North Sea
Wind Power Hub

MODULAR HUB-AND-SPOKE: SPECIFIC SOLUTION OPTIONS

Case studies have demonstrated technical feasibility

The Consortium

The North Sea Wind Power Hub consortium has joined forces to realise climate goals. The consortium her work is based on research, stakeholder interaction and experience from earlier projects.

Port of Rotterdam

Biggest port in Europe with a strong ambition to become the most sustainable port in the world

ENERGINET

Danish transmission system operator working for a green, reliable and sustainable energy supply of tomorrow

gasunie

European energy infrastructure company serving the public interest and facilitating the energy transition by providing integrated infrastructure services

TenneT

TenneT is a Dutch-German electricity TSO and is one of Europe's major investors in national and cross-border grid connections on land and at sea in order to enable the energy transition.

Executive Summary

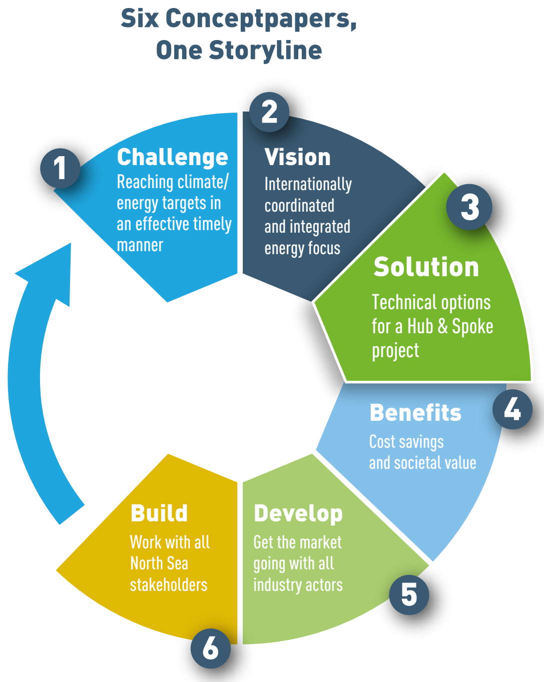
The modular Hub-and-Spoke concept needs to be translated into feasible project solutions.

Desktop studies have demonstrated technical feasibility of the Hub-and-Spoke concept for different locations, sizes and configurations. The design allows for a step-by-step roll-out which can adapt to specific local conditions.

A final conceptual design for a first project requires a balanced assessment of costs, benefits and environment.

Six concept papers, one storyline

The goal of the concept papers is to inform North Sea stakeholders, and the general public, of the results the NSWPH has obtained working on the modular Hub-and-Spoke concept over the last two years. The six concept papers tell one story: from the challenge to meet the Paris Agreement, through the solution building on the modular Hub-and-Spoke concept, to the next steps required to meet the Paris Agreement timely and in a cost-effective manner.



The Hub-and-Spoke concept needs to be translated into feasible project solutions

Several initiatives such as the North Seas Energy Cooperation[i] and long-term strategies and plans[ii] have hinted at integrated North Sea infrastructure development. The Krieger's Flak combined transmission asset and interconnector will bring integrated infrastructure into practice, while also German offshore HVDC connections for offshore wind farms serve a Hub function by connecting multiple offshore wind farms. The consortium sees the modular Hub-and-Spoke concept including P2X[1] conversion as a building block in a step-by-step and international coordinated roll-out to facilitate the large-scale roll-out of offshore wind energy. It is a first-of-its-kind project due to the combination of the following aspects:

- combining offshore wind transmission and interconnection infrastructure thus leveraging synergies to increase asset utilisation, reducing the relative costs of both functions,
- reducing the need for grid extensions beyond 2030 by (i) internationally coordinating the onshore connection of offshore wind energy, and by (ii) using P2X (e.g. power-to-Hydrogen) conversion and adapting and utilising the existing gas infrastructure,
- facilitating a step-by-step roll-out of projects through its modular design to find an optimal balance between scale and development times and investment phasing. Each specific project can adapt to its specific physical environment,
- realising significant scale, as modular hub sizes from 10 GW up to 15 GW are foreseen.

