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Spatial Optimization for Energy Island Location and Cable Routing Considering Offshore Zoning

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Spatial Optimization for Energy Island Location and Cable Routing Considering Offshore Zoning

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Abstract. The energy hub concept presents a compelling opportunity to channel electricity from offshore wind farms to the grid, facilitating cross-border energy trading and conversion. However, one of the main challenges lies in the strategic identification of a suitable energy island location and the establishment of an interconnected cable routing path. Part of the complexity arises from the need to navigate offshore zoning regulations and accommodate various spatial uses within the offshore area. This paper exhibits a case study to explore the spatial optimization for a potential offshore energy hub in the North Sea. It aims at finding out an optimal spatial configuration of the offshore energy hub, such that the island location and the associated cable routing do not infringe upon keep-out zones while strategically positioning the hub closer to high-capacity wind farms. To achieve this goal, detailed geographical data incorporating offshore zoning information is leveraged for spatial optimization. The Dijkstra's algorithm is then applied to identify the optimal island location and cable routing path. The effectiveness of this spatial optimization methodology is demonstrated through a case study involving offshore wind farm sites in the North Sea. Given the real geographical data, simulation results underscore the efficacy of the Dijkstra's algorithm in determining the optimal energy hub layout. In particular, an optimal spatial design is achieved, based on cable lengths, asset capacities, offshore zoning and island/platform location for a potential offshore energy hub in the North Sea while ensuring compliance with keep-out zoning regulations.

1. Introduction

Over the past years, offshore wind has grown a pivotal role not only in achieving the European climate goals, but also enhancing the energy security and decarbonization efforts. European Union (EU) presented a new target to increase offshore wind installed capacity to 65 GW in the North Sea by 2030 – supplemented by 20 GW of green hydrogen – with a more ambitious target of 150 GW by 2050 [1]. These goals are highlighted in the Esbjerg agreement [2] between Belgium, Denmark, Germany and the Netherlands which aims at making the North Sea a green power plant in Europe. Not only that, but energy production is more and more decentralized and far offshore due to for e.g. better wind resource [3], public opposition for wind turbines close to land [4] etc.

In this context, the concept of the offshore energy hub emerges as an enticing proposition. It offers a solution for aggregating electricity generated by various offshore wind farm (OWF) sites into an offshore energy island‡ and channeling it into the national electricity grid as well as providing the possibility of cross-border energy trading and conversion, i.e., Power – to – X system§. For instance, the Hub-and-Spoke configuration proposed by the North Sea Wind Power Hub consortium [5] seems to be a promising solution to interconnect countries along with an alternative configuration that features conversion to hydrogen. Energy hubs thus provide additional flexibility and act as enablers for increasing the offshore wind capacity in the future integrated energy supply. However, one of the key obstacles lies in pinpointing the potential energy island location, and devising the interconnected cable routing path i.e. hub layout, especially in the densely occupied offshore area of the North Sea. The North Sea encompasses a variety of uses (e.g. military zones, natural reserves) and complex offshore zoning as shown in Fig. 1. How to factor those physical constraints, and identifying the most economically viable island location and the cable routing path constitutes the core challenge.

Numerous studies have concentrated on spatial optimization, typically addressing specific facets of the problem rather than approaching the optimization holistically. Meanwhile, a considerable number of studies have focused on the routing optimization within the wind farm, such as [7], [8], [9], [10]. A recent study from Backstrom [11] and Warden focused on export cable routing using GIS environmental heat maps. The results show a mapping of the area based on environmental risks and how the routing algorithm can provide routes of minimal impact. In addition, Ho [12] utilized genetic algorithms to optimize cable routing for OWF collectors and offshore substations (OSSs) to minimize the total investment cost. However, actual spatial usage data was not considered for routing. Brosschot [13] dived into more parameters of spatial complexity and usage (i.e. slope, aspect) and analyzed scenarios that feature interconnection in the North Sea comparing electricity with hydrogen networks using a cost surface and other techno-economic parameters. Nevertheless, these studies do not analyze integration with energy islands being the links between OWFs and onshore grids and tackle the question of locating the optimal island position.

