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TNO report

North Sea Wind Power Hub (NSWPH): Benefit study for (1+3) potential locations of an offshore hub-island

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North Sea Wind Power Hub (NSWPH): Benefit study for (1+3) potential locations of an offshore hub-island (Compressed Results)

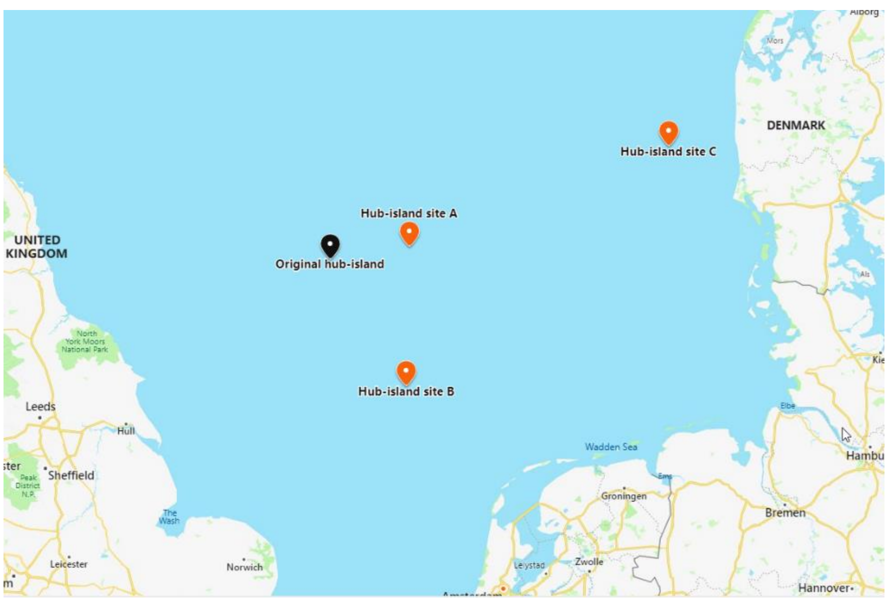
Installation or O&M	Scenario	Key assumptions	Locations (see map below)	Annual Cost effect[1] (M€/yr)	Annual Cost effect (% of annual installation or OPEX costs)	Cost Effect per MW installed or MWh produced
Installation	Presence of marshalling harbour on hub-island	Four wind farms (0.975 GW each) installed per year, totalling 3.9 GW installed per year.	0:	-/-47.3	-/-9.8%	-12118
			A:	-/-44.9	-/-8.4%	-11513
			B:	-/-34.6	-/-7.2%	-8864
			C:	-/-31.4	-/-6.7%	-8049
Installation	Accommodation of personnel on hub-island during commissioning with SES vessels	Four wind farms (65 turbines each) commissioned per year, totalling 260 WTs commissioned per year.	0:	-/-2.2	-/-0.5%	-569
			A:	-/-3.1	-/-0.6%	-803
			B:	-/-3.0	-/-0.6%	-779
			C:	-/-4.2	-/-0.8%	-1079
Installation	Sheltering for vessels in the leeway/ in port of hub-island	Sheltering of major installation vessels only required at H_s[2] > 5.0 m	0:	-/-0.3	-/-0.06%	-69
			A:	-/-0.7	-/-0.1%	-168
			B:	-/-0.3	-/-0.05%	-68
			C:	-/-0.3	-/-0.07%	-86
O&M	Accommodation of O&M personnel on hub-island	Four wind farms (0.975 GW, 65 turbines each) maintained per year. Total O&M for 3.9 GW, 260 turbines per year	0:	-/-2.7	-/-1.7%	-0.14
			A:	-/-3.6	-/-1.9%	-0.19
			B:	-/-1.0	-/-0.6%	-0.05
			C:	-/-0.8	-/-0.5%	-0.04
O&M	Warehouse for large WTG spare parts on hub-island	Large spare parts for four wind farms (3.9 GW in total, 260 turbines) stored in warehouse on island	0:	+/+0.1	+/+0.1%	+0.01
			A:	-/-0.7	-/-0.4%	-0.04
			B:	-/-2.6	-/-1.5%	-0.14
			C:	+/+0.2	+/+0.1%	+0.01
O&M	Sharing of O&M jack-up barge from hub-island (in combination with warehouse for large WTG spare parts on hub-island)	Jack-up barge shared between multiple wind farm zones (each zone comprises four wind farms amounting to total capacity of 3.9 GW)	0:	-/-11.2[3]	-/-7.1%	-0.59
			A:	-/-12.4	-/-6.8%	-0.66
			B:	-/-14.1	-/-8.1%	-0.75
			C:	-/-13.7	-/-7.9%	-0.73

