshore transmission assets



The optimiser requires a topology to perform the analysis

Graph topology setup

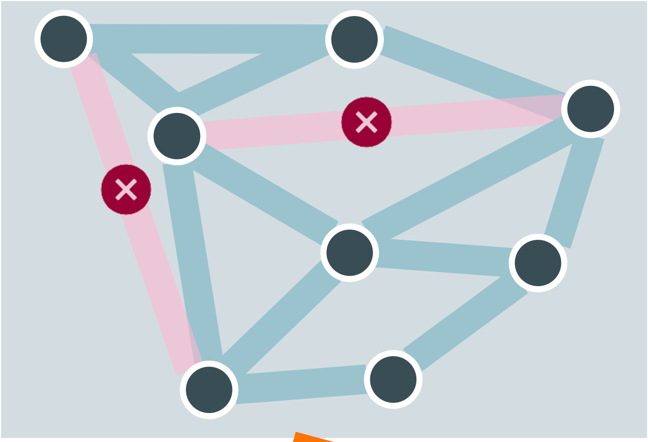
***How is the graph** obtained?*

Scenario Building

GIS Analysis

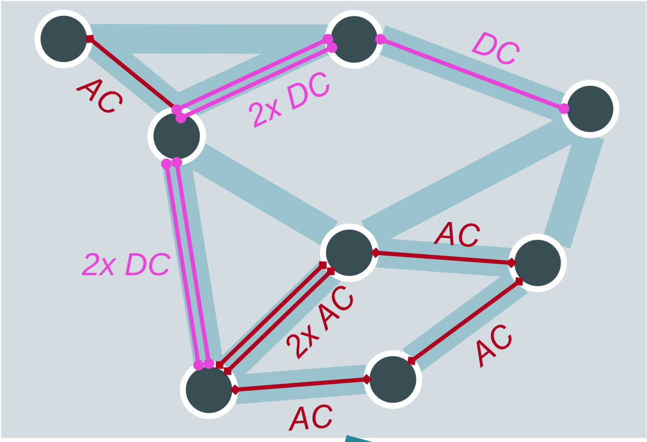
Graph with permissive elements

***Which nodes** can be linked with each other?*



Solved grid topology

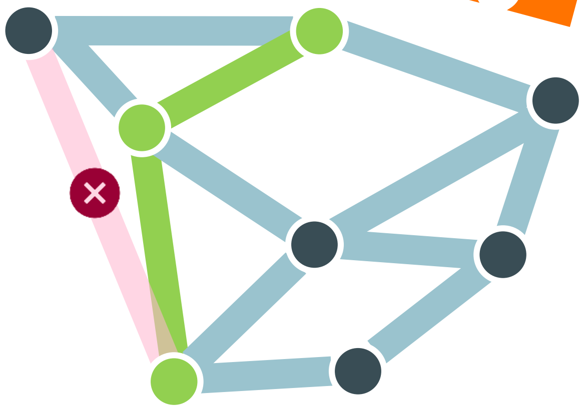
***Which** cable type and capacity populate each link?*



The concept of permissive and active graph elements is the core element of the capacity expansion problem

Initial graph

GIS analysis



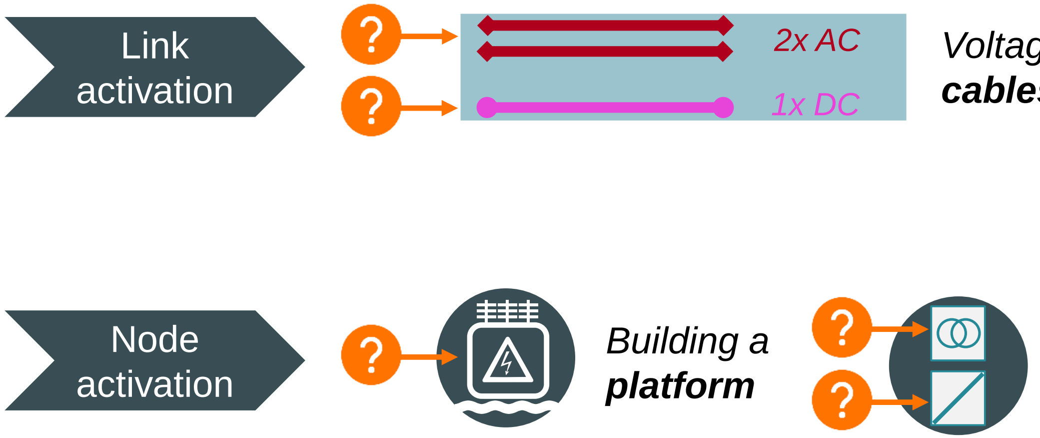
Excluded in pre-processing

Activated elements

Permissive elements

Discrete decision making

Market Model



Voltage type & number (int) of ***cables*** *to satisfy capacity request*

Building a ***platform***

Voltage type & number (int) of ***converters or transformers*** *to satisfy capacity request*

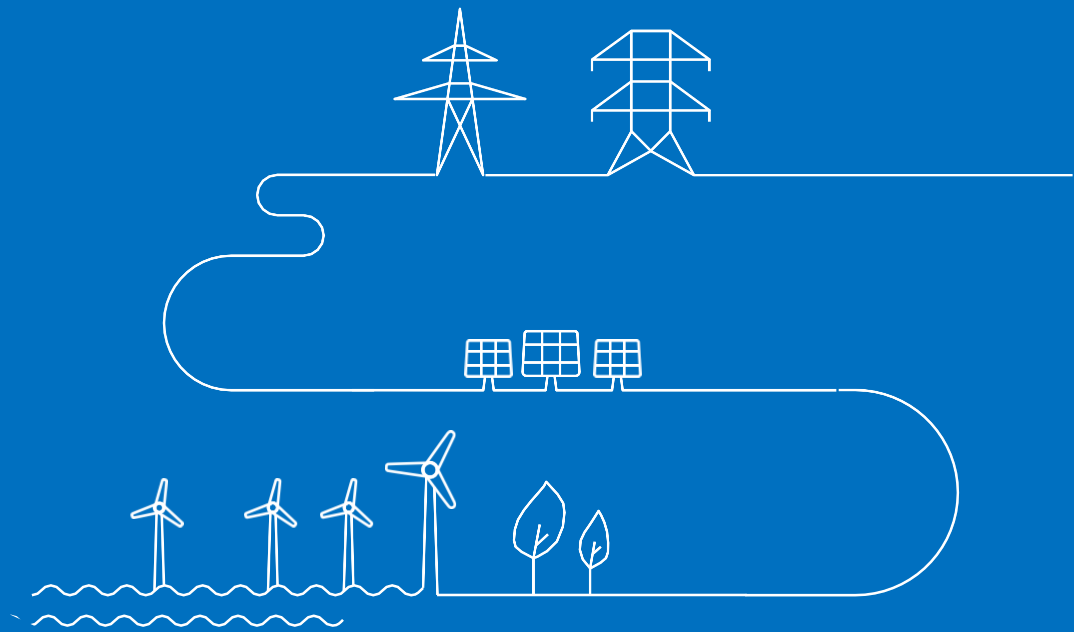
Activation problem requires two discrete variables per link and three per node

Setting the Scene

Framework development

Results

Discussion



GIS analysis is the missing link in data pre-processing and post processing

Added Value

- ✓ *Validate input data*
- ✓ *Setup topology bottom up*
- ✓ *Avoid heuristics*

The optimisation problem is divided in three steps. It is structured in QGIS and solved in Julia

Step 1 | Pre-processing (QGIS)

- **Spatial Analysis**: Organise nodes
- **Geometric Clustering**: Setup graph topology

Step 2 | Power Market Description (julia)

- **Mixed Integer Linear Program** Iterate over graph
- **Dispatch & Investment** Activate elements optimally

