Offshore grid topology optimisation with a geographical information system

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Abstract. A novel methodology is investigated to identify and optimise large scale offshore grid topologies connecting multiple wind farms and countries with each other. A Geographical Information System (GIS) is setup to cluster wind farms and create a permissive graph topology. Its purpose is to propose grid layouts with potential hub locations and landing points bottom-up in a fully analytical toolchain, while avoiding manual scenario building. A coupled market model performs the investment optimisation into new lines on the GIS created graph. This two-step procedure is demonstrated at the example of the Baltic Sea Region for the target year 2040. It can be found, that future offshore topologies benefit from bundled transmission paths and many clustered wind farms. A sensitivity analysis reveals that the topology results are sensitive for wind farm location assumptions and pre-defined interconnectors or hubs. Not least, the capability of the onshore grid to integrate the influx of offshore wind power and the level of detail it is modelled in, directly reflects on the topology results for the offshore grid. It is concluded that optimising the future offshore grid is a quest of pan-European scale which benefits heavily from geo data based pre-processing in a GIS.

1. Introduction

Offshore power transmission is expected to play a key role in the European energy transition [1]. At the example of the Baltic Sea, two supportive trends can be identified, namely increased ambitions to generate electricity with offshore wind farms [2, 3] and expected stronger interconnection both, from the Baltic States and from the Nordic States to central Europe [4]. With less than 3 GW of wind farm capacity installed in 2020 the bulk of offshore power transmission infrastructure is thus yet to be seen [5].

Both trends face a constrained onshore grid with limited number of nearshore substations to land cables at. The question evolves whether a foreseeable overlap of transmission needs of wind farm connections with power market interconnections could be bundled into a hybrid infrastructure [6].[1] Previous work, both from academia and industry identify such an approach as a pillar of the future offshore grid development and demonstrated its superiority over independently optimised radial wind farm connections in parallel to interconnectors [2, 10–13].

In face of this co-optimisation rationale, a complex transmission capacity expansion problem evolves. It is a network problem which entails discrete decision making for investment into

[1] This paper uses alternative wordings found in [7–9], such as hybrid assets and multi-purpose interconnectors as synonyms.

transmission corridors, voltage types, intermediate offshore hubs and the choice of onshore points of connection. For large geographical scopes such a problem quickly becomes intractable for the exponentially growing number of existing solutions and combinations thereof [14]. A commonly applied complexity reduction both in academia [13, 15, 16] and industry [2, 12, 17–19] is manual scenario building and the exemplary analysis of very few hub layouts based on pre-analysis or expert choice. While this approach is light and fast, it is at risk to oversee additional feasible and potentially outperforming topology solutions.

Purpose of this paper is to introduce a novel methodological approach to address this drawback. It divides the aforementioned problem into two linked optimisation problems, namely the main problem performing the optimal investment decisions into offshore (hybrid) transmission assets (c.f. step 2 in figure 1) and the minor problem preparing this decision making by providing a structured and pre-selected set of options to chose from (step 1). A pre-processing with help of a Geographical Information System (GIS) is proposed and demonstrated at the case of Baltic Sea Region (BSR). Leveraging the wealth of domain knowledge entailed in the geo data of wind farm locations and onshore substations, the rationale for the GIS analysis is complexity reduction. Combinatorially existing, yet physically infeasible "solutions" from the complete graph can be filtered resulting into a reduced set of permissive network elements to be processed in subsequent market simulations.

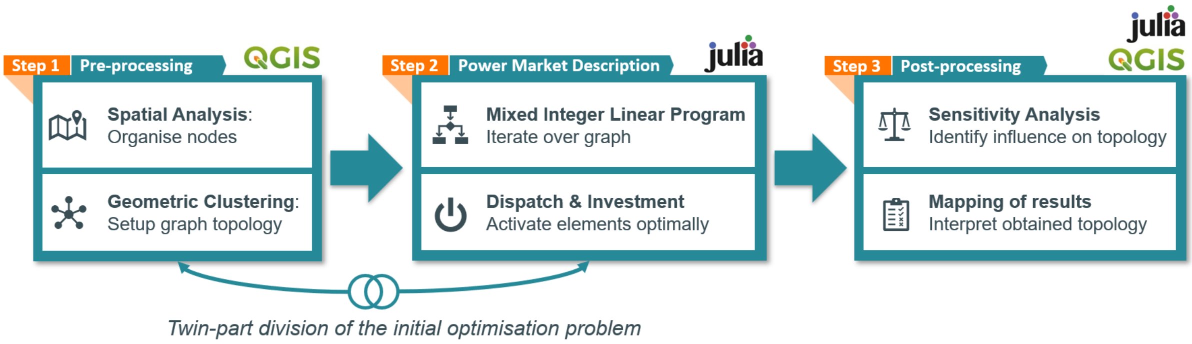

Figure 1. Processing steps in this analysis.