In this paper, we present a case study to explore the spatial optimization of a potential energy hub in the North Sea taking into account various spatial usage at

‡ Energy islands refer to existing physical islands, artificial sand islands but also platforms [5].
§ It is important to note the distinction made between energy hubs and islands:

- **Offshore hub**: Energy hubs are envisioned as multi-carrier offshore energy systems consisting of energy production, conversion and/or storage that are connected to the shore via national (transport) corridors or interconnected internationally. They are also places where several sector coupling activities are undertaken including platform electrification, CO2 storage, Power2Gas (hydrogen), and natural gas production [6].
- **Energy Island**: Physical island or platform that features conversion and interconnection infrastructure while it enables other functions as well (e.g. maintenance port).

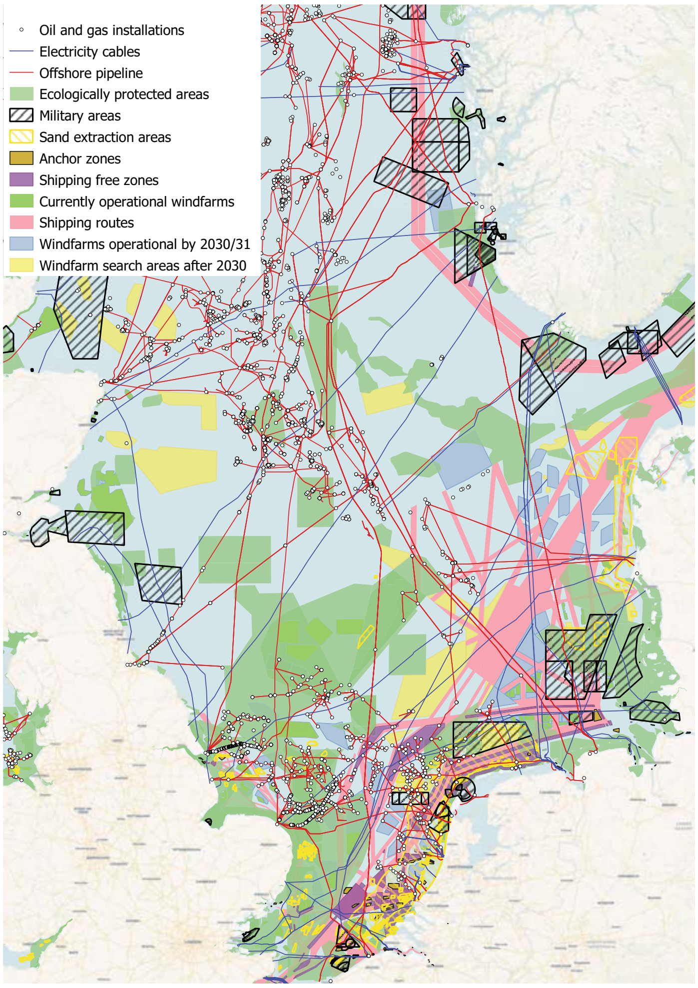

Figure 1: Spatial usage within the North Sea.

the same time (i.e. ecologically protected areas, shipping lanes, military zones, sand extraction). The aim is to optimize the island location together with the associated cable routing minimizing the interference with keep-out zones and favoring locations closer to higher production capacities. Existing cable corridors are not taken into account and thus, a greenfield approach was used, since as Brosschot [13] concluded reusing infrastructure leads to minimal savings. In particular, geographical data with information on offshore zoning formulated into a weighted graph is used as inputs for such a spatial optimization. Then the Dijkstra's algorithm is utilized to determine the optimal island location and cable routing that minimizes the length of the interconnection infrastructure while respecting the existing offshore zoning. The whole process was integrated in a tool, which given a desired topology and asset location performs an offshore hub spatial optimization, tracking down an optimal location for an energy island and providing an optimal cable routing. The cases that are shown, demonstrate the impact of offshore wind up-scaling and its integration, on offshore cable routing and island locations. The hub layout differences between cases are directly

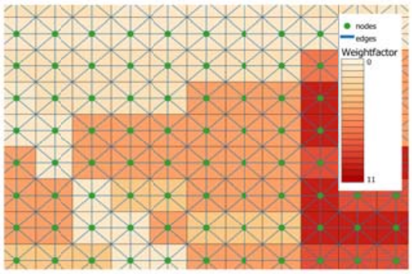

Figure 2: Visualisation of a part of the graph. The coloured rectangles in the background indicate the weight factor assigned to the area. The edges in this graph range from 6 to 9 kilometers.

related to the changes in asset(i.e. wind farms) capacities and locations. Depending on the general search area for the hub and relevant planning, the island locations can vary significantly or slightly showing the localized nature of the optimization problem.