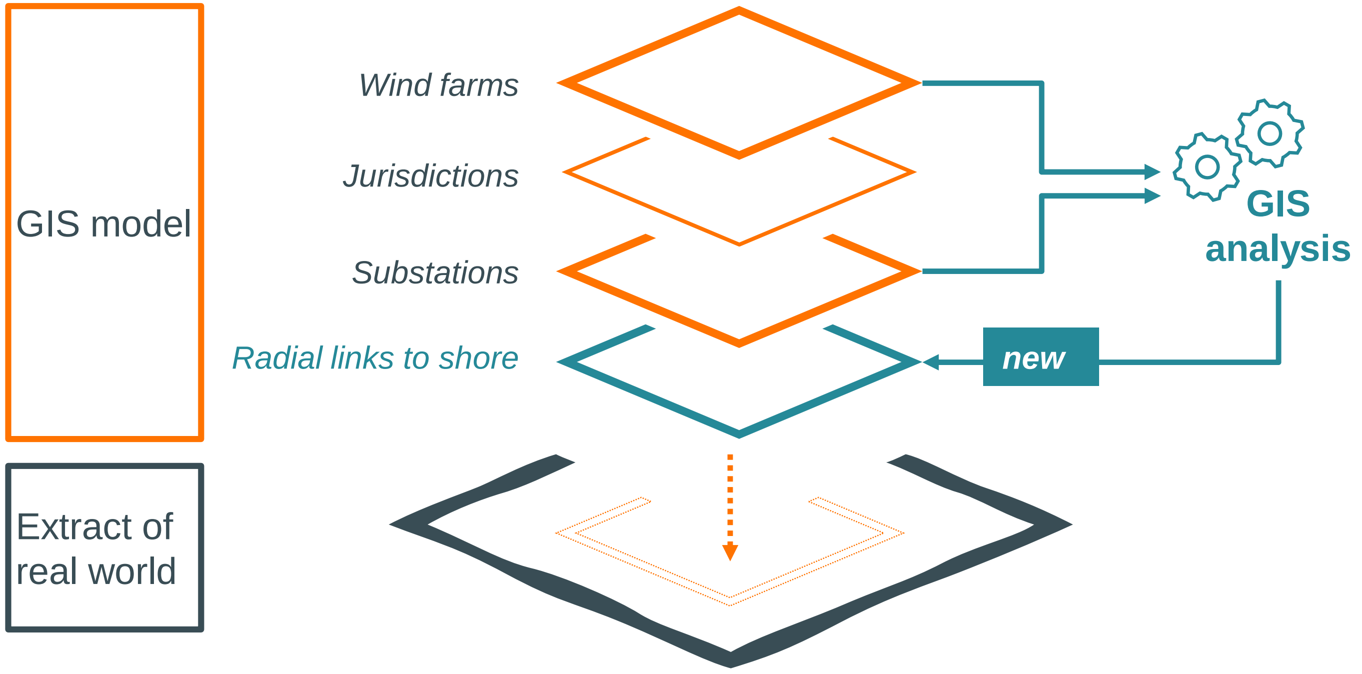
Step 3 | Post-processing (julia, QGIS)

- **Sensitivity Analysis** Identify influence on topology
- **Mapping of results** Interpret obtained topology

Twin-part division of the initial optimisation problem

A Geographic Information System (GIS) handles import, management, analysis and presentation of spatial information (geo data)

Geo data is organised in layers



GIS analysis handles queries sequentially

- **Where** and **When** is something?
- **What** and **How much** of it is nearby?
- How can features be **classified**?
- Which locations service a region **optimally**?
- Which **optimal path** links them?

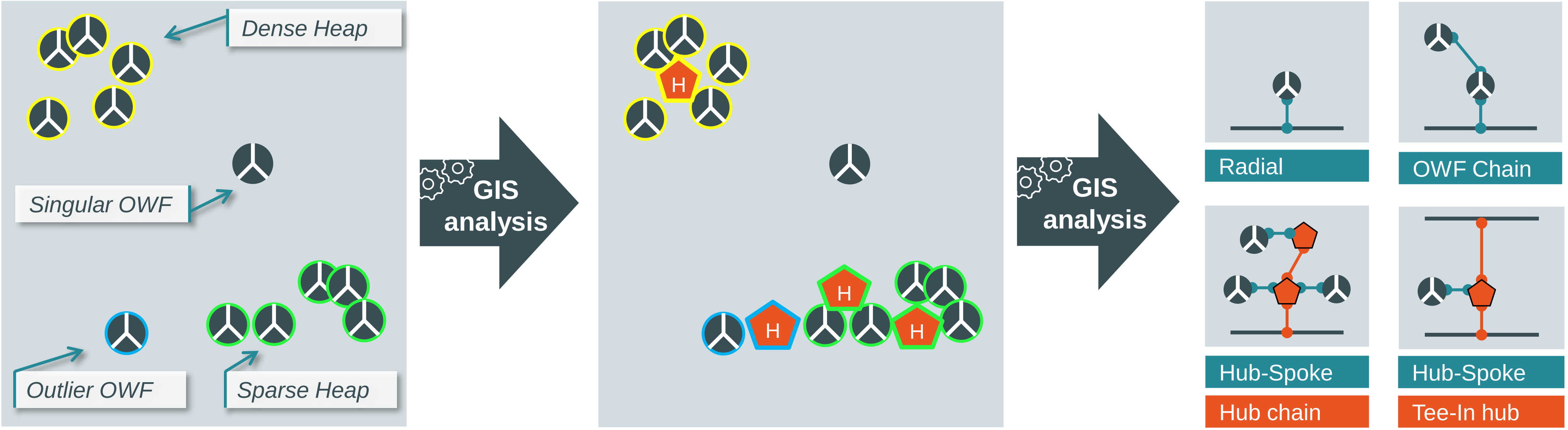
Source: Ralf Bill (2016): Grundlagen der Geo-Informationssysteme 6. Auflage