With help of a sensitivity analysis on the results (step 3), benefits and limits of the proposed framework are discussed. The focus is put on the methodological framework, hence no implication towards likelihood or favourability of any discussed offshore wind farm assumption and grid topology is intended. In fact, the following study does not represent a future offshore grid outlook but spotlights drivers of (in-)efficiencies in offshore grid development with respect to the extend of clustered wind farms and grid topology.

The remainder of this report is structured as follows. Section 2 introduces the concept of GIS analysis in energy system modelling and motivates the contribution of this work to the existing literature. Section 3 sketches, how the output of GIS analysis can be processed, before section 4 applies the proposed setup to a small case study of the Baltic Sea Region. The findings are discussed and summarised in sections 5 and 6, respectively.

2. GIS in context of energy system modelling

Related work and purpose of GIS analysis

A GIS is a computer-aided system for modelling and processing of spatial tasks. It handles import, management, analysis and presentation of spatial information [20]. In context of energy system modelling, GIS analysis are conducted for resource potential studies to exploit knowledge of geo-referenced meteorological parameters such as wind speeds or solar irradiation [21, 22].

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Another focus of GIS analysis in the existing work so far is the optimisation of array cables inside wind farms [23, 24] and optimal allocation of weather dependent generators in large scale energy system models [25]. The strength of GIS analysis to perform an analytical topology creation among many wide spread wind farms is less deployed to the authors best knowledge. Ref [14, 26] outline, however, a potential use case for GIS analysis, namely clustering of neighbouring wind farms into larger wind power hubs. This paper expands on this notion and scales the GIS pre-processing to a larger region and more granular resolution of the topologies under investigation. A geometric clustering technique is developed that returns a permissive (offshore) graph topology (nodes and links) which contains elements fulfilling pre-defined permissive rules. The permissive rules are defined as parameters upfront and allow a purely analytical setup of the graph. This facilitates post calibration by changing the parameters for the permissive rules. Maintaining an analytical procedure during topology setup, distinguishes the GIS pre-processing from the scenario building which usually builds on expert knowledge, heuristics or previous studies. While the identification of the specific clustering algorithm is an academic discussion on its own (c.f. e.g. [27]), this paper focuses on the mere feasibility demonstration and the required minimum level of information to perform such analysis. Further investigation of tools and data mining is advised nonetheless.

Permissive graph topology creation
In order to create a permissive graph topology for a subsequent optimiser to iterate over, three processing steps are necessary as visualised in figure 2. First, a clustering algorithm identifies typical distributions of wind farms. Expanding from ref [28] it should discover clusters within wind farm heaps of arbitrary shape. Both dense (almost circular shaped) and sparse heaps (loose chains of wind farms with aritrary center) should be identified accurately. Also outliers (wind farms with only one prospect of clustering) and singular wind farms (no clustering prospect) should be identified non-arbitrarily. In other words, the clustering procedure should be free of bias towards a specific size, shape or other characteristic of the identified clusters.

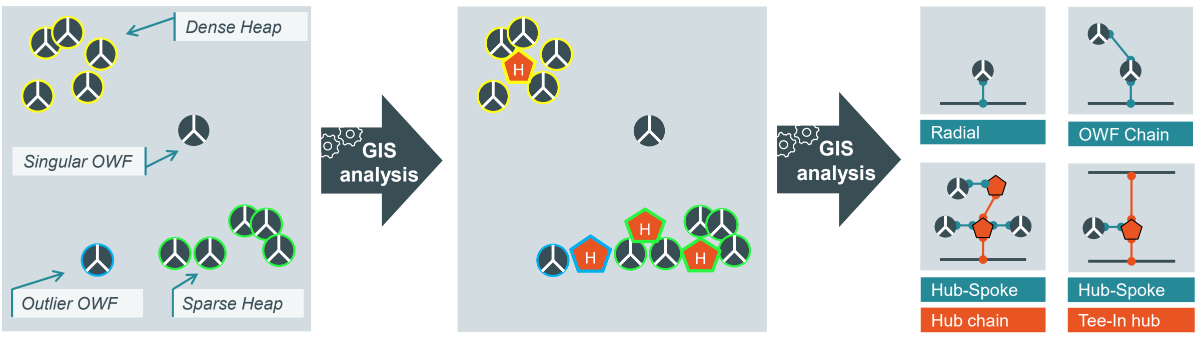

Figure 2. Permissive graph topology creation in GIS with clustering and link creation.

In a second step, partitioned wind farm nodes receive permissive hub locations, i.e. the GIS proposes locations of physical platforms or energy islands in the sea, based on pre-defined distance thresholds as laid down in table 1 as “Hub-Spoke length limit”. Limiting the required clustering parameters to a necessary minimum (here: only distance) is desirable, since the number of optimal clusters is usually hard to predict upfront. The algorithm should obtain this on its own [28].