2. Methodology

The Dijkstra's algorithm – reviewed with other options in [14, 15] – is an optimization method to seek the shortest weighted paths between nodes in a graph. The Dijkstra's algorithm is selected since it suits this particular optimization problem being able to find the shortest path from any node to all the other specified nodes and was also preferred in [13], one of the spatial usage studies mentioned in the introduction. It is applicable for all types of (weighted) graphs and its time complexity is quadratic $O(n^2)$. In this case after optimizing for all possible nodes, the one with the lowest objective value is selected. To formulate the weighted graph for the energy island spatial optimization, the geographical data‖ about the predefined area activities and zones, the potential reuse of corridors and their corresponding weight factors in the North Sea is used.

The area of interest in the North Sea is provided as a rectangle of coordinates, together with the desired coarseness to generate a vector image containing all the above geographical information for each rectangle. This vector image is utilized to generate the weighted graph in the NetworkX python package [19]. A node is generated at the center of each rectangle and edges are generated with the other eight closest nodes, indicating that from each node, there is an edge in the four cardinal directions, e.g. North, East, South, West, and in the four diagonal directions, e.g. North East, South East, South West and North West, as these can provide a significantly shorter route, as shown in Figure 2. This graph is designed with edges ranging from 6.0 to 9.0 kilometers. Each edge will thus contain information about its total length, the nodes it connects and the spatial uses which are the average of the rectangles it is connecting.

The nodes have been picked at the center of the rectangles as the spatial uses have

‖ The geographical information for North Sea zoning was collected based on various sources, including Emodnet map viewer from the European Commission, Noordzeeloket, OSPAR data information management system and North Sea energy code project[16],[17],[18],[6].

been defined at the rectangles, and thus if two nodes on the edges would have been picked, an edge in one of the main cardinal directions could not have its spatial uses impact defined as it is not clear which data to use since the edge is 'on the edge' of the two rectangles.

Finally, there are a few options to change and adapt the topology of the graph. First, as the offshore routing is explored, all edges entirely on land or passing land for over 50% of their length are excluded. The exclusion of these edges is particularly relevant for the islands located in the North Sea as one does not prefer to take the lines on land for a few kilometers and then go back to the seabed, as well as other relevant factors for routing onshore are not considered in this optimisation. Secondly, additional edges can be added to the graph to represent existing infrastructure that can be re- or co-used.

The weighting factors are based on the info from the work in [13], that considered a cost surface to represent the value of avoiding or favoring each area for pipe or cable routing, Table 1. The weight factor for the edge, $F_{(u,v)}$, is the sum of the weighting values of the spatial uses relevant for that edge, except for locations where there is already a corridor, then solely this corridor determines its weight factor. Furthermore, re- or co-using a pipeline, e.g. the additionally added edges for re- and co-use get the weight factor only associated with the pipeline reuse. If no specific spatial uses are defined for an area, the weight factor remains 1.0. Figure 2 shows an example of how the edges and nodes are distributed over the area with the weight factors defined as described above.

Given the specific wind farm sites and the onshore landing point which act as terminal nodes T, the Dijkstra's algorithm aims at determining the shortest weighted path to every node in the graph. The optimal island location I is the starting point from which, the routing to the wind farm sites and landing point, are then determined simultaneously by selecting the node with the minimum sum of all weighted shortest paths from the terminal nodes. In addition to the geographical data, the production/consumption of energy of a terminal node determines the required capacity of the electricity cable, taken into account with a capacity cost factor C_T. This completes the objective function in eq. (1), which is subject to constraints that ensure a fully connected network of the terminal nodes. The objective in this case is a spatial value that considers cable lengths and capacities as well as quantifies the impact of offshore zoning. A further step would be a cost calculation but it is not the purpose of this study. The focus of this paper is to compare different scenarios based only on distances, asset capacities and zoning and not an exact cost calculation. As per the constraints these are partially included in the graph in the sense that the nodes define also the degrees of freedom for the routing from each node. The other constraints ensure that the weight and the length along a path are positive. Without loss of generality, no additional cost factors are included for the island location itself in this study, however, it can be included by adding a weight for the island depending on its location C_I, this does require information on how to specify these weights based on the type of hub (e.g.