Concrete project definitions and conceptual designs are required to assess the feasibility of the vision for a Hub-and-Spoke concept in an international coordinated roll-out. A conceptual design of a first Hub-and-Spoke project depends on many factors including:

- location and physical environment,
- proximity and capacity of offshore wind farms that the hub is required to support,
- final energy demand requirements and transmission capacity and spatial restrictions at onshore connection points (electricity, hydrogen, heat etc.),
- interconnection requirements of surrounding countries,
- and required permitting and commissioning timelines of the Hub-and-Spoke project.

At this moment there is a lack of concrete transmission asset project commitments, spatial planning coordination and a clear and steady roll-out of offshore wind deployment beyond 2030. Innovative technologies need to be scaled up which requires time and a clear market perspective. This introduces uncertainty as to which technical option of the Hub-and-Spoke concept is favourable. Considering the uncertainty and various defining factors, the consortium investigated different technical options to demonstrate technical feasibility of the concept.

Desktop studies have demonstrated technical feasibility of the Hub-and-Spoke concept for different locations, sizes and configurations

One of the goals of the consortium has been to demonstrate technical feasibility of the Hub-and-Spoke concept. In addition, the consortium wants to understand the main techno-economic, environmental and planning impacts and drivers of different hub and spoke designs, locations and options for integration in

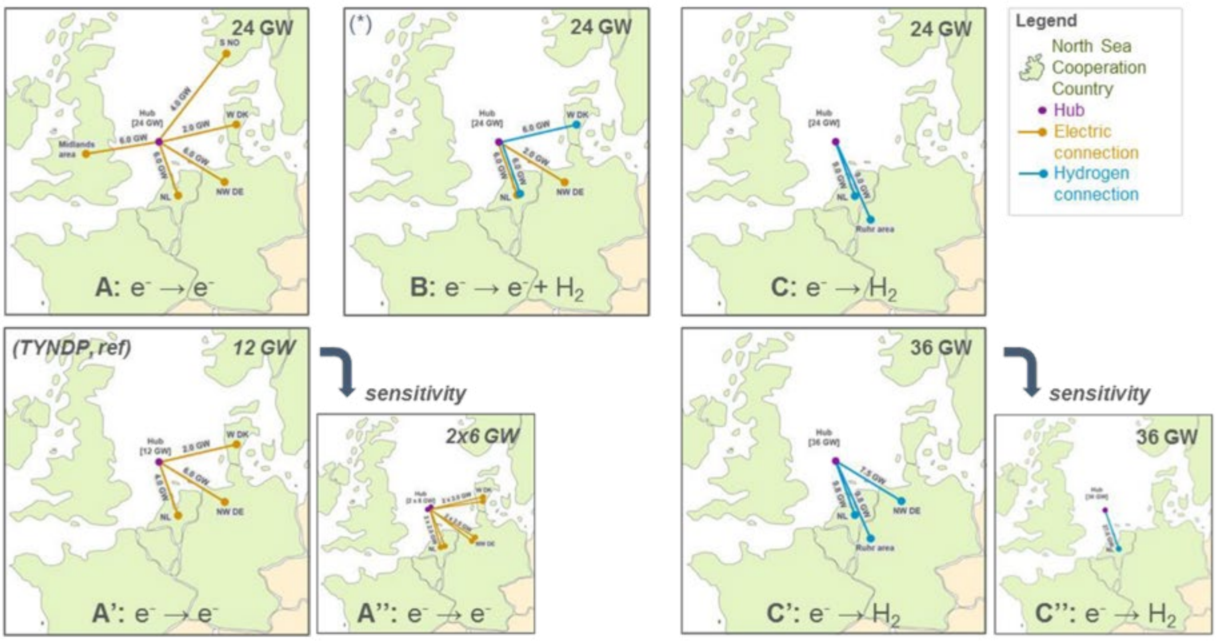
[1] *P2X includes power-to-gas (mainly H2 as well as methane) and other options (such as fuels, feedstock, food, oxygen, residual heat, etc.)*

the onshore energy infrastructure. To achieve this the consortium has engaged in several techno-economic evaluations for a range of "investigative configurations". These configurations consist of a combination of location, total offshore wind capacity connected to the hub and connection capacities to different countries. The selected configurations do not imply any preferred set-up, but rather have been used to explore the entire parameter space. During this past period the following investigative configurations have been investigated.