Finally the identified nodes are linked with different link types following the permissive rules laid down in table 1 as “Chain length limit”. This includes more traditional topology types such as direct radial links from a wind farm to shore or several chained wind farms. When wind farms of a heap connect to a common hub, the link type is denoted "hub-spoke", alluding to the spokes of a wheel. Hybrid connection proposals are obtained, when a given hub is connected to more than one shoreline. It is then denoted "tee-in hub" for the "T"-shape of the intersection of wind farm and interconnector.

MiniMax game for wind farm clustering
Acknowledging the aforementioned considerations and the discourse on the applicability of clustering algorithms [29, 30], two algorithms are selected for a synthesis, namely *k-means* and *density based clustering* (DBSCAN). They are chosen for their complementary strengths in the context of spatial wind farm clustering. This synthesis is best described as a MiniMax game and illustrated in figure 3. Two algorithms are running against each other, where one agent tries to minimise the number of hubs and the other one tries to maximise it. This allows to compensate for the biases that both would impose on the procedure if applied singularly.

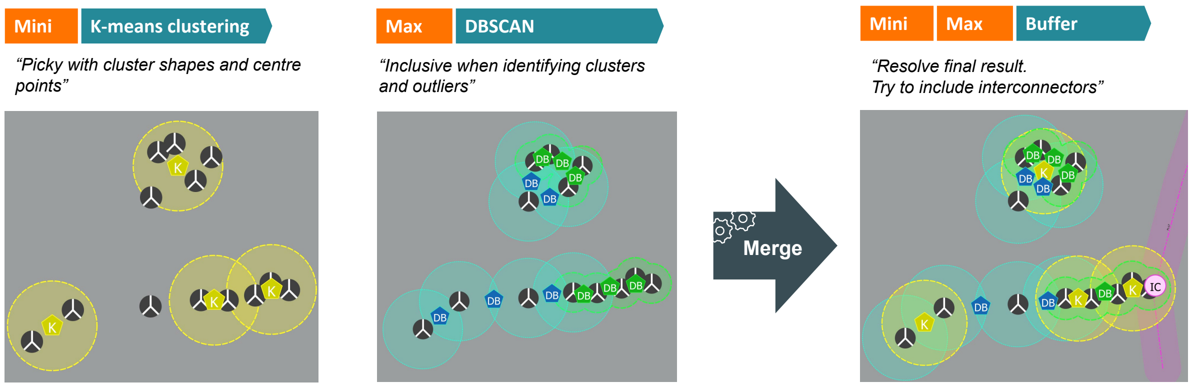

Figure 3. Illustration of k-means clustering (yellow hubs), DBSCAN (green) with outlier search (blue), identification of tee-in hubs (red) and redundancy filtering.

The *k-means* algorithm represents the minimising agent in the clustering procedure. By design, it tries to limit the number of clusters and is picky with respect to shape and size of such clusters. While circular clusters (dense heaps) are easily found, sparse heaps are either disregarded or arbitrarily partitioned. Outliers are frequently disregarded. In other words, if a group of wind farms is not dense and circular enough for the number of "available" k clusters it is likely to be overseen by *k-means*. It thus returns a lower estimate of cluster centre points for the point creation step.

DBSCAN on the contrary reaches out to outliers, which allows the identification of arbitrarily shaped sparse heaps. By design several intermediate "centre" points are obtained in such a procedure, which enhances the previously found *k-means* point creation. Such intermediate centres result from the the pairwise evaluation of reachabilities and density connections in the scanning procedure. Each possible pair of wind farm points is evaluated for vicinity which creates many more sub groups. The threshold is defined as a maximum circumcircle in kilometers. Vicinity to potential interconnectors (i.e. lines) can also be scanned for, creating the possibility to include tee-in hub proposals in the graph. Searching incrementally, creating a chain of neighboured wind farms may fail to recognize global centres of otherwise dense heaps. In this respect, density based clustering is the maximizing agent. It returns a high estimate of cluster centre points.

In a final processing step a redundancy check ensures that hub locations, that both *k-means* and DBSCAN identified are only considered once. The GIS then continues in the topology creating by adding links and completes the graph. From this stage on, any kind of optimisation tool can take over and iterate over the graph. For demonstration purposes one simple model is introduced in the next section.