(Green: Annual cost effect >10 M€/year; Orange: Annual cost effect 1-10 M€/year; Uncolored: Annual cost effect < 1 M€/year or N.A)

[1] For annual installation and O&M of 3.9 GW of wind farms
[2] Significant wave height
[3] Out of this, 2.73 M€/yr (~24%) is a direct benefit of the hub-island. The rest (8.46 M€/yr or ~76%) is from sharing of the jack-up barge. A similar ratio is seen at all four locations

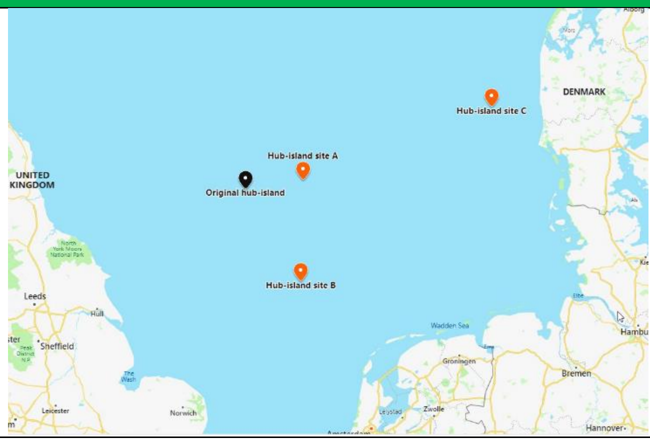
Scenario	Description	Locations (see map below)	Result	Annual Cost effect (M€/yr)	Annual Cost effect (%)
Installed capacity beneficial range	Tipping point (km) between hub-island and onshore harbour where installation from hub-island is beneficial	0:	104km (108GW)	-/-28.9[4]	-/-6.2
		A:	88km (77GW)	-/-26.3	-/-5.0
		B:	85km (72GW)	-/-21.2	-/-4.5
		C:	80km (40GW)	-/-17.5	-/-3.8
O&M beneficial range	Tipping point (km) between hub-island and onshore harbour where O&M from hub-island is beneficial	0:	88km (77GW)	-/-0.7[5]	-/-0.4
		A:	113km (136GW)	-/-2.3	-/-1.3
		B:	67.5km (45GW)	-/-1.2	-/-0.7
		C:	22km (4GW)	-/-0.2	-/-0.1
Effective working time for technicians	To compare additional cost of different transport options from hub-island to onshore harbour for bi-weekly technician transfer	0:	Aircraft	-/-2.3[6]	-
		A:	Aircraft	-/-2.0	
		B:	Fast ferry	-/-0.6	
		C:	Normal ferry	-/-0.9	
CO_2 reduction estimation per year (ton CO_2)	Annual CO_2 emission reduction when using hub-island for installation and O&M of 3.9 GW of WFs	0:	2576.9[7] tons CO_2	-	
		A:	2227.9 tons CO_2		
		B:	1653.4 tons CO_2		
		C:	2037.1 tons CO_2		

(Green: Annual cost effect >10 M€/year; Orange: Annual cost effect 1-10 M€/year; Uncolored: Annual cost effect < 1 M€/year or N.A)



[4] Annual cost effect (or benefit) (M€/yr) is the difference in cost of installing WFs in the installation beneficial range from onshore harbour and hub-island. Given that the yearly installation rate is ~4 GW/year, the benefits will be seen until 108 GW is installed, which would take around 27 years.
[5] Annual cost effect (or benefit) (M€/yr) is the difference in cost of maintaining WFs in the O&M beneficial range from onshore harbour and hub-island (incl. technician transfer cost).
[6] Annual cost for least expensive mode of technician transport (not representing a cost effect or benefit value)
[7] More than 99% of annual CO_2 reduction is due to use of island as a marshalling harbour for installation of WFs

North Sea Wind Power Hub (NSWPH): Benefit study for (1+3) potential locations of an offshore hub-island

