Executive Summary

- Future North Sea offshore wind farms will increasingly be located further from shore. The longer distances to shore and generally deeper waters will increase cost levels when incrementally building on current offshore wind connection concepts (i.e. radial/individual connection).

- An internationally coordinated network development, using a Hub and Spoke concept for the North Sea grid, has a potential to realise cost reductions by utilising optimised offshore connection concepts, economies of scale and synergies with interconnection functionality.

- Also, an international (regional) coordinated approach may reduce the costs for reinforcement of the onshore grid required to absorb large amounts of offshore wind generated.

- To realise the full benefits of an internationally coordinated roll-out scenario a combination of different transmission asset concepts needs to be used, deployed at appropriate times and locations, in a coordinated, step-by-step roll-out.

- An internationally coordinated roll out approach has the potential to reduce the cumulative cost of the transmission infrastructure - to facilitate the large scale offshore wind roll-out and including additional interconnection capacity - for the North Sea by 30%, compared to a national incremental roll out scenario.

- Cost reductions in grid infrastructure present only one benefit of the coordinated roll-out approach. Additional benefits are anticipated based on international exchange between energy markets.

- Even though the Hub and Spoke concept uses larger scale asset solutions, development of the internationally coordinated roll-out scenario is step-wise and modular, allowing flexibility and limiting risks for stranded assets.

Future North Sea offshore wind farms will increasingly be located further from shore. The longer distances to shore and generally deeper waters will increase cost levels when incrementally building on current offshore wind connection concepts

To accommodate future wind power generation capacity estimated at approximately 70-150 GW in 2040 for the North Sea and possibly 180 GW by 2045 in a specific scenario (COP21) conducted by the consortium, large scale infrastructure developments are required. While recent auctions have shown a steep decline in the need for subsidies, several cost factors make large scale, far offshore wind power generation and their transmission assets, more expensive than present projects close to shore. This cost increase is mainly driven by the need for DC technology and longer export cables to transport the power to shore, also resulting in the need for additional offshore AC-DC converter equipment. Far offshore locations typically have deeper water, requiring additional investments in foundations, while the increased distance to port increases installation and operations & maintenance (O&M) cost.

An internationally coordinated network development, using a Hub and Spoke concept for the North Sea grid, has a large potential to realise cost reductions, especially for far offshore locations

The Hub and Spoke concept proposed by the consortium aims to reap the cost reduction potential through an internationally coordinated roll-out (ICRO) of offshore wind and transmission assets. The Hub and Spoke concept offers cost reductions by exploiting a cost-effective combination of proven technologies, asset innovations and a central collection and interconnection hub.

The Hub and Spoke concept ensures a modular build-out approach that can start today without having to rely on cutting edge innovation to reach sufficient maturity and reliability in fields of DC grid protection strategies. The concept is based on a combination of offshore transmission hubs, where power is collected and brought to shore via high capacity (DC) export cables. The export cables are connected to onshore grids in locations with minimal impact on existing grid capacity. By making smart connections between hubs, export cables also provide interconnection capacity.

Q: Are there other, more suitable and technologically ready, asset concepts that facilitate large scale wind power transmission?

The consortium partners are still actively researching other relevant grid concepts and technologies. If their effectiveness is successfully proven, a future North Sea infrastructure may still see combinations of large hubs and smaller DC substation hubs where deemed most cost-effective. This paper describes the conceptual options and benefits of a Hub and Spoke vision.

Through the internationally coordinated approach, the additional costs resulting from increased distance to shore can be offset, utilizing optimized offshore connection concepts, economies of scale and synergies with interconnection functionality

The Hub and Spoke concept combines offshore infrastructure for both power transmission and interconnection capacity, which allows to optimize the overall cost of offshore assets. Furthermore, a truly coordinated offshore grid infrastructure, taking into account long-term developments, also allows for more efficient connections towards the onshore power system by minimizing onshore grid reinforcements and considering direct connection options to Europe’s transmission backbone.