3. Coupling with an investment optimisation model

The investment optimisation model is formulated as a transmission capacity expansion problem. Following the considerations by [31], a transport problem is defined in a mixed-integer linear program. It allows to put the centre of complexity at the combinatorial analysis of the manifold cluster types and permissive links from the GIS analysis. The implementation follows the dispatch optimisation from [32] and is amended by an investment optimisation as follows:[2]

$$min \quad \sum_{\substack{g\in G\\ h\in H}} mc_{g,h} \cdot P_{g,h} + a \cdot \sum_{\substack{l\in L\\ v\in V}} \left(c^{\text{pwr}}_{l,v} \cdot K_{l,v} + c^{\text{fx}}_{l,v} \cdot \Upsilon_{l,v} \right) + a \cdot \sum_{\substack{n\in N\\ v\in V}} \left(c^{\text{pwr}}_{n,v} \cdot K_{n,v} + c^{\text{fx}}_{n,v} \cdot \Upsilon_{n,v} + c^{\text{act}}_{n,v} \cdot \Phi_{n,v} \right)$$

In conjunction with this objective function, the proposed methodology entails a sequence of trade-offs to be made in the search for an optimal future offshore grid topology. The first trade-off is enforced at the interface of the dispatch term (1$^{\text{st}}$) and investment terms (2$^{\text{nd}}$ and 3$^{\text{rd}}$) of the objective function. While the model cannot actively decide to build new wind farms (they are fixed "for free" outside the model), it can decide whether a proposed wind farm is indeed connected to the grid or not (i.e. including it in the set of all generators G of the model). Connecting it, imposes grid connection cost in form of above mentioned grid layouts but adds cheap renewable electricity in the merit order of the dispatch model (low marginal cost per generator and hour $mc_{g,h}$ per power output $P_{g,h}$. If the discounted cost of transmission system investment (multiplier a) outweighs the gains on the dispatch side over all simulated hourly time steps $h \in H$, the wind farm is not connected. This could be the case for remote wind farms which are far away from the shore or for wind farms with unfavourable wind conditions.

Secondly, the model can decide whether a connection is realised in AC or DC technology. The choice of voltage type $v \in V$, for a given transmission asset then also defines the required equipment per node $n \in N$ and link $l \in L$. While no hard coded threshold for AC cables (distance or power limit) is included in the model, a tipping point from (cheaper) AC layouts to (more costly) DC layouts is enforced via the cost model of such lines. It is designed as a stepwise linear cost increase with fixed cost $c^{\text{fx}}_{n,v}$ per unit installed cable $\Upsilon_{l,v}$ and variable cost $c^{\text{pwr}}_{l,v}$ per power rating $K_{l,v}$ as defined in [33–36]. High fixed cost and low variable costs for DC systems versus low fixed costs and high variable costs for AC systems introduce a tipping point in the model beyond which investments change from AC to DC preference.

Thirdly, the pre-processing of wind farms into clusters, chains and tee-in hubs enforces an investment cost trade-off between concentrated grid layouts and scattered ones. Concentrated layouts come at the additional cost of physical offshore platforms or islands in the sea (introduced by the integer variable $\Phi_{n,v}$ at fixed cost $c^{\text{act}}_{n,v}$), which require additional node equipment of transformers and converters per unit (fixed cost $c^{\text{fx}}_{n,v} \cdot \Upsilon_{n,v}$) and power rating (variable cost $c^{\text{pwr}}_{n,v} \cdot K_{n,v}$) respectively. They save, however, on the cable investments, since the hub-spoke links, that connect wind farms to platforms nearby are dimensioned smaller. This is accounted for with "MVAC" cost parameters for short distance cables (c.f. table 1). Scattered layouts on the contrary save on platform investment and equipment but require longer and larger cables. The quest for the optimiser is now to strike the balance between new lines and new platforms in the sea.

[2] Find the nomenclature of symbols in the appendix.

4. Case Study

A demonstration of the proposed methodology is applied to the Baltic Sea Region. The purpose of this case study is a demonstration of concept and does not allow any conclusion on the favourably nor probability of any of the shown topology results. In fact, this study does explicitly not present a draft deployment plan or target for the future Baltic offshore grid. Consider the chosen input data an arbitrary choice and the obtained results as example outputs to support conceptual and rather qualitative conclusions.

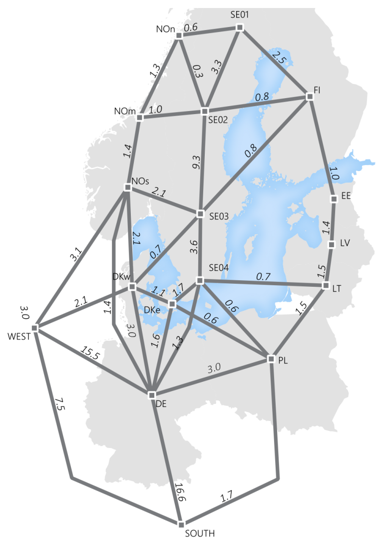

Figure 4. NTC [GW].

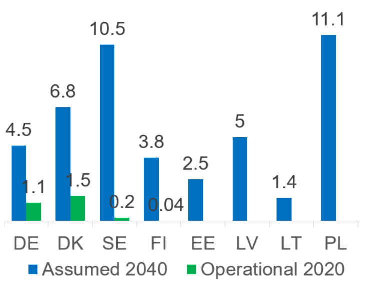

Figure 5. Wind farms [GW].