Geometric clustering observes the set of all wind farms and identifies heaps

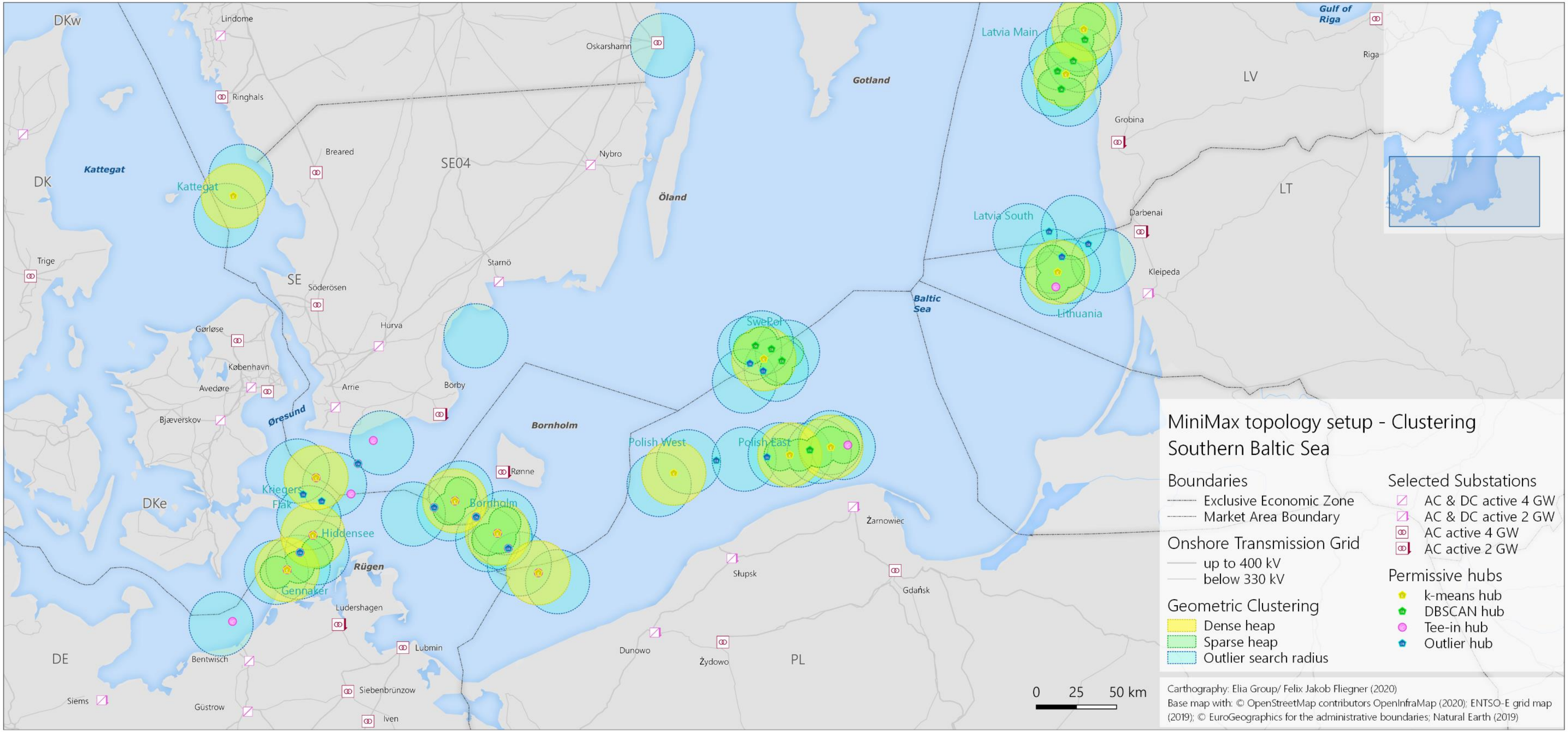
Typical distribution of wind farms…

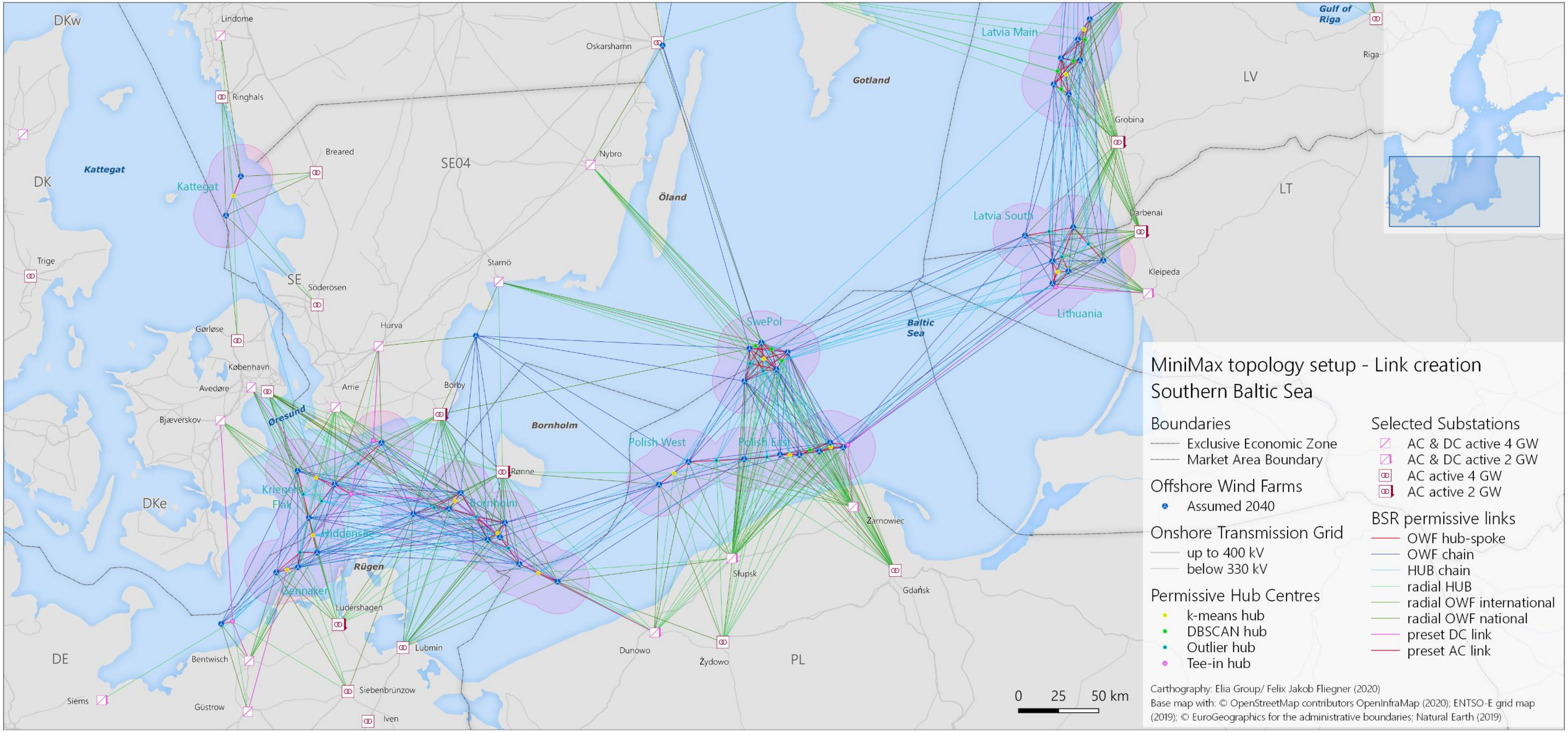
…partitioned into heaps with obtained hub locations…

…linked with different types of permissive links



Source: Adapted from Ester et al. 1996, Svendsen 2013


MiniMax topology setup - Clustering
Southern Baltic Sea
Boundaries
Exclusive Economic Zone
Market Area Boundary
Onshore Transmission Grid
up to 400 kV
below 330 kV
Geometric Clustering
Dense heap
Sparse heap
Outlier search radius
Selected Substations
AC & DC active 4 GW
AC & DC active 2 GW
AC active 4 GW
AC active 2 GW
Permissive hubs
k-means hub
DBSCAN hub
Tee-in hub
Outlier hub
0 25 50 km
Kattegat
Latvia Main
Latvia South
Lithuania
SwePol
Polish West
Polish East
Kriegers Flak
Hiddensee
Gennaker
Bornholm
Baltic Sea
Gotland
Öland
Rügen
Øresund
Gulf of Riga
DKw
DK
DKe
DE
SE
SE04
LV
LT
PL
Carthography: Elia Group/ Felix Jakob Fliegner (2020)
Base map with: © OpenStreetMap contributors OpenInfraMap (2020); ENTSO-E grid map (2019); © EuroGeographics for the administrative boundaries; Natural Earth (2019)