Based on the analysis the following overarching conclusions have been derived:

Hub size and foundation type: From a techno-economic perspective an optimal hub size is in the range of 10-15 GW of connected offshore wind farm capacity. Decreasing the hub size reduces the benefits scale. Further increase of the size however induces some limitations. Wind turbines can be connected directly to a hub through subsea inter-array cables. The limit of this direct inter-array to hub connection is approximately 12 GW of wind capacity[2]. If larger wind farm capacities are connected directly, the inter-array cables become too long and AC collector platforms are required to connect wind turbines beyond 12 GW to a hub. These collector platforms result in additional costs. As the share of hub CAPEX in the total offshore asset scope (wind farm and transmission assets) is modest (3-7%), the potential for benefits of scale of using a hub with larger capacity is limited. In addition, wake and blockage effects increase significantly for

Investigated key configurations



A number of key configurations have been investigated by the consortium to assess feasibility of the Hub-and-Spoke concept

[2] *assuming a wind farm density for the area around the hub of approximately 6 MW/km²*

larger hub and offshore wind farm clusters. This is addressed more specifically in a next section on the impact of location on the Hub-and-Spoke design.

Note that when an offshore wind farm cluster of, for example, 24 GW is considered, similar levelised cost of energy (LCoE) levels are observed for 4x6 GW, 2x12 GW and 1x24 GW hub configurations. The cost benefit for the smaller hub sizes stemming from a direct connection of wind turbines through array cables, is largely offset by the required additional interconnection assets (cables and substations) to facilitate the required interconnection levels between the hubs. In addition, it is found that a 12x2 GW configuration would be significantly more expensive in terms of LCoE (up to 12%, compared to the 4x6 GW configuration) as the 2 GW platforms carry a higher CAPEX and OPEX compared to other configurations. Note that only steel platforms were considered in this analysis, not gravity-based foundations which may reduce costs further.

Hub substructures can be based on different foundation types:

- sand island – this has been investigated for 12, 24 and 36 GW – with an approximate construction time of 8 years;
- caisson island – suitable for smaller hubs of approximately 6 GW and in shallow waters <25 m depth, with estimated three years construction time which is highly dependent on wave and wind speed conditions; or
- platforms, using a jacket or gravity-based structure as foundation, with an approximate three years of construction time.

It is found that where island-based foundations generally reduce investment costs and can enable larger scale interconnection hubs at lower costs compared to platform-based hubs, the smaller platforms can reduce environmental impact, planning risk and construction timelines.

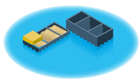
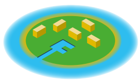
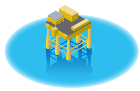
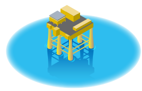
Each foundation type will have a different potential environmental impact. The placement of a sand island will locally affect the ecological and potentially the hydrological (i.e. local water currents) functionality in the reclaimed area. The footprint (i.e. the physical disturbance of the sea bed) of an island will be considerable and its magnitude will mostly depend on the water depth of the selected sand location. The impact on species (fish, mammals, birds and bats) is not fully understood. In general, a sand island will likely attract species that will benefit from the reclaimed land for resting, feeding and breeding. Fish and other species that are hindered by the vicinity of a sand island will be displaced from the reclaimed area. However, the numerous wind turbine foundations in the vicinity of the hub will create new benthic areas in otherwise uniform areas which can attract/increase fish abundance and shellfish beds and hence create feeding grounds for both seals and some marine mammals. The caisson and platform foundation types were not studied from an environmental impact perspective in detail yet.
Some of the other potential use functions of a hub (e.g.