Scenarios (Installation)	Cost effect €/MW installed	Key assumptions	Key drivers for cost effect
Locations: - Original location (0): UK, 108 NM (nautical miles) from British coast (Scarborough) - Location A: NL, 135 NM from Dutch coast (Harlingen) - Location B: NL, 78 NM from Dutch coast (Den Helder) - Location C: DK, 32 NM from Danish coast (Søndervig) The ports used for installation and O&M are listed in *Table 1* in Appendix. The cost effects (€/MW installed or €/MWh produced) mentioned in this table result from the difference of installation and O&M costs from hub-island and onshore port.			
Marshalling harbour on hub-island for installation of foundations and WTs	0: -12,118 A: -11,513 B: -8,864 C: -8,049	1. 4 * 65 wind turbines[1] (WTs) installed per year. Total of 3.9 GW/yr installed. 2. WTs, foundations supplied to hub-island by regular feeders/ barges in the good weather season, prior to installation year. 3. Modelling based on historical windspeed and waveheight data (shown in Appendix *Table 2)*. 4. Sufficient hub-island marshalling harbour space (10 to 11.5 ha per GW of WF) available at all time to accommodate the required foundations plus WTs (see *Table 3* in Appendix). 5. Inflation rate of 2.5% per year used on day rates as given from industry consultation sessions held in 2018.	1. Higher benefits when the distance from hub-island to fabrication and installation ports[2] increases (distance of Location 0>A>B>C). 2. Installing both foundations and WTs from hub-island would approximately (and expectedly[3]) double the cost savings compared to only installing foundations (*Figure 1* in Appendix). 3. Using regular feeder vessels to supply components from fabrication ports to offshore site is more expensive than using jack-up vessels to pick up the foundations and wind turbines due to low speed[4] and low workability of the feeders compared to the jack-up vessels (*Figure 1* in Appendix).
SOV/SES stationed on hub-island during commissioning of WFs	SES (24*7): **0: -569** A:.-718 **B: -779** **C: -1,079** SOV (24*7): 0: -472 **A: -803** B: -531 C: -905	1. Commissioning takes 144-man hours per turbine; 3 technicians simultaneously work on one turbine. 2. Shift pattern is 2 weeks-on 2 weeks-off for both SOV & SES. SOV works 24*7, whereas for SES both 12 hour and 24*7 shifts are modelled. 3. Two SOV's (with 30 technicians per shift) work in parallel to perform commissioning from hub-island. 4. With SES, technicians stay overnight on hub-island, whereas with SOV, they stay on SOV overnight. With SOV, the island is used every two weeks to exchange technicians and spares. 5. When technicians work in day shift (12 hrs), four SESs work in parallel to match the time taken by three SESs in the 24*7 shift. 6. 3.9 GW installed per year are commissioned per year.	1. Avg. H_s at Location A>B>C>0 (*Table 2* in Appendix); SES with 24*7 shift is preferred at Locations 0, B and C due to lower cost and high flexibility. SOV is preferred for Location A due to higher workability (workability for SES is limited due to rougher weather conditions). 2. SES operations assume overnight personnel accommodation on the hub-island, the costs of which are not included in this analysis. 3. Minimum cost of commissioning WTs at all four locations is between 2.75M€ and 4M€ per GW installed. (*Figure 2* in Appendix). 4. Lower avg. H_s results in lower commissioning cost[5] (Location A>Location B>Location C>Location 0) (*Figure 2* in Appendix). 5. Using SES with 12 hrs (only day shift pattern) is always the most expensive option for commissioning from hub-island. This is because commissioning is modelled at the end of the year (with rough weather progressively increasing) and working only in day shift increases the number of working days.
Sheltering base in lee of hub-island/ in onshore harbour	0: -69 A: -168 B: -68 C: -86	1. Sheltering for large installation vessels[6] is only required when H_s is above 5.0 m. 2. Based on historical weather during 2004 – 2013, H_s > 5.0 m occurs only a few times per year. Most of these occurrences last only a few hours on average. Besides the actual sheltering time for vessels, the travel time to and from the sheltering location is used to calculate reduction in working days.	1. In Location A, sheltering occurs around 10 times/year (2-3 times more compared to other locations), leading to slightly higher cost savings when installing from hub-island. 2. At all locations, savings are due to lesser number of days lost for vessels (~60-70% of reduction), and lesser fuel usage (~30-40%) when sheltering in hub-island.