A levelized cost of energy (LCoE) analysis for far offshore locations reveals that the ICRO approach can realise substantial cost reductions compared to the currently practiced national incremental roll out (NIRO, or "business as usual"). The consortium partners have carried out preliminary analyses of various infrastructure alternatives, as applied in the recent Kriegers Flak project,

Q: How would you evaluate the cost reductions that can be achieved through additional interconnection capacity and improved supply chain effectiveness?

considered for the expected IJmuiden Ver offshore wind development, as well as potential future large-scale connections centrally located in the North Sea (e.g. on/near Dogger Bank). In Figure 1 an explicit comparison is made between the LCoE of the Borssele offshore wind farm and the potential far-offshore location at/near the Dogger Bank.

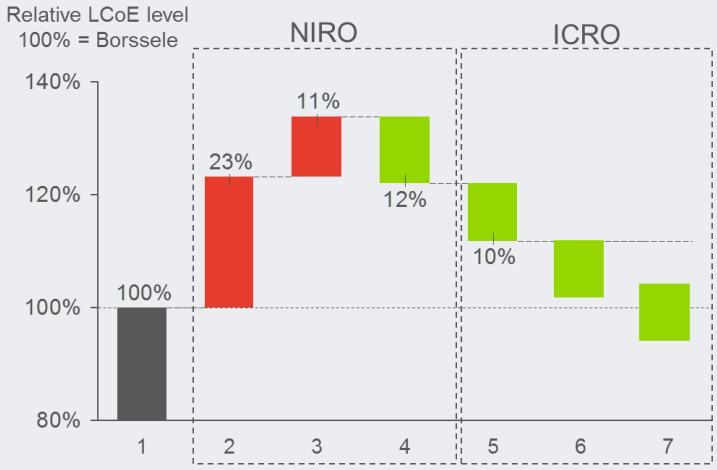


Figure 1 Analysis of the different cost components in the levelized cost of energy (LCoE) for a far offshore location (on/near Dogger Bank) compared to the - close to shore - Borssele location. ① Reference case - Borssele offshore wind farm. ② Increased cost - due to an increased distance to shore, increased water depth and the requirement for DC infrastructure. ③ Increased cost - due to increased wake losses in a larger capacity offshore wind zone. ④ Decreased cost - due to increased yield from better wind resource. ⑤ Decreased cost - due to an innovative grid connection concept (hub and an innovative A/C grid connection concept). ⑥ Decreased cost - due to increased supply chain effectiveness resulting from coordinated roll-out with long term commitments and advantages of scale. ⑦ Decreased cost - due to additional benefits from interconnection.