Three Hub foundation types

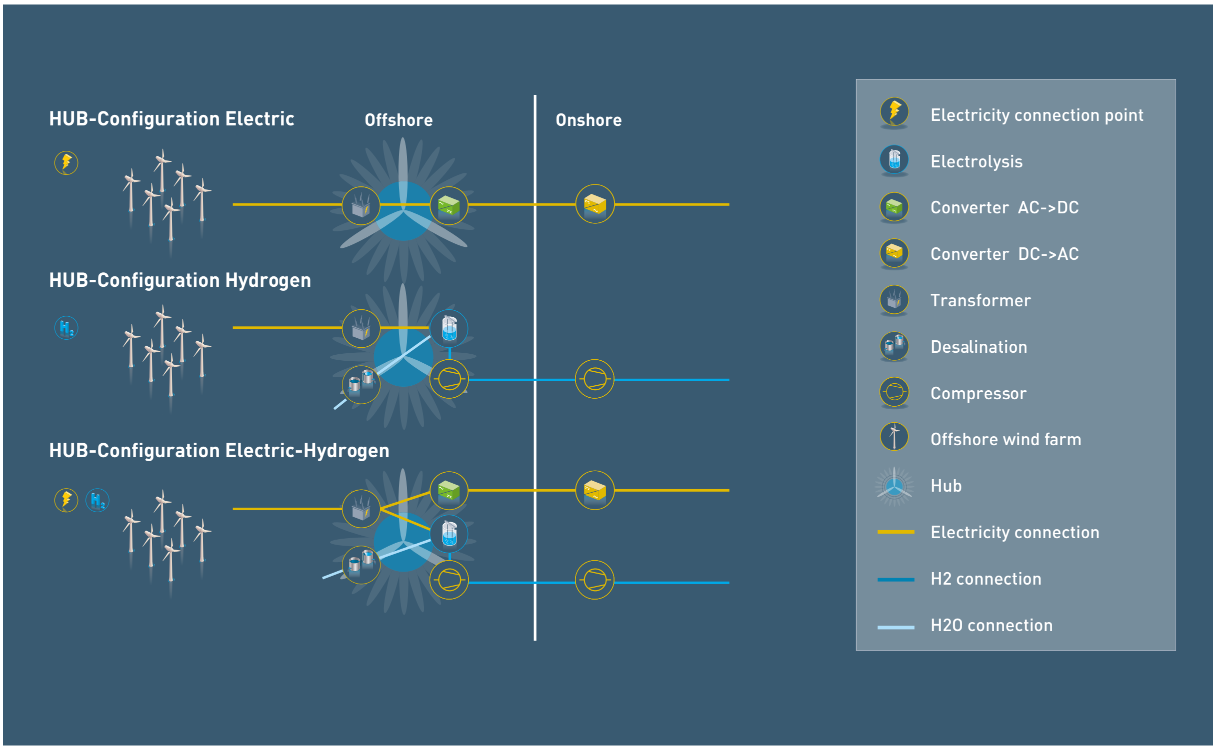
third-party access, air strip) have a substantial effect on hub type design and size, and result in planning risks through longer construction times, thereby more than offsetting the benefits they introduce. Preliminary assessments indicate that annual benefits from these additional facilities do not outweigh the additional operational expenses, let alone allowing for a substantial investment to be made to add those facilities to the hub.

The following table shows a number of key figures for the different Hub-and-Spoke foundation types, as investigated by the consortium, to understand the differences in characteristics and limitations.

An **all-electric** Hub-and-Spoke concept is based on combining wind farm transmission infrastructure and interconnection assets, and only electric transmission of energy. In the investigated concepts, wind farms are either connected at infield cable voltage directly to the hub (66 kV in this case; when within 25 km radius of the hub – which represents approximately 12 GW of

	Caisson Island	Sand Island	Platform	Gravity Based Structure
				
Water depth limitations	< 25m	<40m	<45m	larger 100m
Construction time	3-4	6-8	3-4	3-4
Size limitations	6 GW	>36 GW	2GW	Units up to 6 GW (tbc)
Phasing & modularity	No	Not for hub	Yes	Yes
Maturity	Middle	Middle	High	Units - High Linking - Middle
Footprint on seabed	High	High	Low	Middle
Accessibility	Limited Sheltered	Sheltered	Unsheltered	Unsheltered

Hub configuration: Different hub configurations were investigated by the consortium including all-electric transmission, combined electricity and hydrogen transmission, and fully hydrogen connected. For any given hub size, the total investment costs (CAPEX) for the transmission assets are found to be similar for all-electric, all-hydrogen and combined electricity and hydrogen configurations. Also, the spatial requirements are similar for the different configurations.



capacity), or through collector platforms (for all capacity above 12 GW) where power is transformed to 380 kV AC (alternating current) and transmitted to the hub. On the hub, 66 kV wind power is transformed to 380 kV, and together with the power from the collector platforms converted from AC to DC (direct current) power at 525 kV to minimise losses when transmitting power over significant distances to shore. Export cables transmit the power to the onshore connection points where an onshore converter station will convert and transform power back to AC power at the required voltage level of the onshore grid.