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function of sea depth) and the impact of operation and maintenance on the ecology.

$$\begin{aligned} &\min_{I,\delta_{(u,v)}} C_I + \sum_T \sum_{(u,v)} D_{(u,v)} F_{(u,v)} \delta_{(u,v)} C_T, \\ &\text{where } C_I \geq 0, D_{(u,v)} \geq 0, F_{(u,v)} \geq 0, C_T \geq 0, \delta_{(u,v)} \in \{0,1\}. \end{aligned} \tag{1}$$

C_T, $D_{(u,v)}$ and $F_{(u,v)}$ denote the cost factor for the terminal nodes T which in practice are the capacities of the production/consumption nodes (wind farms/connection points), the length of edge (u, v) to display the distance between two arbitrary connecting nodes u and v (used to calculate cable length), and the weight factor on the edge between them that encapsulates the offshore zoning, respectively. Furthermore, $\delta_{(u,v)}$ indicates the decision variable to select the edge and I is the optimum island location at which each path from a terminal node should end.

Table 1: Weight factors to create a cost surface for the optimization algorithm.

Spatial use	Weighting value
ecology	5.1
sand extraction	3.42
shipping lanes	1.66
military	1.53
cable corridor	0.78
pipeline reuse	0.1

3. Case study

As shown in Fig. 3, three scenarios are considered to illustrate the spatial optimization for a potential offshore energy hub in the North Sea. The results of the optimization in terms of spatial values and cable lengths are summarized in Table 3. A grid of 100by100 pixels is used over an area of ca. 432000 square kilometers. The hub integrates the electricity from OWF sites and from the cross-border trades into the national grid. The information on the wind farms in each scenario is shown in Table 2. The search area for the case study is based on Hub East from the North Sea Energy Atlas [6]. Starting from wind farms located in this area, expansion scenarios are analyzed to demonstrate hypothetical future grid expansions and their impacts on optimal routing and spatial value. Note that for the shore connection points, locations for other existing cable landing points are based on the information from [20]. The connection points are hypothetical and their capacities are adjusted based on an equal split among participating countries. In an actual application, further analysis would be needed based on cross-border trading agreements etc. to define the capacities for these landing points. It is also important to mention that the existing wind farms were included to demonstrate the impact of upscaling offshore wind. In reality, existing OWFs have contractual and technical limitations that restrict export infrastructure changes, unless there is a re-powering or another condition that would require the changes.

Table 2: Summary of wind farm and connection point information, used in the case studies [20], [21], [22].

Type	Name	Location	Status	Capacity (GW)	Latitude (deg)	Longitude (deg)	Scenario
wind farm	Gemini	NL	Operational	0.600	54.03600	5.96000	A,B,C
wind farm	Riffgat	GER	Operational	0.108	53.69000	6.48000	A,B,C
wind farm	Borkum Riffgrund 2	GER	Operational	0.450	53.96670	6.49560	A,B,C
wind farm	Borkum Riffgrund 1	GER	Operational	0.312	53.96670	6.56230	A,B,C
wind farm	Merkur	GER	Operational	0.396	54.03330	6.54997	A,B,C
wind farm	Nordsee One	GER	Operational	0.332	53.97890	6.81390	A,B,C
wind farm	Gode Wind 1 and 2	GER	Operational	0.582	54.05000	7.03000	A,B,C
wind farm	Deutsche Bucht	GER	Operational	0.252	54.30497	5.79900	A,B,C
wind farm	Veja Mate	GER	Operational	0.402	54.32120	5.86030	A,B,C
wind farm	Ten noorden van de Waddeneilanden	NL	Development Zone	0.760	54.02300	5.65600	B,C
wind farm	Doordewind I+II	NL	Development Zone	4.000	54.24720	4.11280	B,C
wind farm	Nordlicht I	GER	Concept/Early Planning	0.930	53.64510	6.71900	B,C
wind farm	EnBW He Dreiht	GER	Pre-Construction	0.900	54.36500	6.18597	B,C
wind farm	BARD offshore 1	GER	Operational	0.400	54.35830	5.97500	A,B,C
wind farm	Horns Rev 1	DK	Operational	0.160	55.52970	7.90610	C
wind farm	Horns Rev 2	DK	Operational	0.209	55.60000	7.59000	C
wind farm	Horns Rev 3	DK	Operational	0.406	55.69440	7.68330	C
wind farm	Thor	DK	Pre-construction	1.000	56.36950	8.01430	C
wind farm	Nordsøen 1	DK	Development Zone	5.000	56.45420	8.07770	C
wind farm	Vesterhav Nord/Syd	DK	Under Construction	0.344	56.61997	8.01997	C
wind farm	Sandbank	GER	Operational	0.288	55.18997	6.86000	C
wind farm	DanTysk	GER	Operational	0.288	55.14000	7.20000	C
wind farm	Butendiek	GER	Operational	0.288	55.01897	7.77403	C
connection point	Hooksiel	GER	Hypothetical	-	53.63070	8.02580	A,B,C
connection point	Eemshaven	NL	Hypothetical	-	53.43860	6.83550	A,B,C
connection point	Endrup	DK	Hypothetical	-	55.52310	8.71840	C