DKw
DK
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SE04
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PL
Kattegat
Gotland
Öland
Bornholm
Rügen
Baltic Sea
Gulf of Riga
Øresund
Latvia Main
Latvia South
Lithuania
SwePol
Polish West
Polish East
Kriegers Flak
Hiddensee
Gennaker
Lindome
Ringhals
Breared
Oskarshamn
Nybro
Starnö
Söderösen
Hurva
Gørløse
København
Avedøre
Arrie
Borby
Bjæverskov
Trige
Rønne
Riga
Grobina
Darbenai
Kleipeda
Żarnowiec
Słupsk
Gdańsk
Dunowo
Żydowo
Lubmin
Ludershagen
Bentwisch
Siems
Güstrow
Siebenbrünzow
Iven
0 25 50 km
MiniMax topology setup - Link creation
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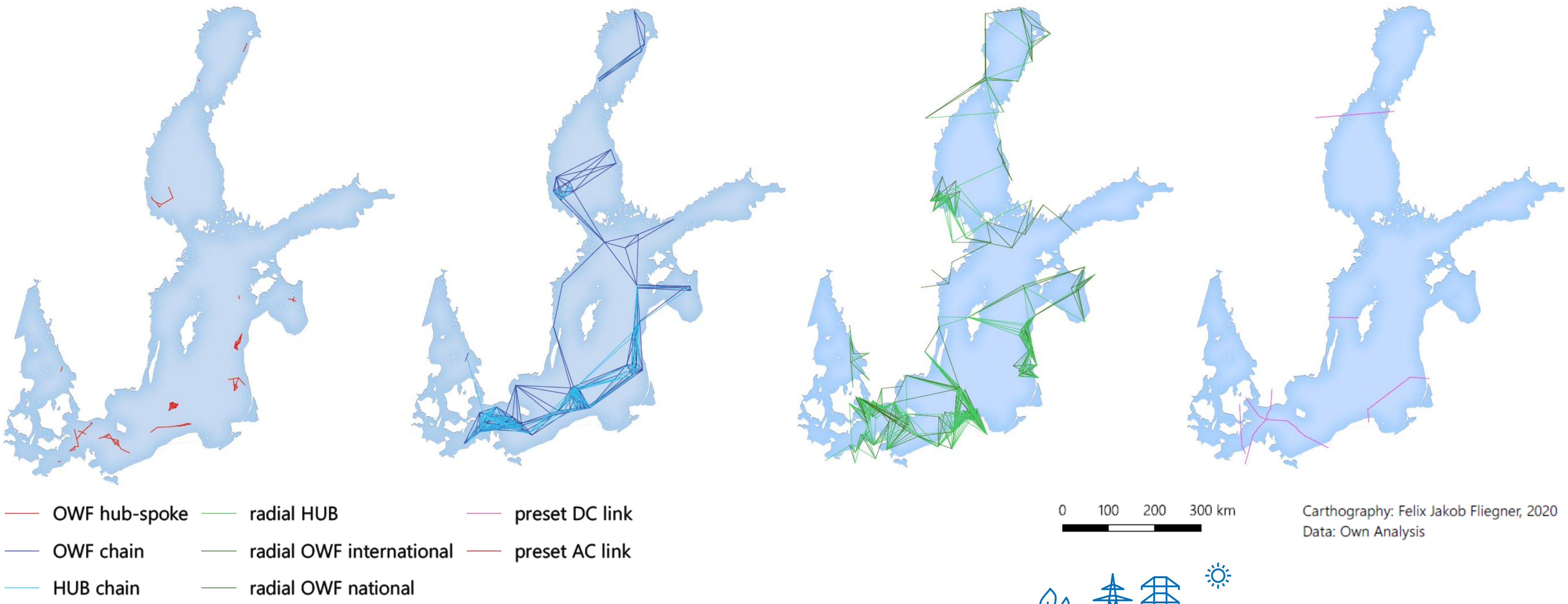
up to 400 kV
below 330 kV
Permissive Hub Centres
k-means hub
DBSCAN hub
Outlier hub
Tee-in hub
Selected Substations
AC & DC active 4 GW
AC & DC active 2 GW
AC active 4 GW
AC active 2 GW
BSR permissive links
OWF hub-spoke
OWF chain
HUB chain
radial HUB
radial OWF international
radial OWF national
preset DC link
preset AC link
Carthography: Elia Group/ Felix Jakob Fliegner (2020)
Base map with: © OpenStreetMap contributors OpenInfraMap (2020); ENTSO-E grid map (2019); © EuroGeographics for the administrative boundaries; Natural Earth (2019)

Overlay of hub-spoke links, chains and radial connections to shore creates the permissive topology

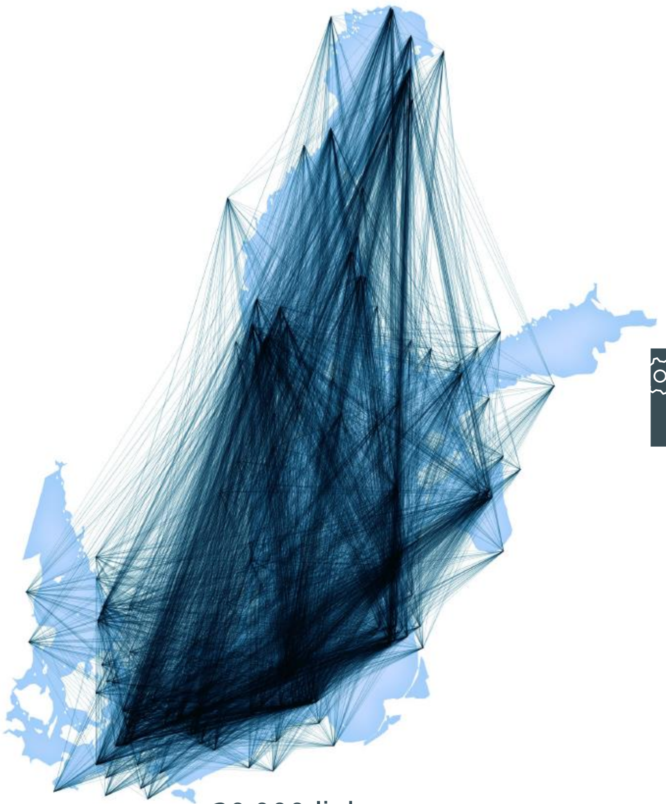
Hub-Spoke links | OWF and hub chains | Radial links | Preset links



Carthography: Felix Jakob Fliegner, 2020
Data: Own Analysis

GIS link creation reduces complexity by factor 10

Complete graph



20,000 links

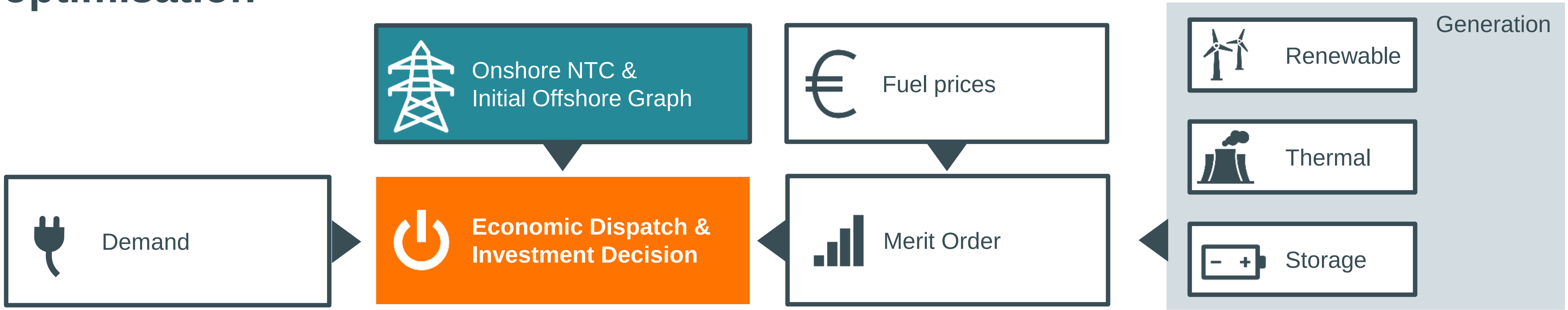
$4 * 10^{6000}$ combinations

Permissive links

1,300 links

$2 * 10^{400}$ combinations

MILP performs integrated economic dispatch and investment optimisation



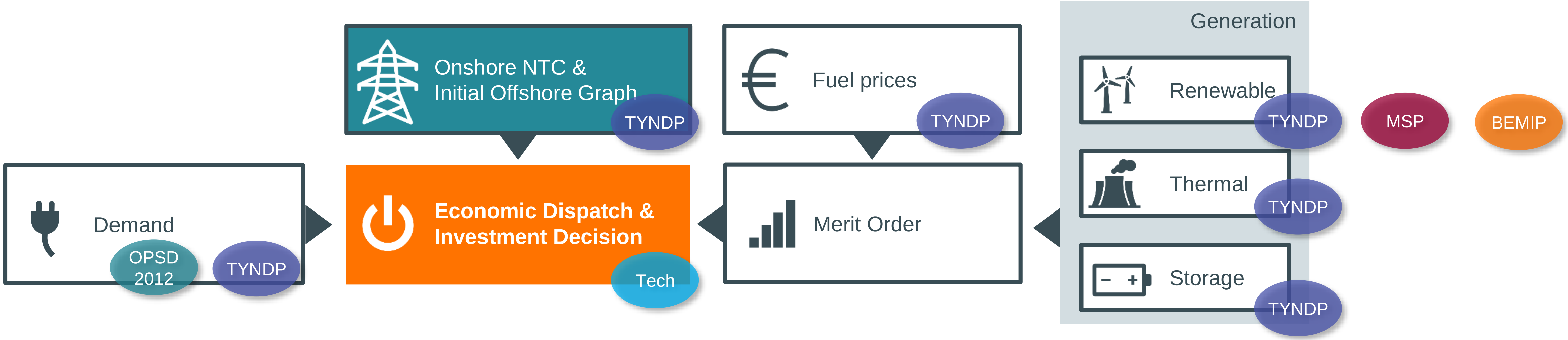
Dispatch | Link activation | Node activation

$$\boldsymbol{min}\ \ t * \sum_{\substack{h \in H \\ g \in G}} mc_g * \mathbf{P}_{g,h} + a * \sum_{\substack{l \in L \\ v \in V}} \left(len_l * c_{l,v}^{len,p} * \mathbf{K}_{l,v} + c_{l,v}^{f} * \boldsymbol{\Upsilon}_{l,v} \right) + a * \sum_{\substack{n, \in N \\ v \in V}} \left(c_{n,v}^{p} * \mathbf{K}_{n,v} + c_{n,v}^{f} * \boldsymbol{\Upsilon}_{n,v} + c_{n,v}^{act} * \boldsymbol{\Phi}_{n,v} \right)$$