A potentially **all-hydrogen** connected Hub-and-Spoke concept would convert, offshore, all wind power to hydrogen and transport it through pipelines to shore. The connection of wind farms up to the 380 kV voltage level on the Hub is nearly equal to the all-electric configuration as described above. One small difference is that the power from the windfarms connected directly with 66 kV to the hub may feed the power to gas conversion system directly without transforming to 380 kV first. On the hub, power is transformed and converted down to 400 V DC to feed the electrolyser. Desalination will be required on the hub to provide on-spec (desalinated) water for electrolysis. The electrolysis units are based on a modular design to be scaled up to the required GW capacity. Currently two technologies are investigated: alkaline and proton exchange membrane (PEM). Hydrogen is compressed to a pressure of 50-70 bar for pipeline transmission to onshore connection points and storage locations. Reuse of existing pipelines is considered feasible.

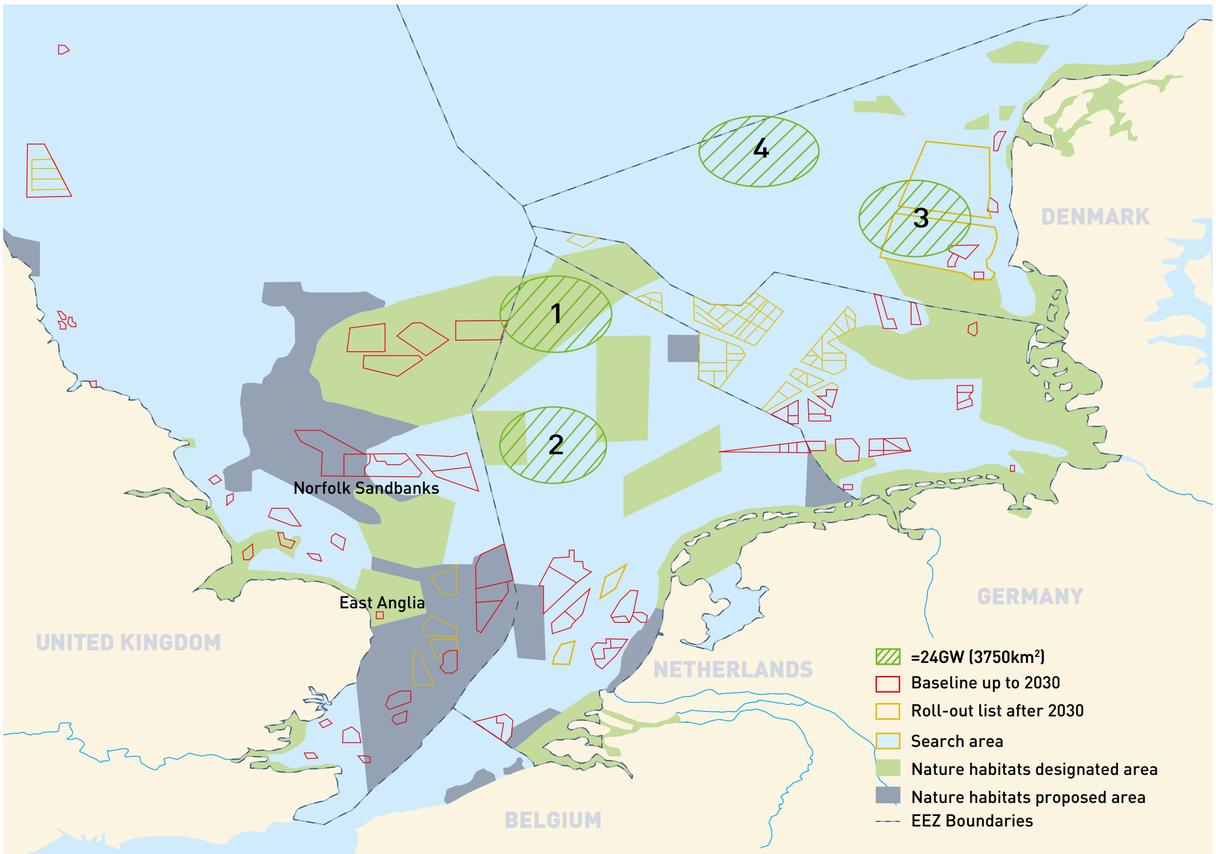
A **combined electricity and hydrogen** connected Hub-and-Spoke concept combines the above-mentioned concepts to allow for combined transmission asset and interconnector functionality, and power-to-Hydrogen conversion and hydrogen transmission. In this concept, the share of hydrogen conversion and transmission can be varied based on onshore demand centre and energy system needs.