Scenario A is the baseline scenario and comparisons to its spatial values are made. The results in terms of spatial values and cable lengths are summarized in Table3. The present case study illustrates the optimization results where the spatial value (as described in the methodology) varies with the scaled-up grid. In addition, a comparison is made between maintaining the island location of the baseline scenario (only routing the cables) and a re-optimization of the location. In general, the Dijkstra's algorithm is able to take into account the physical constraints in the spatial optimization, avoiding the areas with high weight factors if possible in all scenarios. In Scenario A, the island interconnects Germany and the Netherlands, connecting to a number of existing wind farms in the region. In Scenario B, connection to additional planned wind farms is included in the optimization and the routing adapts the cable paths accordingly. The island location is seen in Fig. 3 to move towards the west from its baseline location and several kilometers of additional cabling are added. This scenario results in a 2-fold increase in the spatial value relative to the baseline. Re-optimizing the island location results in about 4% spatial value reduction compared to keeping the same location with Scenario A. In Scenario C there is an additional connection to Denmark and more Danish and German wind farms. Apart of the new cable routing there is also a shift of the island towards the north to counterbalance the additional costs that a longer export cable connection to Denmark and the additional wind farms would impose. The optimal island location in this case reduces the spatial value by ca. 2% and the hub has over a thirteen-fold increase in spatial value from the baseline scenario. In summary, the proposed method shows good performance in optimizing the spatial configuration of a potential offshore energy hub with the consideration of physical constraints of offshore keep-out zoning in the North Sea. Thanks to optimized re-configuration, the spatial value is thus significantly reduced in both future expansion scenarios.

Table 3: Optimization Results

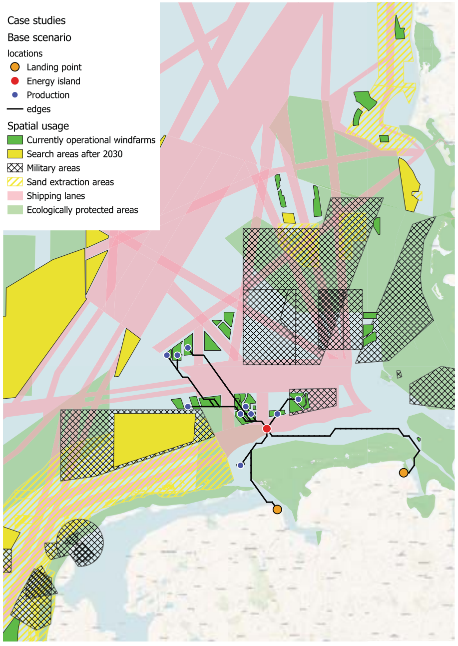
Scenario	Spatial Value	Cable length (km)
A	84601	866
B (re-optimized)	258728	2007
B (only routing)	268647	1521
C (re-optimized)	1246191	4376
C (only routing)	1273763	4959