Generation | Activated links | Activated nodes

MILP: Mixed Integer Linear Program | NTC: Nominal Transfer Capacity
Source: Adapted from Weibezahn & Kendziorski 2019

Input data retrieved from TYNDP with modifications



OPSD 2012 — Open power system data from 2012, scaled to 2040

TYNDP — TYNDP 2020 Scenario Report, National Trends 2040

MSP — Marine Spatial Planning by each BSR state as of 07/2020

BEMIP — Baltic Energy Market Integration Project final report 2019

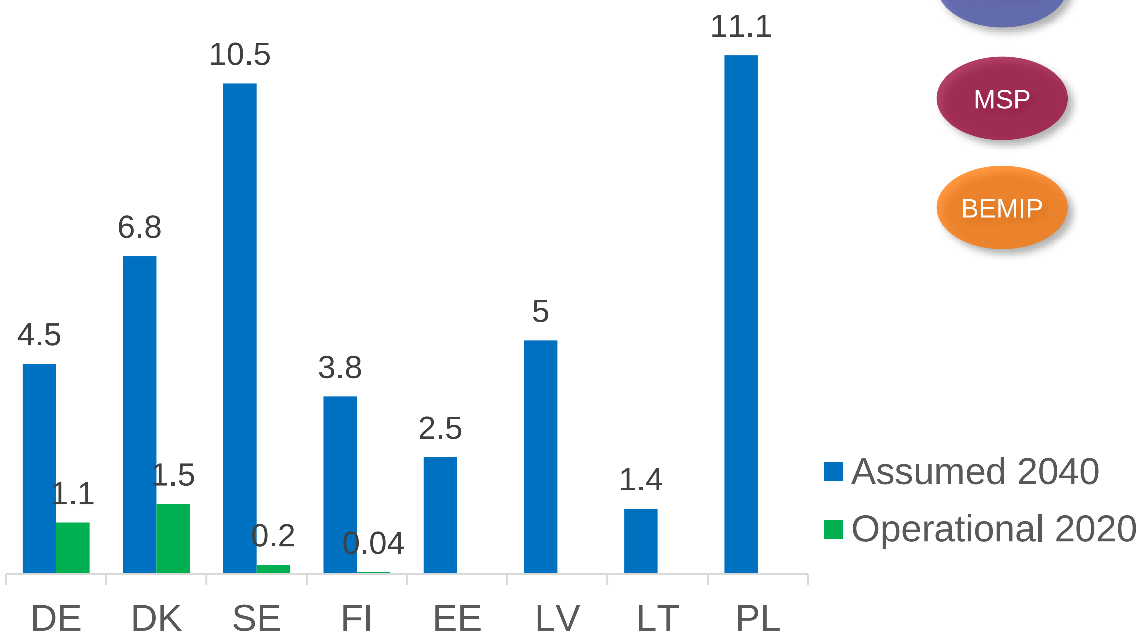
Tech — Technology parameters from various sources

Source: Adapted from Weibezahn & Kendziorski 2019

Start grid, generation capacities and fuel prices based on TYNDP NT 2040

Offshore wind capacity assumptions in GW

Total: 45 GW

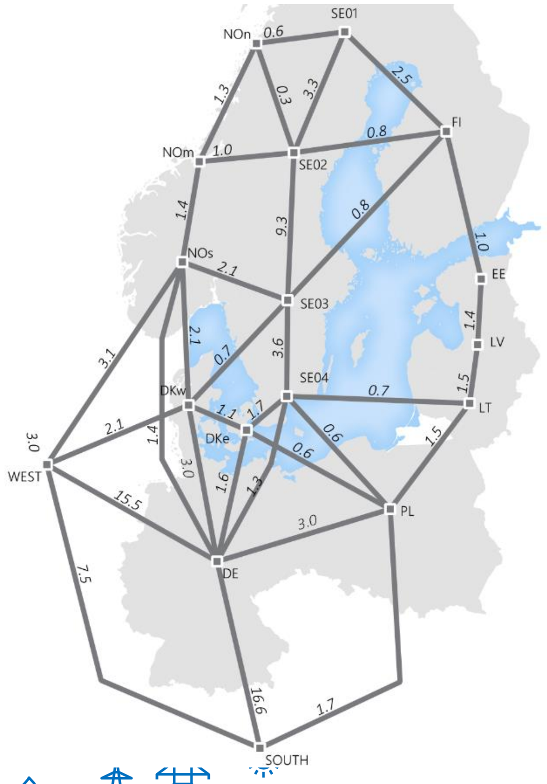


TYNDP

MSP

BEMIP

X-border NTC assumptions based on TYNDP NT 2040



TYNDP

Sources for assumptions: Marine Spatial Planning by all BSR states, TYNDP Scenario Report 2020 NT 2040, BEMIP 2019

Modelling is done in three steps to reduce computational complexity

Step A **Warm start**

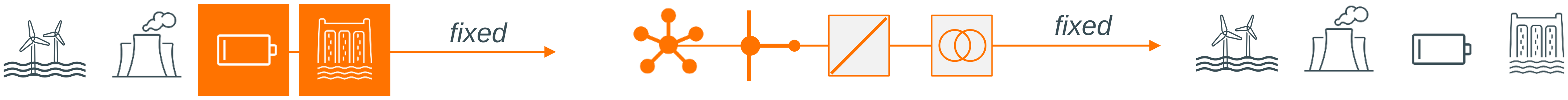
6 h resolution

Step B **Topology optimisation**

25 h resolution

Step C **Re-Run dispatch**

6 h resolution



Step A:
- Storage dispatch

Step B:
- Activated Elements
- Sensitivities

Step C:
- Power Flow
- Curtailment

Simplifications

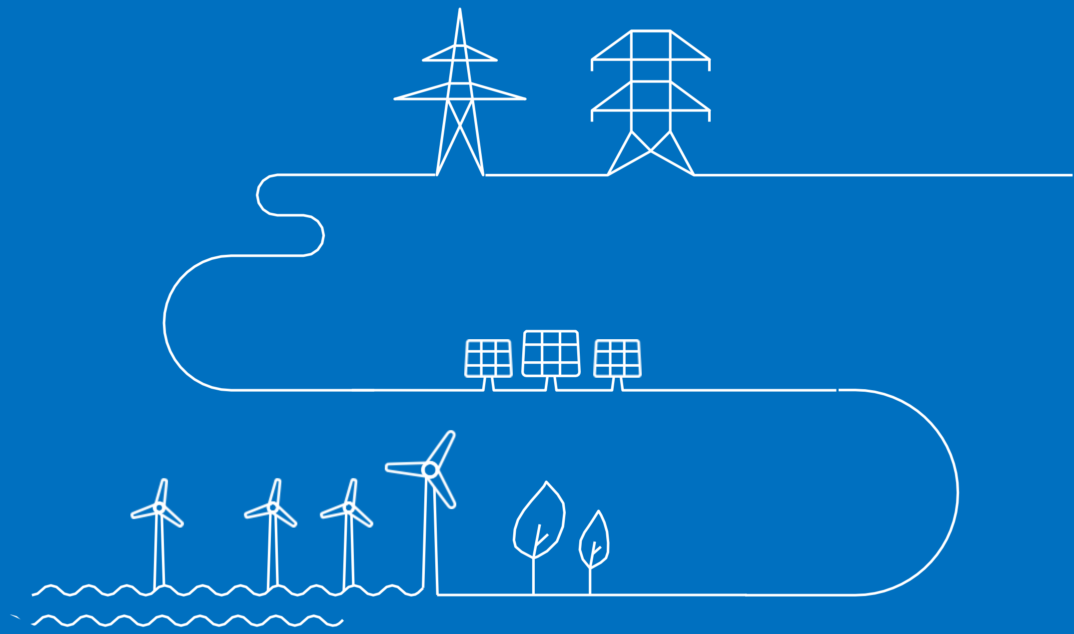
- Climate year 2012
- No contingencies (n-1)
- No CBA for investments
- Wind farms “for free”
- No co-optimised onshore grid
- Power flow NTC based