The power system of the region is modelled zonal with fixed cross border NTC as shown in figure 4. Western and Southern Europe are aggregated in two additional market areas respectively. Both, the NTC, generation capacity assumptions per fuel type and market area with power prices are taken from TYNDP 2020 scenario report National Trends scenario [37]. The target year is 2040 and all optimisation takes place in one shot for that year. Given the long lead time towards 2040, some minor deviations are made from the TYNDP scenario as will be elaborated in the next paragraphs.

The wind farm assumptions are based on [2] with adaptations from latest project developments [38, 39] and the marine spatial plan drafts by each country as of June 2020. Wind farms with commissioning date before 2026 were excluded from this exercise. The resulting set of wind farms accumulates an offshore capacity of 45 GW (c.f. figure 5)and exceeds the TYNDP offshore assumptions by far. For the sake of this analysis they are overwritten here.

This case study does not assume interconnection increases beyond what is listed in TYNDP. By design, however, additional capacity crossing the sea may well be build inside the model if efficient. On top, all interconnectors with commissioning date after 2026 are given to the market model as tee-in candidates for the introduced routine of clustering wind farms into nearby submarine transmission corridors. In that way TYNDP assumptions are taken as a lower boundary of the future interconnection level in the Baltic Sea grid. Hosting capacities for all onshore substations where the model can land cables ($\widehat{ntc}_{l,v}$) are arbitrarily fixed to 4 GW for voltage levels above or equal 380 kV and 2 GW for all others. This constraints the amount of power, that may be landed at a given substation.

All weather dependent time series data is based on the climate year 2012. Renewable energy availability is retrieved from reanalysis data by [40, 41], who provide the data open access for a wide range of climate years.[3] Onshore PV and wind are aggregated into one time series per country. Offshore wind data is retrieved per cluster. Electricity demand is taken from historical records for 2012 [42] and scaled up to meet the annual energy demand indicated in TYNDP. A structural change in demand side flexibility towards 2040 is therefore neglected. Natural inflow into hydro reservoirs is taken from historical data for 2012 [43, 44].

The calculations for the GIS analysis are conducted in the open-source GIS QGIS[4] in

[3] `https://www.renewables.ninja/`
[4] `https://qgis.org/en/site/index.html`

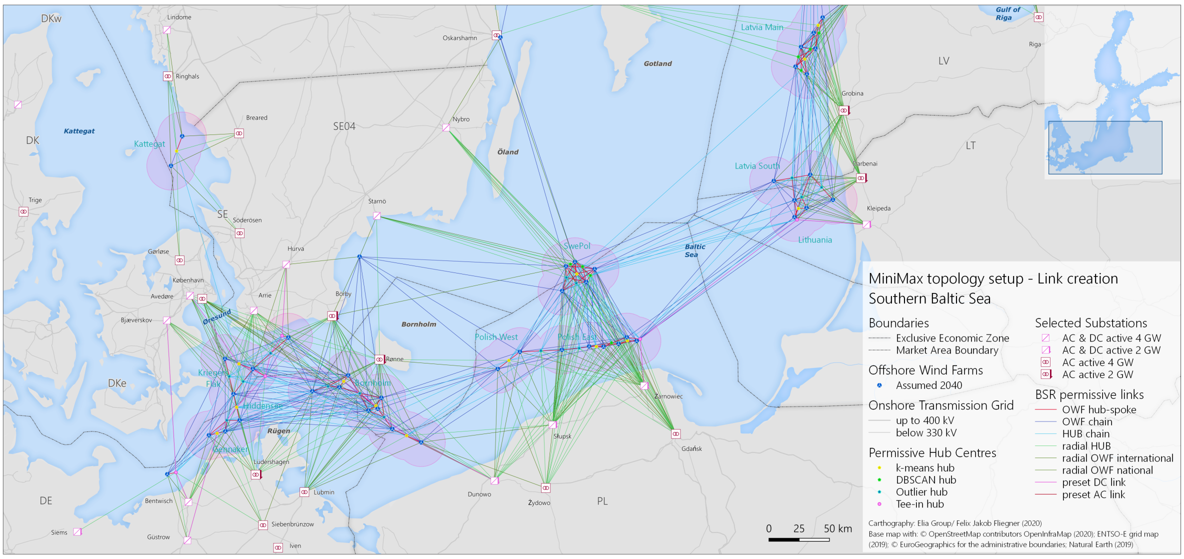

Figure 6. Map of identified permissive links in GIS.

version 3.10 “A Coruña”. The programming language JULIA[5] is used with the JuMP package for the market simulations and mixed integer linear programming [45, 46]. This analysis uses Version 1.4.1, which is available open-source and licensed under MIT license. It applies the GUROBI solver which was available in an academic license.