Scenarios (O&M)	Cost effect €/MWh produced	Key assumptions	Key drivers for cost effect
Using hub-island as an O&M base for technicians and small spares	0: -0.14 (SOV) A: -0.19 (SOV) B: -0.05 (SOV) C: -0.04 (SOV)	1. Annual production from 3.9 GW WFs is approx. 18700 GWh, based on almost 4800 full load hours per year. 2. SOV and SES operate in day shifts with bi-weekly crew rotation. 3. With SES, technicians stay overnight on hub-island, whereas with SOV, they stay on SOV overnight 4. Cost associated with maintaining the island not included (also cost for port, accommodation for technicians etc. not included) 5. Spare parts < 2 ton are handled by SOV; heavier spare parts are transported by jack-up barge from onshore warehouse.	1. For all four locations, O&M costs with SOV from hub-island is cheaper than with SES. This is due to the lower workability of SES. (See *Figure 3* in Appendix*)*. 2. Using SES (with Hs limit = 1.5 m) is more expensive (esp. at Locations A and B) due to low workability/ accessibility (42% and 49% respectively).
Large warehouse at the hub-island to store small and large spare parts	0: +0.01 A: -0.04 B: -0.14 C: +0.01	1. Spare parts weighing between 2 and 100 tonnes will be stored in the warehouse on the hub-island. Warehouse floor area estimated around 0.75 to 0.8 ha (see *Table 4* in Appendix). 2. Cost of constructing and cost for maintaining warehouse is not included in the O&M costs of the hub-island.	1. There is no significant benefit/loss with the presence of a large warehouse on hub-island for all locations.
Shared jack-up barge stationed at the hub-island in combination with large warehouse	0: -0.59 A: -0.66 B: -0.75 C: -0.73	1. Replacement of large parts using a jack-up barge requires a workable weather window of 24 to 48 hours. 2. Day rate of a jack-up barge permanently under contract for WF operations is assumed to be 33% cheaper than spot market chartering by individual owners.	1. For all four locations, similar benefits are seen when a jack-up barge is shared from hub-island. 2. Around ~25% of cost saving is a direct benefit of operating the jack-up barge from the hub-island. The remaining (~75%) is obtained from reduced day-rate as a result of jack-up barge sharing. This 75% cost reduction therefore, can also mainly be achieved when sharing a jack-up from onshore ports.

[1] Wind turbines, each with nominal power of 15 MW.

[2] Without a hub-island, fabrication ports are used for installation of WTs and foundations; and installation ports are used for scour protection, infield cable laying/burying and commissioning.

[3] Expected since the cost of installing foundations is approximately the same as that of installing WTs, due to using jack-up vessels.

[4] Speed of feeder vessel is assumed to be half the speed of jack-up vessel.

[5] This is different from the cost effect due to commissioning, which is shown as the black line in *Figure 2*.

[6] Distinction of large installation vessels made based on their day rates. Vessels with day rates less than 10k€ (mainly personnel access vessels) are considered as small vessels.