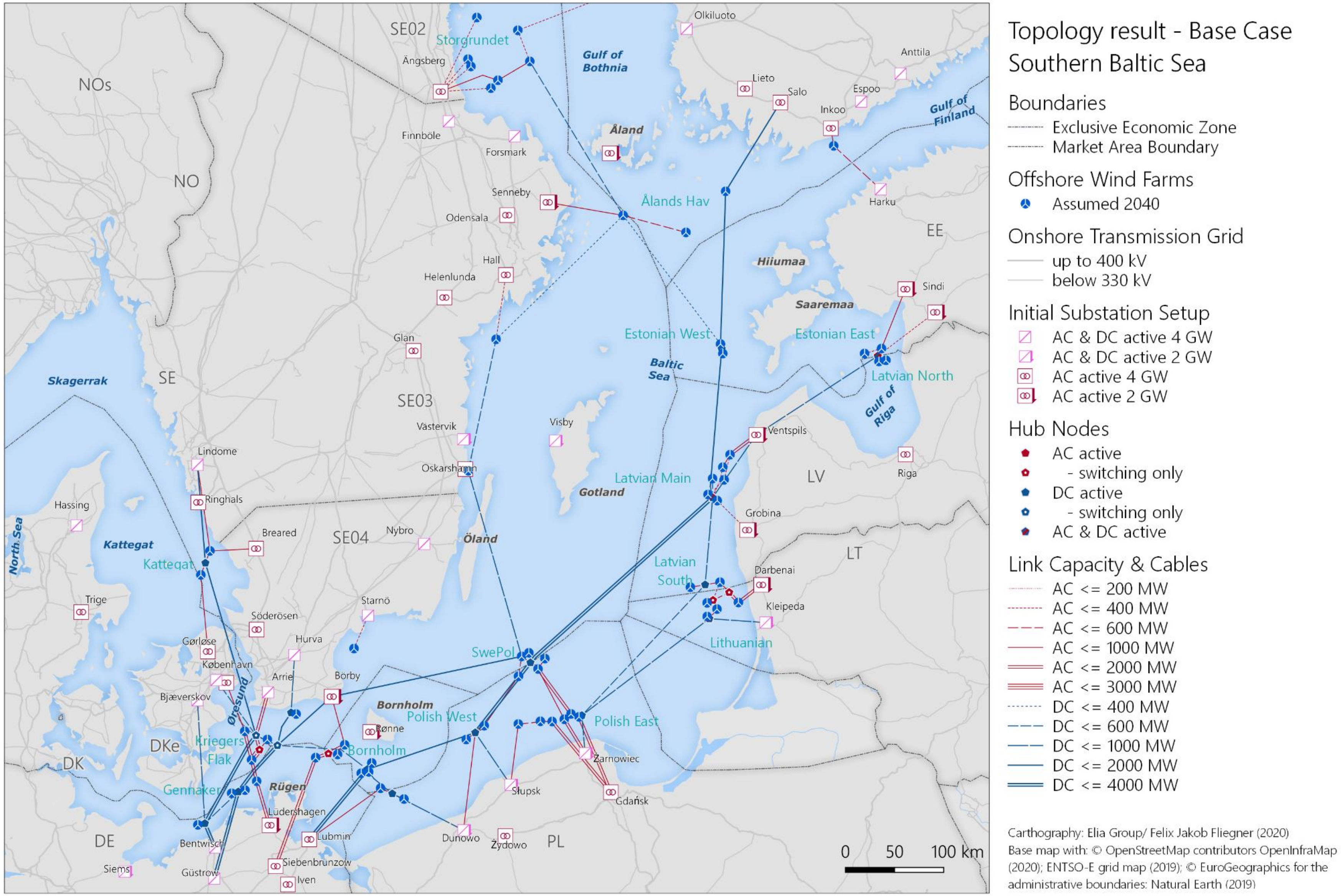
Setting the Scene

Framework development

Results

Discussion





Observations

- All wind farms connected
- Connections undersized
- Connections asymmetrically
- high concentration of infeed
- Strong bundling of paths
- High link utilisation
- North-South power flows
- Detours around congestions

Under the given assumptions the Baltic Offshore grid describes a bundled backbone with several hybrid assets routed across it

Wind farms

- Almost all wind farms either part of a chain or clustered in a hub
- Connecting links to wind farms are undersized
- Clustering and chaining of wind farms leads to **high concentration of grid-infeed**

Topology

- Strong interconnection North to South & East to West
- **Asymmetrical capacity rating**: stronger towards high demand side
- **Detours** around congested onshore substations

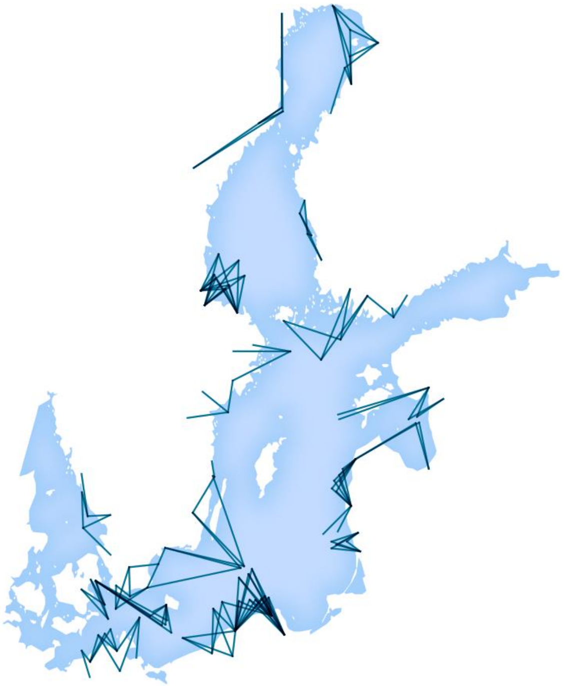
Utilisation

- Mean flow from north-east to south-west
- Reverse flows signal storage charging in Nordics
- Bundling of transmission tasks into paths **maximises link utilisation**
- Maximised wind power evacuation opportunities **without redundant capacities**

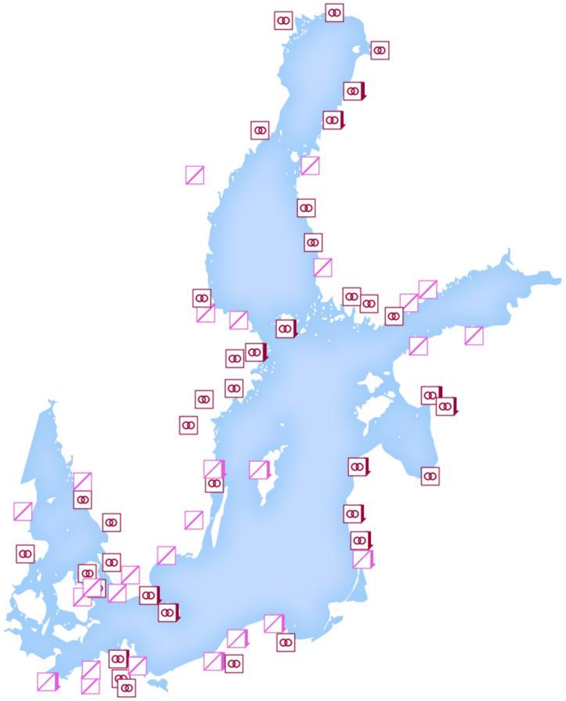
Sensitivity analysis investigates impact of three constraints onto resulting topology and dispatch

Test 1 No link preset

Test 2 Wind farms national radial only



Test 3 Strong onshore grid



The framework is impacted most by wind farm assumptions, onshore grid aggregation and preset links

No link preset

- Exchange capacities still realised but more bundled with other links
- No cables “for free”: fewer hubs and cables built
- Chaining and clustering of wind farms unchanged, curtailment increased