5. Results and Discussion

GIS topology creation

The output of the permissive graph topology creation in GIS is shown in figure 6. It reveals many regions of high wind farm density resulting in at least one clustering prospect for 59 of all 71 assumed wind farms. This translates into 88 % of offshore wind power that could be clustered. The analysis further reveals additional interconnection prospects beyond the presets from TYNDP. In fact, almost every cluster is connected to more than one shoreline, creating an abundance of hybrid asset opportunities. Both observations underline the wealth of grid development prospects and high synergies to be identified.

Notice, that each node (hub or wind farm) is at least indirectly connected with any other node in the graph. It implements the desired output of a sufficiently reduced, yet all-embracing graph over the entire study perimeter. For each pair of nodes, an ordered set of chained links can be found to connect them.

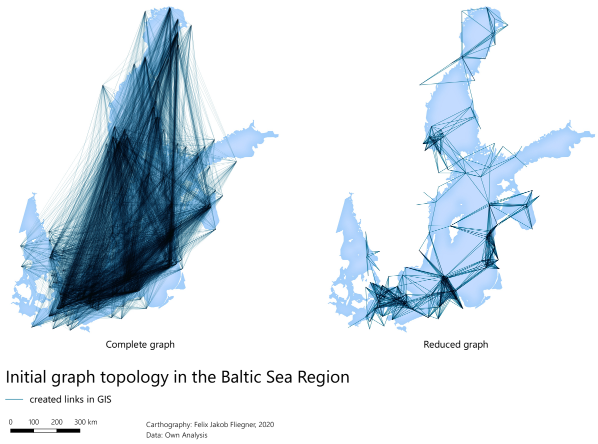

Figure 7. Complexity reduction in GIS.

[5] `https://julialang.org/`

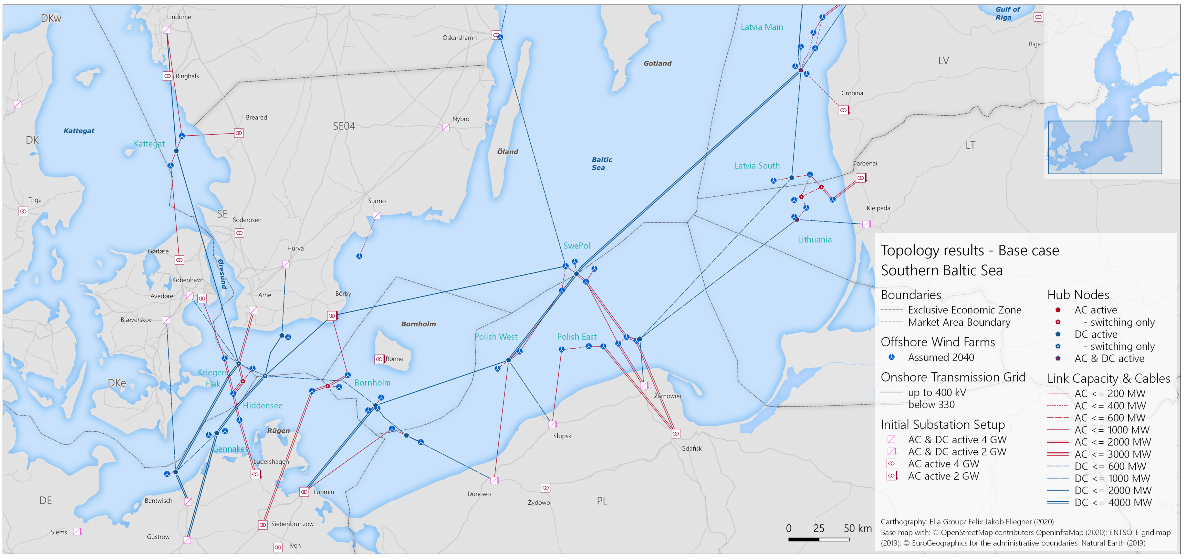

Figure 8. Map of base case topology results.

It may contain several link types stacked next to each other such as hub-spoke links, hub chains or radial connections. For the mere connection of two nodes it does not matter which link types enable it, as long as it exists in the final graph. Such a connection is denoted as path, where several paths may be routed via the same links, i.e. they are bundled. In that way, similar connection corridors no longer require two separate links in the graph but can be investigated at once.

The piece-wise chaining of links denotes the central element of complexity reduction achieved by the GIS topology set-up. This is ensured by linking two clusters via their mutual closest hub member and not any other member further inside the cluster. Understand, that this observation is a direct consequence of the GIS parametrisation, i.e. the definition of circumcircles for the search of neighbours in DBSCAN. For the elongated Baltic Sea this parametrisation might look different than for more compact water basins such as the North Sea. Study figure 7 for a visual presentation of the achieved complexity reduction for the presented case study.

Optimised offshore grid

The investment optimisation results for activated links and nodes are shown in figure 8. All 71 wind farms are connected to the grid, i.e. the integration of 45 GW wind power is seen feasible in the context of this simulation. A slight under dimensioning of transmission cables connecting individual wind farms reveals, however, that the offshore grid is not designed to integrate the "last kWh" into the system. 5.6 TWh of wind energy are dumped annually, which is induced by the strict cost trade-off from the investment model.