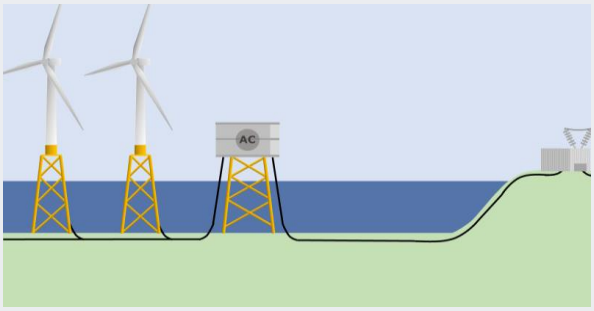
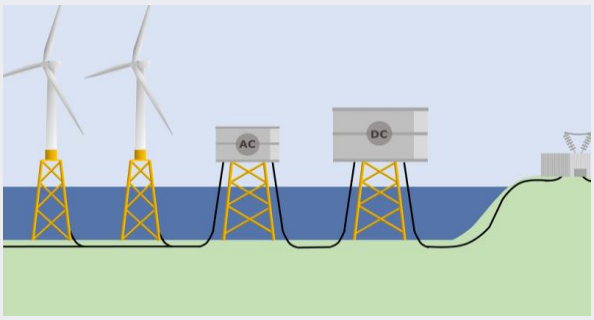
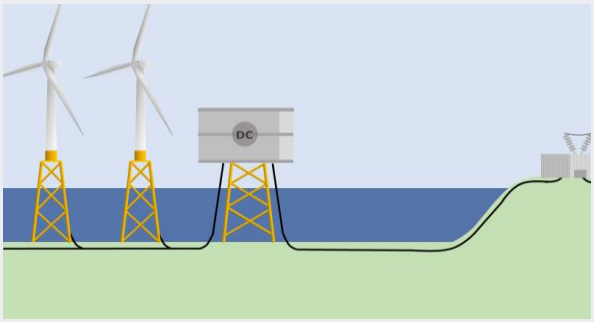
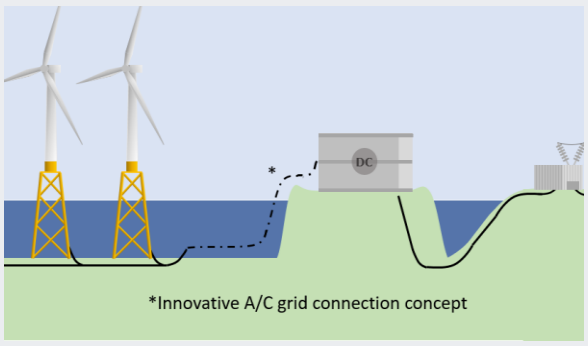
To realise the benefits of an internationally coordinated roll-out scenario a combination of different transmission asset concepts needs to be used, deployed at appropriate times and locations, in a coordinated, step-by-step roll-out

In a first LCoE analysis the consortium has studied various design and process options to minimize the levelized cost of energy for society.

Table 1 outlines the asset concepts that were identified and used in the cost evaluations of both NIRO and ICRO scenarios, including the Hub and Spoke concept.

To evaluate the cost differences between the NIRO and ICRO scenarios, a roll-out of large scale offshore wind capacity and additional interconnection capacity for the North Sea towards 2040 has been developed. The roll-out is based on already connected or designated offshore wind areas and the identification of potential new sites progressively further offshore and in deeper waters. Depending on location and area size, the different grid connection concepts are selected throughout the envisaged roll-out. The build out of required interconnection capacity is considered in parallel, and hybrid concepts - combining in-feed of offshore wind electricity and interconnection capacity - are selected where these are expected to bring additional value. In the internationally coordinated roll-out also onshore grid integration cost are minimised through efficient connections towards the onshore power system by minimising onshore grid reinforcements and considering direct connection options to Europe's transmission backbone.

Table 1 Description of different offshore wind grid connection concepts for the NIRO and ICRO scenarios.

NIRO	ICRO	Description	Illustration
220 kV HVAC platforms		Current practice - Radially connected wind farms (relatively close to shore, generally <80 km) via an AC grid connection.	
320 kV HVDC platforms, with AC collector platforms	n/a	Current practice - Radial connection of several wind farms more than ~100 km from shore.	
n/a	66kV lines directly connecting to a 525 kV HVDC platforms	Higher DC voltage increases the capacity of single export cables. Connecting wind farms directly to the HVDC platforms via 66kV AC cables, creates additional cost benefits over connection with AC collector platforms and intermediate cabling between the AC and DC platforms.	
n/a	66kV collector lines to an island hub with 525 kV HVDC assets	For windfarms exceeding 4 GW in size, an innovative A/C grid connection concept is used to transport power to a hub. On the hub/island HVDC assets convert power to DC for transmission to shore. By connecting hubs to each other and to different countries, interconnections can be realised in a cost-effective way (Hub and Spoke)	

An internationally coordinated roll out approach has the potential to reduce the cumulative cost of the transmission infrastructure - to facilitate the large scale offshore wind roll-out and including additional interconnection capacity - for the North Sea by 30%, compared to a national incremental roll out scenario

Cost reduction for the ICRO scenario, relative to the NIRO scenario, is driven mainly by following components:

- Reduced onshore **grid reinforcement** costs (-8%) – For large scale off shore electricity generation, onshore infrastructure needs to be upgraded to transport and distribute the electricity. In a coordinated approach, export cables are no longer by default connected to the nearest connection point onshore, but rather to parts of the onshore grid of the North Sea countries, where excess transport capacity is available to accommodate the additional supply. In this manner, onshore grid reinforcement costs are reduced.
- Reduced **interconnector** costs (-5%) – The future energy system of the North Sea requires more interconnection capacity than today. In the coordinated roll-out approach synergies between both interconnection and wind farm transmission assets are pursued, by realising hybrid connections. This results in a cost reduction through a reduction of the total **interconnector cable length** and reduced costs for **substations**. The wind farm export cables are assumed to have significant capacity available for pooling of flexibility sources (onshore reserves) when countries are in need of interconnection capacity, i.e. in low-wind situations. In a coordinated approach, the connection of interconnectors and export cabling can be combined both on hubs and onshore, and therefore share largely the same substation infrastructure.
- **Export cable** costs (-2%) – Through the coordinated approach, power can be collected from larger or more wind farms before the electricity is exported to shore. Larger scale power collection allows higher transmission voltages and a larger cable capacity, reducing the relative cable costs [M€/GW/km].
- **Wind farm transmission asset** costs (-15%) – The Hub and Spoke concept reduces costs for the wind farm transmission assets by employing a combination of hubs with an innovative A/C grid connection concept, and stand-alone higher voltage, which reduces costs compared to the currently used DC platform and AC collector platform setup. Hubs (and their DC assets) reduce costs compared to DC platforms, and the innovative A/C grid connection concept reduces costs compared to AC collection platforms and the intermediate cabling.

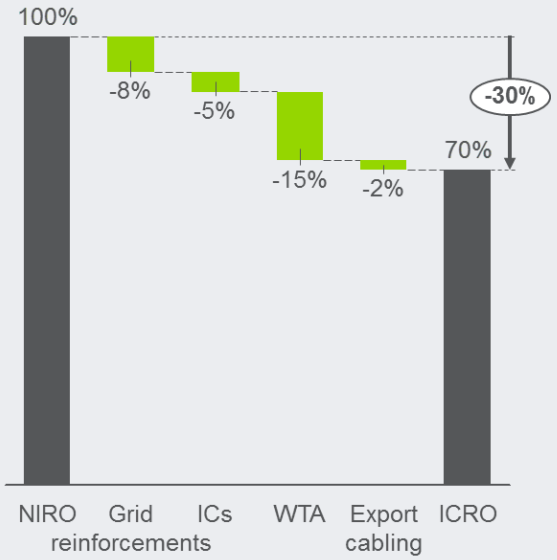


Figure 2. Breakdown of the difference in investment costs between the NIRO and ICRO approaches.

Cost reductions in grid infrastructure present only one benefit of the coordinated roll-out approach. Additional benefits are anticipated based on international exchange between energy markets

The Hub and Spoke concept is a cost effective way to combine offshore wind integration with additional interconnection capacities. Several public studies (Electricity Highways, Fraunhofer Optimal Pathways, TYNDP) - have highlighted the need for additional interconnection to ensure reliable system operation by exchange of flexibility services. Also pure market integration benefits of the additional interconnections by providing more cross-border capacity can be analysed. The consortium has performed a pre-feasibility study which estimates the effects and feasibility of the NSWPH concept from an energy system- and market perspective by assessing energy system indicators (e.g. RES production etc.) and socio-economic benefits (consumer-/producer surplus and congestion rents). The starting point of the analysis is the 2030 TYNDP18 *Sustainable Transition* (ST30) scenario which leads into two different paths towards the 2040 TYNDP18 *Global Climate Action* (GCA40) and the 2040 TYNDP18 *Sustainable Transition* (ST40) scenarios. The total deployment of offshore wind capacity in the period 2030-2040 in Denmark, Germany and the Netherlands amounts to 16 GW and 36 GW depending on the TYNDP18 scenarios. The pre-feasibility considers these capacities in two situations; two business-as-usual situations where the offshore wind capacity (16 and 36 GW) is radially connected to each nation and two alternative situations where the wind capacity is allocated close to the NSWPH which is connecting Denmark, Germany and the Netherlands.