Aim	Scenarios	Results	Key assumptions	Key drivers for cost effect
1.	Installed capacity beneficial range with marshalling harbour on hub-island (To find tipping point (km) between hub-island and onshore harbour until which OWF[7] installation from hub-island is beneficial)	0: 104km (108GW) A: 88km (77GW) B: 85km (72GW) C: 80km (40GW) (Additional sensitivity of tipping point calculation according to #GWs installed in *Table 5* and *Table 6*)	1. Installation of 3.9 GW/yr of WTs is modelled to find tipping point. 2. To find tipping point, distances of 20 km, 50 km, 80 km and 110 km between hub-island and installed WF are considered. (Results in Appendix *Figure 5, Figure 7, Figure 9* and *Figure 11).* 3. For each sensitivity, the corresponding distances (and travel times) of WF from all fabrication ports is calculated. 4. A wind farm power density of 6.4 MW/km^2 is assumed to calculate OWF capacity in GW[8]. 5. The investment and operation/maintenance costs for the hub-island are not considered.	1. Benefits for WF installation from hub-island are shown in circular areas with tipping point between hub-island and onshore ports as radius. (Appendix *Figure 4, Figure 6, Figure 8 and Figure 10).* 2. There is always added potential benefit for installing WFs on the other side of hub-island (away from the coasts with the fabrication ports). The circular areas are therefore seen as minimum potential benefit. 3. The potential benefit for Location 0 is the highest since it lies farthest from all fabrication ports. 4. For Location C, the beneficial range (in km) is the lowest due to its proximity to the Danish coast. Also, the benefit in GW is low, due to the non-circular shape of beneficial range (*Figure 10* in Appendix*).*
2.	Effective working time of technicians for yearly O&M (To compare cost of different transport options from hub-island to onshore harbour for bi-weekly technician transfer)	Cost for technician transport: 0: 2.31 M€/yr (Aircraft) A: 1.98 M€/yr (Aircraft) B: 0.61 M€/yr (Fast Ferry) C: 0.94 M€/yr (Normal Ferry) Effective technician work time (2-week shift) (shift reduced with losses for de-/ mobilisation): 0: 166 h (Aircraft) A: 166 h (Aircraft) B: 164.5 h (Fast Ferry) C: 163.5 h (Normal Ferry)	1. Assumptions for travel time of various transport modes at each location is in *Table 7*. The times are based on vessel speeds. 2. Cost per trip for aircraft: 50k€; helicopter: 15k€; fast ferry: 20k€; normal ferry: 10k€. 3. It is assumed that 45 technicians are transferred at the end of 2 weeks by aircraft/ferries. In the case of helicopter, 9 technicians are transferred at one go. 4. If travel time for vessels transferring technicians is greater than 4.5hr, it is assumed that technicians unavailable till the start of next shift due to obligatory resting time (See Appendix *Table 9*). 5. Investment, operational and maintenance cost of airstrip, heliport and/ or harbour is not taken into account.	1. The cost of technician transport at each location with different modes of transport are shown in *Table 8.* 2. Locations 0 and A are far away from the shore. Hence the use of ferries results in technician unavailability until the start of next shift, resulting in resource delays. Aircraft therefore seems the cheapest option for technician transfer. However, for a final decision, the investment and operational cost of an airstrip should be considered, which may very well outweigh the marginal benefits of technician transfer costs seen here. 3. For Location B, fast ferry results in technicians immediately available after a transfer, making it cheaper[9] for personnel transport than a normal ferry, which results in unavailable technicians until the start of next shift. 4. For Location C, normal ferry results in technicians immediately available after transfer and due to lower cost per trip.
3.	O&M beneficial range (To find tipping point (km) between hub-island and onshore harbour where O&M from hub-island is beneficial)	0: 88km (77GW) A: 113km (136GW) B: 67.5km (45GW) C: 22km (4GW)	1. For each location, the cheapest mode of technician transport (from Aim 2 result) is chosen for O&M from hub-island, in addition to SOV as access vessel. 2. To find tipping point, WFs at distances of 40%, 45% and 50% of the distance between hub-island and onshore harbour are considered. (Results seen in Appendix *Figure 13, Figure 15*, *Figure 17* and *Figure 19*). 3. A wind farm power density of 6.4 MW/km^2 is assumed to calculate OWF capacity in GW[8].	1. Benefits for O&M are shown in circular areas with tipping point[10] between hub-island and WF as radius. (Appendix *Figure 12, Figure 14*, *Figure 16*, *Figure 18*). 2. There is always added potential benefits for O&M of WFs on the other side of hub-island (away from the coasts with the onshore O&M ports). The circular areas are therefore seen as minimum potential benefit. 3. The potential benefit for Location A is highest and Location C is lowest since they lie farthest and closest to their corresponding O&M ports, respectively. 4. Compared to savings with installation facility on hub-island, O&M savings are only a few M€/year for 3.9GW of WF's maintained and are therefore not as significant.
4.	WT deterioration (% difference in OM Effort (M€/yr) between assumed bathtub curves and original failure rates)	Sensitivity 1: 0: -0.5% A: -0.05% B: -0.05% C: -0.38% Sensitivity 2: 0: 3.2% A: 3.1% B: 3.0% D: 3.1%	1. Default failure frequency, equipment and repair time for various maintenance categories in *Table 10*, *Table 11*. 2. Two sensitivities studied with WT bathtub curves: Sensitivity 1: Years 1-5: Default failure freq.+ 10% Years 6-20: Default failure freq.- 10% Years 20-30: Default failure freq.+ 10% Sensitivity 2: Years 0-2: Default failure freq. + 30% Years 2-15: Default failure freq. Years 15-30: Default failure freq. +2% annual increase	1. Results are averaged for all O&M scenarios for each location (Appendix *Table 12* and *Table 13*). 2. Change in annual O&M Effort at all four locations is negligible for WT bathtub curves assumed in Sensitivity 1. 3. Slight increase in annual O&M Effort at all hub-island locations is seen for WT deterioration assumed in Sensitivity 2.
5.	CO_2 reduction estimation per year (tonnes CO_2) (Annual CO_2 emission reduction when using hub-island for installation and O&M of 3.9 GW of WFs) (I&C: Installation & Commissioning O&M: Operation & Maintenance)	0: I&C: 2576 ton-CO_2 O&M: 0.6 ton-CO_2 A: I&C: 2225 ton-CO_2 O&M: 2.9 ton-CO_2 B: I&C: 1648.2 ton-CO_2 O&M: 5.2 ton-CO_2 C: I&C: 2033.4 ton-CO_2 O&M: 3.7 ton-CO_2	1. For each location, following scenarios are considered to calculate CO_2 reduction (*Table 14* and *Table 15*): • Installation of foundations and WTs from onshore harbour v/s hub-island marshalling harbour • Commissioning using SOV from onshore harbour v/s SOV/SES from hub-island • O&M from onshore harbour v/s O&M from hub-island (including biweekly technician transfers) • Shared jack-up barge from onshore harbour v/s shared jack-up barge from hub-island 2. The frequency of movement of installation and O&M vessels at all onshore harbours and at hub-island are in Appendix *Table 16* and *Table 17*. 3. Tank to wheel (TTW) emission factors for CO_2 are used from Stream Freight Transport 2016. With tonne-km for each vessels and emission factors, the tonnes of CO_2 emissions are calculated. 4. For each vessel, tonne-km is calculated based on the product of distance travelled by vessel (km) and sum of component and personnel load on vessel (tonne). 5. For aircraft, CO_2 emission values are referred from a Carbon Independent article. 6. Technology upgrade of newer, cleaner engines is not considered in this study, although it is expected in future.	1. Emission reductions while installing WFs from hub-island are particularly high. This is because jack-up vessels only transport 3 components per trip in the onshore installation scenario, whereas feeder vessels transport 5 components per trip to the hub-island, resulting in far less distance travelled. 2. The total load carried by all vessels is the same for both hub-island and onshore harbour cases. 3. Reduction in emissions are a result of decrease in travelling distances in the hub-island cases. 4. For Location B, installation CO_2 emissions are lower than other locations because the sum of distances from island to all fabrication ports is lower than for other locations. 5. For Locations 0 and A, CO_2 emission reduction due to O&M from hub-island are lower than for Locations B and C due to the use of aircraft for technician transfer (Appendix *Table 15*). Aircraft is assumed for Locations 0 and A due to seemingly lower[9] personnel transfer costs, although other transport modes could result in higher/lower CO_2 emission reductions depending on the additional investment and operational costs that they need.