This trade-off also drives a high concentration of transmission paths. While six wind farms are connected radially, the majority is either clustered into central hubs (27) or chained (38). Long-distance, high-capacity chains are realised in DC technology and hub-spoke links and short-distance paths are realised in AC, confirming the above made considerations. Such chains are mostly asymmetrically installed, where the leg towards the high load countries in mainland Europe is stronger then the legs towards the north or east. This observation represents a funnel effect where wind power from foreign countries is mainly integrated into the power grid of Germany and Poland, where demand is highest and displacement of thermal generation most beneficial for the optimiser.

Interconnection across the Baltic Sea is substantially expanded beyond what is assumed in TYNDP scenarios. While this observation is partly backed up by an increased north-south and east-west interconnection need it is also induced by the simplified onshore grid modelling in this case study. For instance, the Öresund cable from SE03 to DE is partly caused by a non-existent capacity expansion between SE03 and SE04 onshore. Such "detours" are therefore merely a result of model calibration and less a "true" transmission need.

Sensitivity analysis

Routing bias In a first sensitivity check ("No IC"), the preset TYNDP interconnectors are removed from the dataset, to illustrate the effect of precedent decisions on subsequent topology prospects. Whilst most interconnectors from the input assumptions are confirmed in their cross-border capacity, the overall offshore topology layout changes. Wind farms are still clustered and grouped in a similar way but overall cable installation is reduced (7300 km versus 8400 km in base case). The enforcement of bundled transmission paths is now stronger, with no external presets (i.e. precedent optimisation decisions before new wind farms were added to the scene) constraining it. This observation also signals that exogenous information on the location of preset links, hubs and wind farms is an influential parameter on itself. It underlines the notion of grid investment being residual to generation investment and the impact of step-wise optimisation as opposed to one-shot optimisation as confirmed by [47].

All radial The second sensitivity, enforces only radial and national connection prospects for all wind farms, i.e. hybrid assets cannot be built. Additional interconnections between countries including the formation of backbones, are still allowed. Whilst this sensitivity appears rather strict and unfavourable, it is the most commonly realised offshore topology as of date. The most prominent finding of this sensitivity is the suboptimal connection prospects for remote or far-offshore wind farms. Since some wind farms are located closer to foreign countries, their national connection systems now require costly cables. In consequence some wind farms are not connected at all, leading to a "loss" of four wind farms equal to 3.5 GW in this sensitivity. The remaining wind farms face higher curtailments (8.4 TWh/a versus 5.6 TWh/a in base case) to increase utilisation rates once again. In parallel, many interconnectors are realised in the model, leading to the longest cable lengths among all studied cases (9300 km). In summary, this sensitivity showcases the benefits arising from an interconnected offshore grid with hybrid assets as opposed to radial connections only.

Strong onshore grid The third sensitivity is denoted "strong grid", since it tries to address one blindspot in the base case analysis, namely the onshore grid. The restriction of limited landing capacity for all substations is lifted to infinity, while keeping all other onshore cross border NTC in place. Mind that this sensitivity is incorporating a bias for integrating too much wind energy in each national grid. Since the onshore grid expansion is introduced at no cost for the model, the actual trade-off between grid expansion investment and dispatch improvement from the base case is no longer valid. In line with the no interconnectors sensitivity, the offshore topology is yet again more centralised leading to the highest number of clustered wind farms and overall shortest cable lengths (6600 km). At the same time curtailment of wind power reaches its minimum (1.5 TWh/a), signaling a most effective wind power integration into the system. This effect comes at the cost of highly concentrated wind energy landing onshore. Backbones of up to 8 GW each show up in the analysis, posing a huge integration challenge for singular onshore substations if they were realised in practice. On the contrary, the lifted onshore substation power limits reveal that the pure economic value of wind power in PL and the Baltic States is still high. The model connects more wind in those states than in the base case. The combination of internationally optimised wind farm connections with a strong onshore grid foster a centralised offshore backbone with minimised total link length. In other words, the strong grid sensitivity can also be regarded as an optimistic stance towards the future Baltic offshore grid.

6. Conclusion and Outlook

A novel methodological approach towards offshore transmission infrastructure optimisation has been presented. It separates an otherwise intractable complex optimisation problem into two parts. In a first step a GIS analysis is performed to screen a large set of assumed wind farms and substations for clustering and connection prospects. A MiniMax algorithm clusters wind farms into hubs and identifies permissive links among them while filtering all non-feasible ones from the solution space. The resulting graph topology is given to a mixed integer linear market model which optimises transmission paths. It aims to minimise total investment cost into new transmission capacity while integrating as much wind into the system as possible.