A first Hub-and-Spoke project in the early 2030s is likely to be largely all-electric offshore, because of the expected technical maturity levels of P2X conversion at GW scale. P2X onshore is considered here to address onshore congestion issues resulting from large scale infeed from offshore wind. With further cost reductions and increasing technology maturity at scale towards 2030 and beyond, future Hub-and-Spoke projects are likely to include power-to-Hydrogen conversion to reduce total system costs, facilitate onshore system integration, provide green hydrogen to the market (mobility, heat, industry, feedstock), provide system flexibility and optimise benefits for society.

Location: Four investigative locations have been examined by the consortium to understand the main differences in environmental and techno-economic impact. These locations do not represent a preference for a location for a first project – but have been used to assess different locations specific impacts on Hub-and-Spoke design. They are defined as (1) Dutch EEZ on the Dogger Bank (Natura 2000 area), (2) Dutch EEZ south of Dogger Bank, (3) Danish EEZ west of Jutland and (4) a location in the deeper part of Danish EEZ and part of the Norwegian EEZ.

The locations range in varying distances from the nearest coast and are different in water depth and proximity to marine protected areas. It is important to consider the prominent seabed substrates in each area. Installation of large wind farms and hubs will most likely have a permanent impact on the local habitat, which will have a knock-on effect on the species abundance and biodiversity. The four investigative locations show little difference in relation to fish abundances, although the data shows some variation in composition of species. Potential negative impacts on birds and bats are mostly related to the wind turbine generators and not to a Hub-and-Spoke project. Seals, which are associated to shallower grounds, are more prominent in locations 1, 2 and 3. Here it is possible that in the long term, nature inclusive design of a hub as an island could have a positive overall effect. In general, there still are many environmental data gaps and potential environmental impacts and opportunities should be jointly investigated further with relevant stakeholders.

Increased water depths impact both hub costs and constructability. Costs for a sand island increase more than linear with water depth as increasingly more sand (and a larger footprint) is required. The impact on total



Four locations were assessed by the consortium so far, to test location specific conditions on hub design cost is limited, as island hub costs are only 3-7%[3] of the total CAPEX scope (wind farm + transmission assets). However, the large volumes of deposited sand will put strain on the existing seabed and may have reduced stability. An additional constraint is the requirement of new equipment (e.g. ships) for handling the large size and weight of the armour units required for the revetment of the islands. Sand islands are considered to be applicable to water depths up to 40-50m. For caisson islands the maximum water depth is considered to be 20-25m due to costs and limitations to gravel bed stability at larger depths, making them not a suitable candidate for the deeper locations. Gravity based foundations can be applied for a wider range of water depths depending on the exact design: box type foundations are suitable for water depths up to 25m, where shaft type foundations are suitable for increased water depths. The deeper locations (averages of location #2: 44m; location #4: 53m) result in a relative increase in costs due to more expensive wind farm foundations[4] and hubs[5]. Different seabed types exist between the single locations, such as sand, mud and coarse substrate. This can limit which hub foundation type and offshore wind farm foundation type is feasible to be built.

An initial assessment of the wind yields for the different locations and wind farm cluster sizes showed that no major differences exist in yield between the locations. However, increasing the capacity of the wind farm clusters can significantly increase losses due to wake and blockage effects, resulting in a difference of approximately 5%-pt. between a 2 GW and 36 GW wind farm cluster[6]. Wind resource potential proportionally impacts the levelised cost of energy for the different locations.