Wind farms national radial

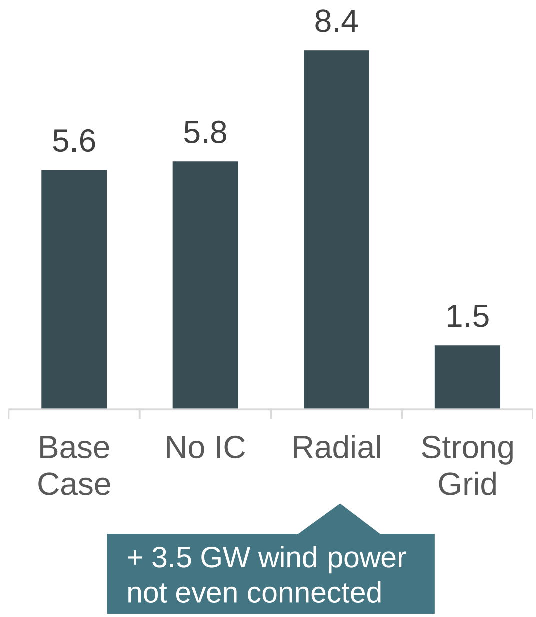
- Lost wind farm infeed (high curtailment & not connected at all)
- Highly redundant links: increased cable length
- Interconnectors enforced

Strong onshore grid

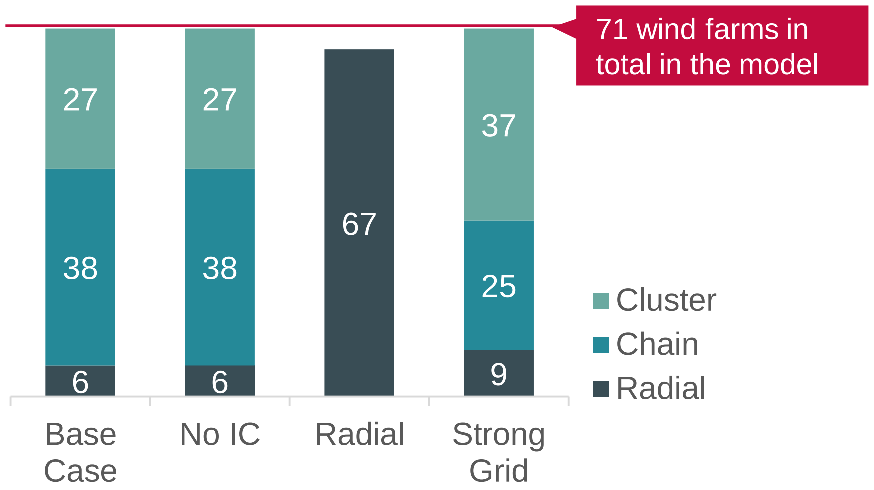
- Most centralised topology with even more wind farm clustering
- Shortest cable lengths & highest power ratings (up to 8 GW)
- PL, LV, LT, EE integrate more wind energy themselves
- **OBS!** Onshore grid expansion is “for free” in the model

The framework is impacted most by wind farm assumptions, onshore grid aggregation and preset links

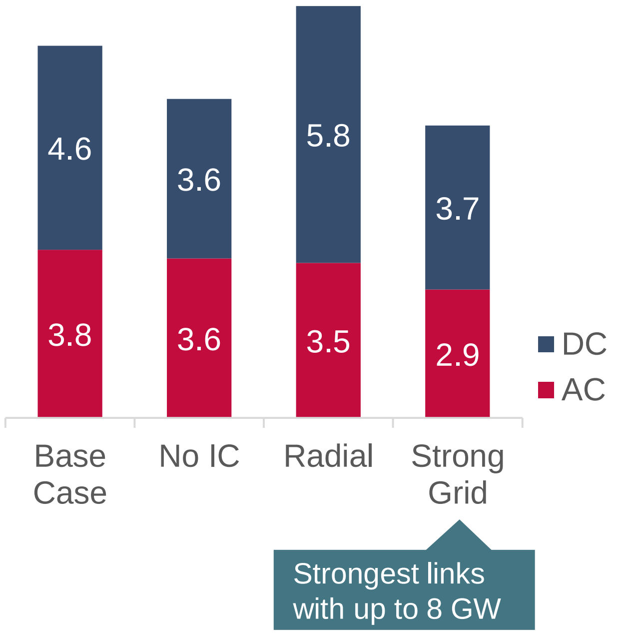
Annual curtailment in TWh



Wind farms per connection type



Total cable length in 1000 km



Setting the Scene

Framework development

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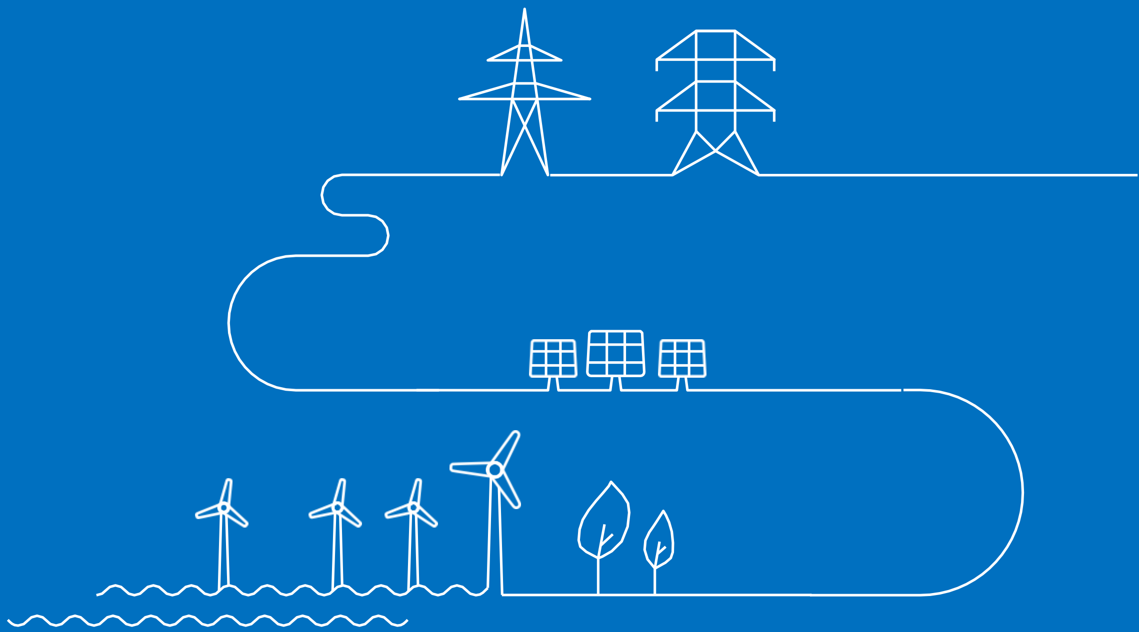
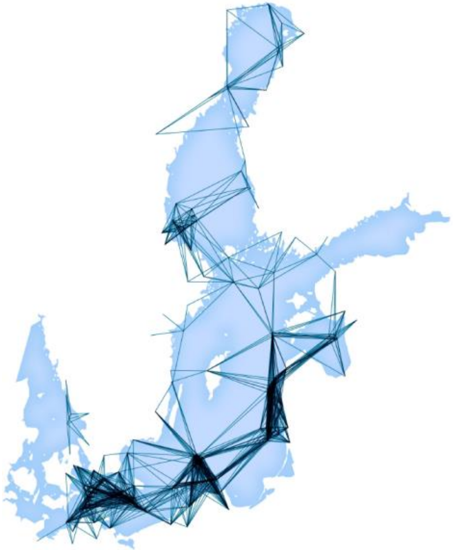


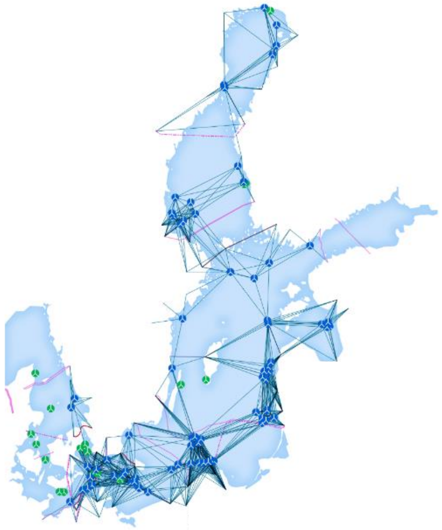
The proposed framework creates a wide range of storylines for the future offshore grid to be investigated