This modular approach avoids manual clustering or scenario building, which is the major contribution of this work. The analysis is no longer limited to a pre-defined set of very few scenario story lines but can perform complex analysis on large geographical scopes at once. The analysis starts bottom up from initial wind farm assumptions and standard building blocks for the offshore grid of the future. While the cost assumptions are linearised and the operational physics simplified a lot, the standard building blocks can be stacked into complex offshore topologies. This enables the presented framework to distinguish between two voltage types and a wide range of grid topologies including radial connections, hub-spoke links, central hubs, chains, submarine cable crossings and tee-in into interconnectors. An important element of the toolchain is that offshore transmission capacities are not fixed ex-ante but can be freely expanded or newly created.

The performance of the model is demonstrated at the example of the future Baltic offshore grid for the target year 2040. It reveals a wide range of clustering prospects for almost all wind farms, even the most remote ones. The GIS pre-processing leads to a tenfold reduction in combinatorial complexity and clears the initial complete topology graph into a filtered one, where first focus regions of offshore activity can be found. It enables the market model to perform discrete decision making on the large scope.

The modelling results suggest that clustering and chaining of wind farms is most efficient and often superior to radial national connections. In most cases such chains and hubs are part of a larger hybrid asset, which connects the wind farms to more than one shoreline. Bundling of transmission paths is, therefore, a central element of the future offshore grid as suggested by the case study. The exact trajectory and size of such transmission assets is, however, subject of high sensitivities both with respect to preset assets in the sea and technological parameters for the building blocks and their cost. Irrespective of the chosen parametrisation, all simulation runs suggest that optimising the future offshore grid is a quest of pan-European scale. Given its size and combinatorial complexity GIS pre-processing can make it a computationally tractable challenge.

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Appendix

Nomenclature for parameters, sets and variables for the case study

Parameter	Symbol	Unit	MVAC	HVAC	HVDC	Reference
Cable length and power cost	$c_{l,v}^{\text{len,pwr}}$	M€/ GW/ km	0.34	0.97	0.19	[48, 49]
Cable length cost	$c_{l,v}^{\text{len}}$	M€/ km	1.4	1.29	0.8	[48, 49]
Cable fixed cost	c_{v}^{fx}	M€ p.u.	2	4	4	[34, 49]
Node power cost	$c_{n,v}^{\text{pwr}}$	M€/ GW	n/a	30	120	[49, 50]
– deduction onshore	$mu_{n,v}^{\text{pwr}}$	%	n/a	-8	-26	[48]
Node equipment cost	$c_{n,v}^{\text{fx}}$	M€ p.u.	n/a	60	40	[49, 50]
Node fixed cost	$c_{n,v}^{\text{act}}$	M€ p.u.	n/a	26.52	175.96	[48]
– deduction onshore	$mu_{n,v}^{\text{fx}}$	%	n/a	-50	-80	[51]
– markup sea ice high	$mu_{n,v}^{\text{act}}$	%	n/a	+7	+7	[2]
– markup sea ice medium	$mu_{n,v}^{\text{act}}$	%	n/a	+4	+4	[2]
Equipment power limit	$\widehat{k}_{n,v}$	GW	1.6	1.6	2	[49]
Cable power limit	$\widehat{k}_{l,v}$	GW	0.4	1	2	[49]
Hub-Spoke length limit	n/a	km	20	n/a	n/a	applied from [33, 49]
Chain length limit	n/a	km	n/a	200	200	arbitrary for GIS
POC limit high hosting capacity	$\widehat{ntc}_{l,v}$	GW	n/a	4	4	own assumption
POC limit low hosting capacity	$\widehat{ntc}_{l,v}$	GW	n/a	2	2	own assumption
Lifetime	d	years	40	40	40	applied from [49]
Discount rate	i	%	5	5	5	own assumption
Annuity factor	a	$\frac{(1+i)^d * i}{(1+i)^d - 1}$	/	/	/	/
Marginal cost of g in h	$mc_{g,h}$	€/MWh	/	/	/	/
Demand at n in h	$d_{n,h}$	GW	/	/	/	/

Table 1: Cost assumptions and technical parameters for offshore transmission assets.

Category	Symbol	Description
Sets & Indices	$n \in N$	Set of all nodes in the model
	$h \in H$	Set of all states (time steps) in the analysis
	$g \in G$	Set of all generators
	$v \in V$	Set of voltage types
	$l \in L$	Set of all links in the model
Variables	$K_{l,v}$	New link capacity on l of type v [MW]
	$K_{n,v}$	New node capacity at n of type v [MW]
	$P_{g,h}$	Generation of g in h [MW]
	$\Phi_{n,v}$	Binary, indicating, whether n is activated of type v or not
	$\Upsilon_{l,v}$	Integer, number if cables built on l of type v
	$\Upsilon_{n,v}$	Integer, number of units of equipment built at n of type v

Table 2: Nomenclature of symbols for the analysis

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