The distance to shore of a specific location affects the CAPEX of transmission assets mainly through increased cable length. Transmission cable costs are approximately 15% of total asset (wind farm + transmission assets) CAPEX scope, for all-electric hub configurations at the Dogger Bank (location 1). Similar, but smaller, impacts are observed for hydrogen

Wind yield potential for different locations and clusters

Location	1	2	3	4
Cluster size: 2 GW	53.9%	53.2%	54.1%	Not studied in detail; expected to be similar to locations 1-3
Cluster size: 6 GW	52.1%	51.3%	52.5%	
Cluster size: 12 GW	50.7%	49.9%	51.0%	
Cluster size: 24 GW	49.7%	48.9%	50.0%	
Cluster size: 36 GW	49.2%	48.4%	49.4%	

The wind yield potential is expressed as a capacity factor. The capacity factor is a measure that represents the equivalent full load hours at maximum generation capacity, divided by the number of hours in a year. E.g. a capacity factor of 50%, means a wind yield potential equal to a wind farm generating at full rated capacity for half of the year. Note that the wind yield potential includes wake and blockage effects but excludes other technical losses.

[3] Range of island hub costs compared to total CAPEX mainly depends on the capacity connected to the hub

[4] location #2 sees a ~10% increase in wind farm CAPEX compared to location #1 at 26m

[5] location #2 sees a ~50% increase in hub CAPEX for a 24 GW all electric hub compared to location #1

[6] Wind resource assessment is based on 15 MW wind turbines with a hub height of 145 m and a 230 m rotor diameter. Wind farm density of 6.4 MW/km^2 is assumed.

configurations where pipeline costs are approximately 3-5% of the total CAPEX scope for the same location. In addition, the OPEX of offshore wind farms will also be affected due to an increased distance to port. Note that locations 3 and 4 generally will put the offshore wind farms further away from where the majority of energy will be transported to as connections to Germany and the Netherlands can be foreseen.

P2X in an energy system perspective: In addition to offshore hydrogen conversion and transmission the consortium is investigating onshore hydrogen conversion and re-using the existing gas infrastructure. This concept has only been investigated from a system perspective (not from a technical and project specific perspective) to assess the potential benefits on a system level, e.g. from reducing the need for onshore electricity grid reinforcements. It considers P2X at onshore connection points, after electrical transmission to shore. Such a configuration uses sector coupling (e.g. hydrogen conversion) to facilitate energy system integration, provide system flexibility and decarbonise end-users. Additional benefits include potential valorisation of oxygen and heat streams from onshore hydrogen production and hydrogen for (synthetic) fuel processes. A more detailed analysis of the specific benefits is given in Concept Paper 4.

A final conceptual design for a first project requires balanced assessment of costs, benefits and environment

The desktop studies investigated several hub types and configurations, capacities and locations and found that a technically feasible solution could be designed for each of the physical conditions encountered at the four locations. The investigated technical options differ in construction time (and planning risk) and environmental impacts, and have a different impact on system costs and societal benefits. The benefits of the Hub-and-Spoke concept are further discussed in Concept Paper 4.

Developing a technical design for a first concrete project requires policy makers to provide:

- clarity on the roll-out of offshore wind capacity post 2030,
- allocation of offshore areas with sufficient collective offshore wind capacity, and
- a balanced assessment of societal cost and benefits, environmental impacts and timelines.

It also requires proper alignment with national and European grid planning processes. Such decisions require vision and direction from policy makers which takes into account feedback from industry, NGOs and TSOs to ensure realisation at lowest cost and highest value for society while minimising environmental impact. The consortium stands ready to facilitate the decision making by providing the techno-economic perspective from grid developments and system impact to the discussion.

Sources

[i] *EC. North Seas Energy Cooperation. https://ec.europa.eu/energy/en/topics/infrastructure/high-level-groups/north-seas-energy-cooperation*

[ii] *Such strategies and plans include the Ten Year Network Development Plan submission by the consortium for a 12 GW hub project connection to Denmark, Germany and the Netherlands by 2035 (ENTSOE, 2018. TYNDP 2018: Project 335 - North Sea Wind Power Hub. https://tyndp.entsoe.eu/tyndp2018/projects/projects/335), Meshed grid activities by the European Commission Tractebel, Ecofys and PWC, 2014. Study of the benefits in Northern Seas Region. https://ec.europa.eu/energy/sites/ener/files/documents/2014_nsog_report.pdf)*

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