Contribution



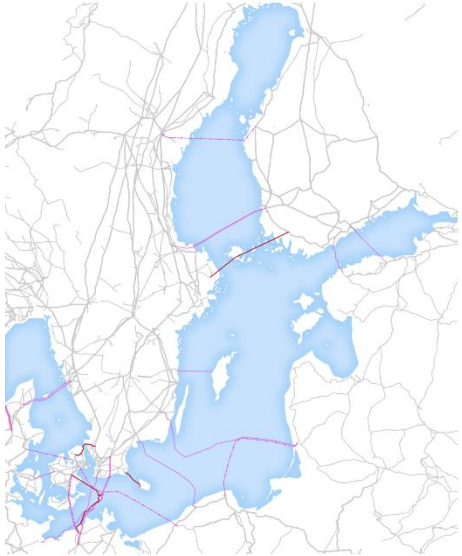
- Endogenized identification of offshore transmission paths
- Pre-Solve with GIS analysis
- Twin part optimisation

Limits



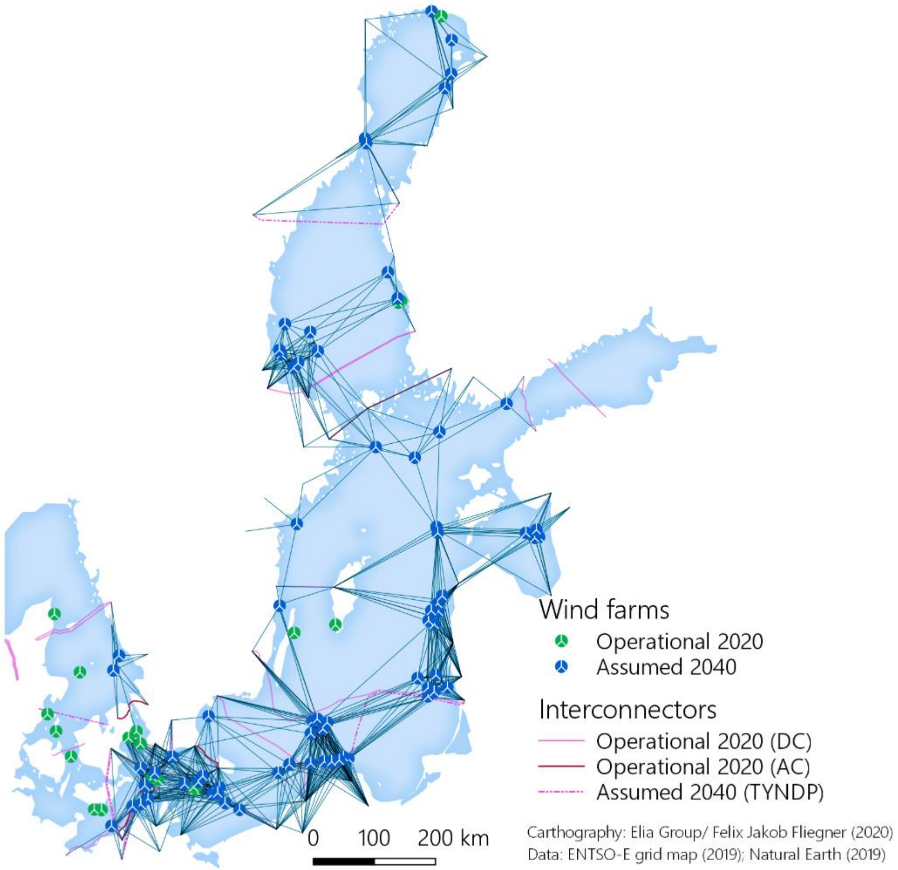
- Fixed wind farms
- Routing bias
- One shot optimisation for 2040

Further Research



- Onshore grid co-optimisation
- Technical interoperability
- Economic feasibility

How to integrate offshore wind optimally while using synergies with interconnectors?



- **Critical inputs**: Wind farms, onshore substations, onshore grid, time scope
- Partially **discrete decisions**, computationally complex to solve
- GIS analysis: **MiniMax clustering** and permissive elements creation (topology)
- MILP: **Dispatch-Investment Trade-Off**: activate links where optimal
- Results: **bundling is efficient**, hybrid assets realised in AC and DC
- Sensitivity: preset links change topology, clustering is beneficial over "all radial", **simplified onshore grid impacts onshore grid the most**
- Cross border synergies: **Analysing the offshore grid of the future is a quest of pan-European scale.**

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Trondheim, Jan 2022

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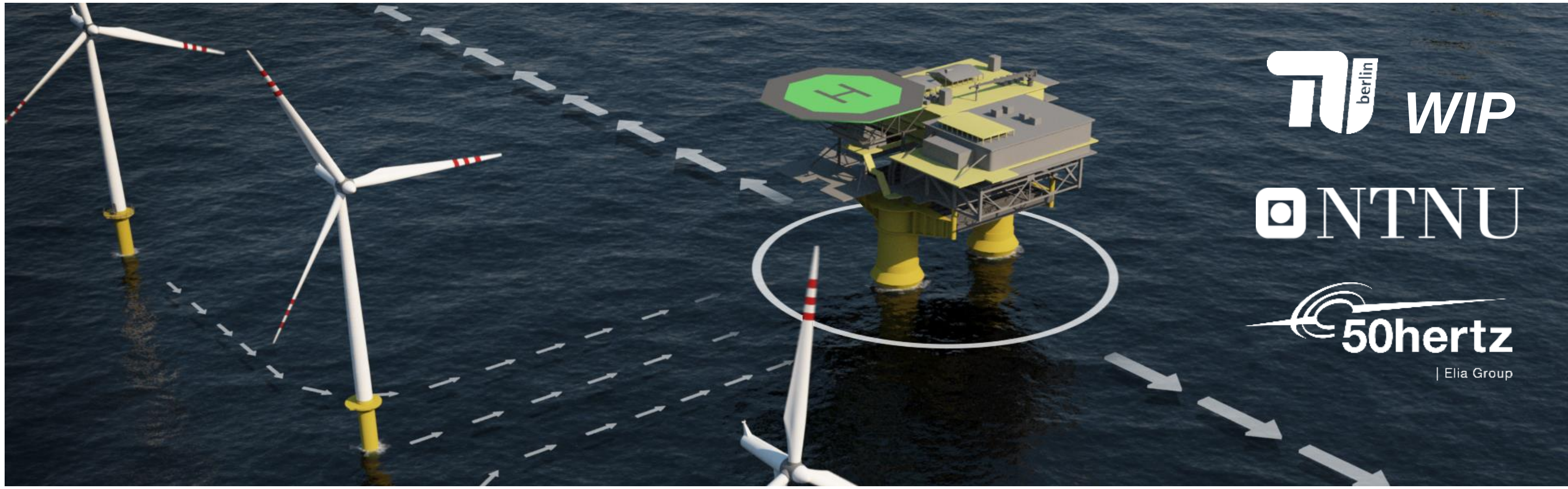
System of the Future - 50Hertz



Interested in further discussion?

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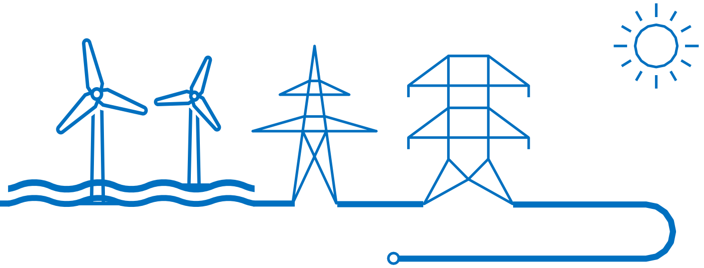
https://de.linkedin.com/in/fliegner



Picture: Kriegers Flak Combined Grid Solution

Worlds first Hybrid Interconnector between DK and DE

Picture: 50Hertz