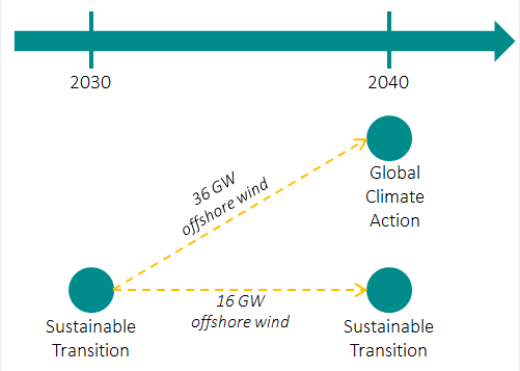


Figure 3. Illustration of the TYNDP18 scenarios applied in the pre-feasibility study. The total deployment of offshore wind in Denmark, Germany and the Netherlands between ST30 and GCA40 is 36 GW and 16 GW between the ST30 and ST40 scenario.

The pre-feasibility study assumes three price areas at the hub – one for each connected country – where the allocated wind capacity from each country is connected to their respective area at the hub. The interconnection capacity between the NSWPH and the mainland is assumed equal to the deployed offshore wind capacity. The initial results of the pre-feasibility study – which should always be considered in light of the pre-conditions and assumptions used – can be summarised as follows.
In both alternative scenarios, the RES production increases using the NSWPH concept due to more beneficial wind resources, and the socio-economic benefits of the interconnectors to the hub (excluding CAPEX costs) amount to approximately 300 million €/year in 2040 for the ST 2040 (16 GW) scenario and to approximately 900 million €/year in 2040 for the GCA 2040 (36 GW) scenario. Note that the socio-economic benefits above are pure revenue only and CAPEX for the transmission infrastructure, costs for reserves, onshore net reinforcements etc. are not included in the figures. This translates to an approximate 10% reduction of the offshore asset LCoE for society. The socio-economic benefits of hybrid connections has been further confirmed in an ongoing analysis for the IJmuiden Ver area where the infeed of 6 GW of Dutch offshore wind and over 3 GW of UK offshore wind is combined with interconnection capacity between the two countries.

An internationally coordinated approach in realizing offshore wind infrastructure results in an internationally aligned roadmap, where international offshore developments can be better matched with suppliers' capacity. In addition, programmatic coordination of offshore developments may result in better interface definitions and improved international standardization. All these factors can result in improved supply chain effectiveness and ultimately reduced development, installation, operation and maintenance costs for offshore wind and the associated electrical infrastructure assets.

Q: What other cost reduction potential or benefits do you see in a coordinated roll-out approach?

While the Hub and Spoke concept uses larger scale asset solutions, development of the internationally coordinated roll-out scenario is step-wise and modular, allowing flexibility and limiting risks for stranded assets

In the coordinated approach, all transmission asset concepts are implemented in parallel over the next decades. A high level, location specific analysis performed by the consortium indicates the distribution of different grid connection concepts (ref. table 1) over time. The future offshore wind connections in the North Sea will likely consist of a mix of several asset concepts, as can be seen in Figure 4. Note that figure 4, while representing a single scenario only (with the possibility for different combinations/permutations) indicates the feasibility of such a roll-out at affordable cost to society.