[7] Offshore wind farm

[8] An area of only 50% around island is assumed to be used for OWFs due to other activities: nature, shipping, oil/ gas etc.

[9] The investment and operational costs for various transport modes haven't been considered, which could tip the marginal benefits of technician transfer costs calculated in this aim.

[10] The accuracy on O&M tipping point threshold is approximately +/- 10 km, due to the stochastic process of failure modelling and inherent variability in the weather data, although running a large number of simulations (~250) compensates for this uncertainty to some extent.

Appendix

1. Location information

Table 1 Hub-island coordinates, installation, fabrication and O&M Ports distances

Code	Location	Location X (N)	Location Y (E)	Distance (in km): Installation ports to hub-island	Fabrication ports (foundations) to hub-island	Fabrication ports (WTs) to hub-island	O&M port to hub-island
0	Original hub-island site	55.085	2.482	Seaton (220km); Sunderland (220km)	Rotterdam (380km); Ijmuiden (220km)	Esbjerg (380km); Eemshaven (340km)	Seaton (220km)
A	Hub-island site A	55.184	3.581	Eemshaven (300km); Ijmuiden (350km)	Rotterdam (310km); Ijmuiden (350km)	Esbjerg (300km); Eemshaven (310km)	Den Helder (250km)
B	Hub- island site B	54.064	3.544	Eemshaven (230km); Ijmuiden(190km)	Rotterdam (250km); Ijmuiden (190km)	Esbjerg (350km); Eemshaven (230km)	Den Helder (150km)
C	Hub-island site C	55.973	7.185	Esbjerg (100km); Eemshaven (300km)	Ijmuiden (430km); Bremerhaven(290km)	Esbjerg (100km); Eemshaven (300km)	Esbjerg (100km)