4. Conclusion

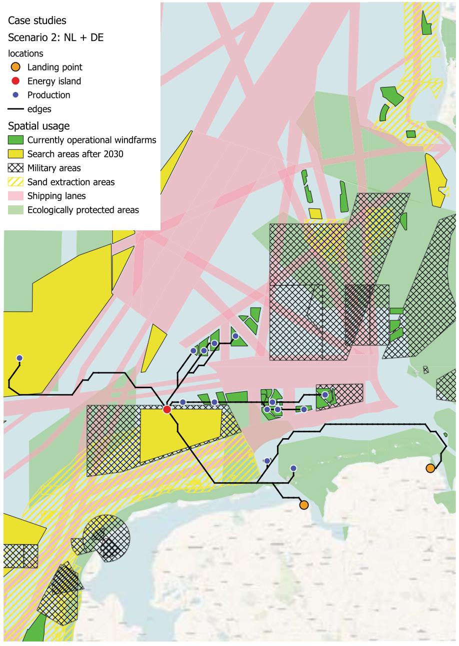
A case study of the spatial optimization for a potential energy hub in the North Sea is presented in this paper. The Dijkstra's algorithm is proposed to optimize the spatial configuration of a potential offshore energy hub in the North Sea. It is effective at determining the optimal energy island location and the cable routing path, which leads to the minimum spatial value. In terms of computational time, for the grid used in this study approximately 4 minutes were required for the calculations and the problem setup with the vast majority of the time required for the problem setup. The results also show that the algorithm tries to minimize the spatial value by moving the island in a way that it is closer to the highest capacities (OWFs or connection points) as expected from the objective function. Thus, there is a shift of the island which is notable in both expansion scenarios B,C from Fig. 3. The optimization results also show a promising reduction of the spatial value when the island location is included in the optimization. In addition, it showcases the significant spatial value increase from the baseline scenario when more OWFs and countries are included or in other words the impact of a future grid expansion. The results indicate the importance of carefully selecting an island location as well as the search area for a hub (e.g. which assets to include, which countries to interconnect) keeping in mind future planning for further integration of OWFs and interconnection between more countries. The significant increase of the spatial value from the baseline to scenario C demonstrates that there is a need to weigh whether single islands that would integrate such capacities are feasible from an economical standpoint. For example it might be more realistic to have more islands/platforms of lower capacity. Not only that, but maybe that could provide more grid security in case of failure. In the end there are additional aspects that should be taken into account together with the offshore zoning and such decisions are taken by transmission system operators who take all these aspects into consideration.

5. Future work

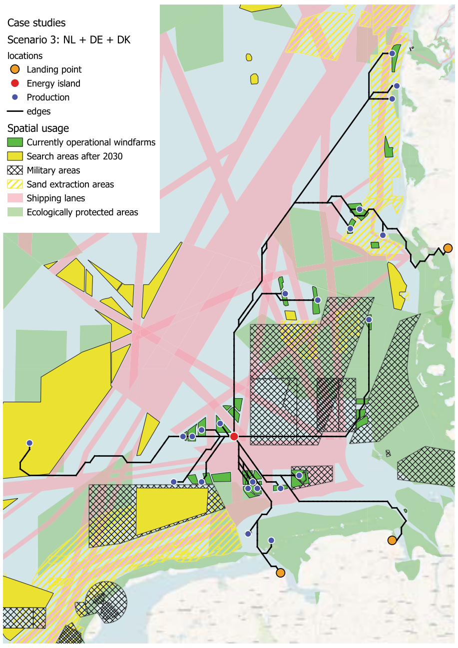
This paper shows that the proposed tool is able to provide the optimal routing for cables and island location within a hub area, considering the mentioned offshore zoning.



(a) Scenario A



(b) Scenario B



(c) Scenario C

Figure 3: Hub east scenarios that feature interconnection between countries and collect OWF electricity. Scenario A features existing Dutch and German OWFs. Scenario B includes some of the planned OWFs for the two countries, increasing the total capacity. Scenario C adds existing and planned OWFs from Denmark.

Adding more GIS layers and their respective penalty factors will help enhance the tool's ability to respect more spatial conflicts (e.g. bathymetry, seabed substrates and others). On top of that there could be limitations imposed for the island location itself, which are not considered here. Another interesting addition, would be an island location optimization based on hybrid carriers (electrons and hydrogen) that routes both pipelines and cables.

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