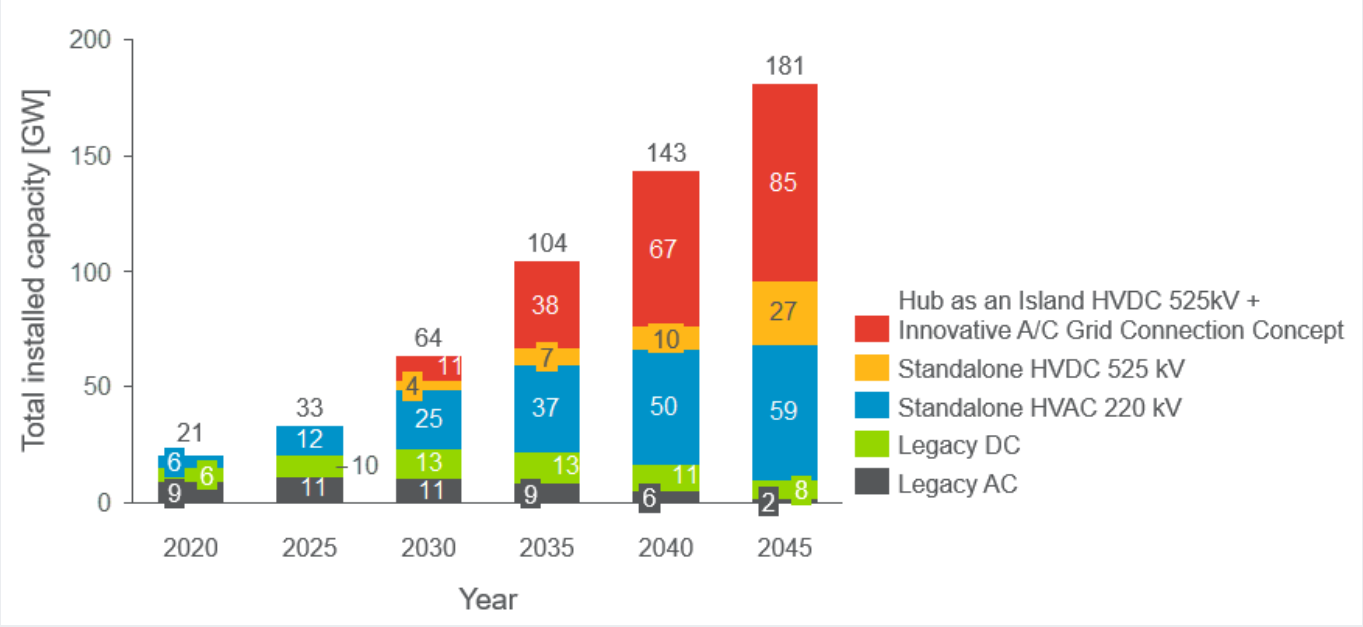


Figure 4 Installed wind power capacity in the North Sea broken down to the different transmission asset concepts for the ICRO approach. Legacy AC refers to currently operational and planned AC radially connected offshore wind farms. Legacy DC refers for currently installed and planned DC connected (German) offshore wind farms. The remaining grid connection concepts refer to Table 1

In the ICRO scenario, grids are developed over a time period of several decades, similar to the national incremental approach. The development over time allows for integration of innovative infrastructure solutions should they become a better fit to alternative asset solutions.

As it currently is, and will be, uncertain what the total future required offshore wind and interconnection capacity will be, adopting a step-by-step development approach provides flexibility and allows integration of future innovations in energy transmission and wind farm design, operation and maintenance.

ABOUT THE NORTH SEA WIND POWER HUB

TenneT Netherlands, TenneT Germany, Energinet and Gasunie joined forces to develop a large scale European electricity system for offshore wind in the North Sea. The NSWPH consortium partners consider the project to be an important possible alternative path of an internationally coordinated roll-out towards accomplishing the green energy transition and achieving the Paris Agreement. By developing the North Sea Wind Power Hub project, the consortium endevours to make the energy transition both feasible and affordable. Central to the vision is the construction of one or more hubs at a suitable location in the North Sea with interconnectors to bordering North Sea countries. The whole system may function as a hub for transport of wind energy, an interconnection hub to the connected countries, a working hub for offshore wind developers and a location for possible Power to Gas solutions.

CONTACT DETAILS

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