Table 2 Average Wind Speed at 10 m and Significant Wave Height for 10-year historical period at hub-island locations

		Windspeed (m/s)					Waveheight (m)				
		Spring	Summer	Autumn	Winter	Year	Spring	Summer	Autumn	Winter	Year
Code	Location	Mar-May	Jun-Aug	Sep-Nov	Dec-Feb		Mar-May	Jun-Aug	Sep-Nov	Dec-Feb	
0	Original hub-island	6.87	6.06	8.33	8.93	7.54	1.45	1.11	1.8	2.08	1.61
A	Hub-island site A	7.9	6.81	9.25	9.98	8.48	1.83	1.31	2.31	2.75	2.04
B	Hub-island site B	7.87	6.75	9.25	9.99	8.46	1.66	1.22	2.11	2.46	1.86
C	Hub-island site C	7.72	7.12	9.71	10.1	8.65	1.41	1.2	1.99	2.24	1.71

2. Re-run scenarios for Installation cases

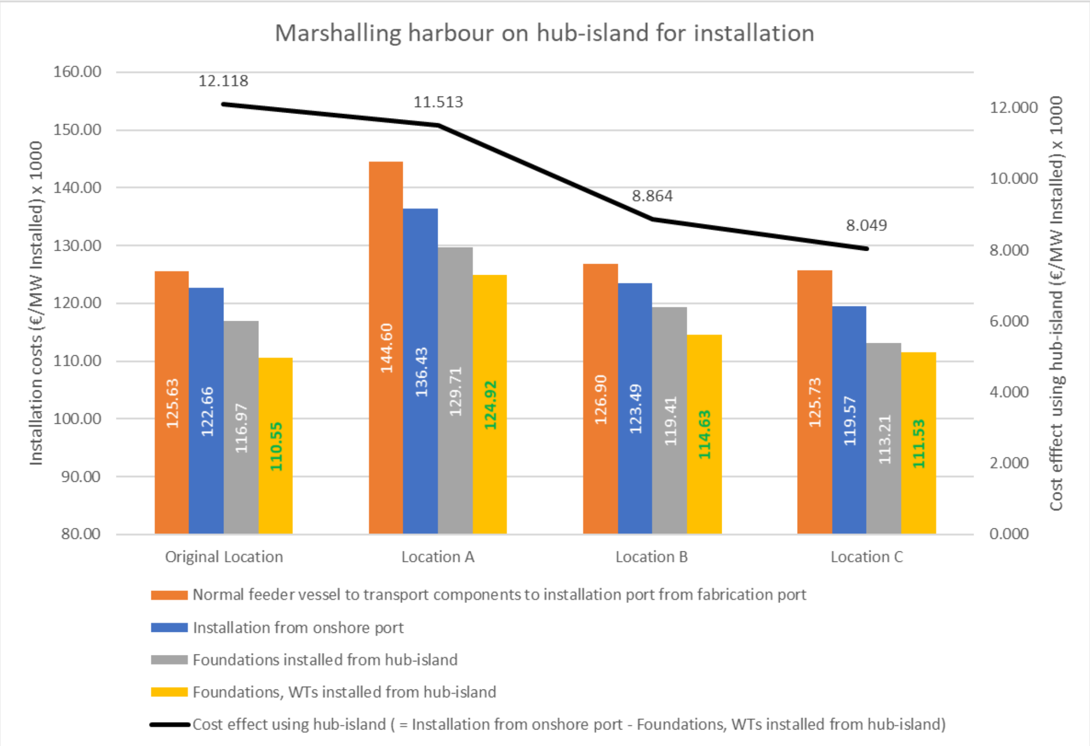


Figure 1 Costs comparison with use of marshalling harbour on hub-island for installation (lowest value at each location in green)

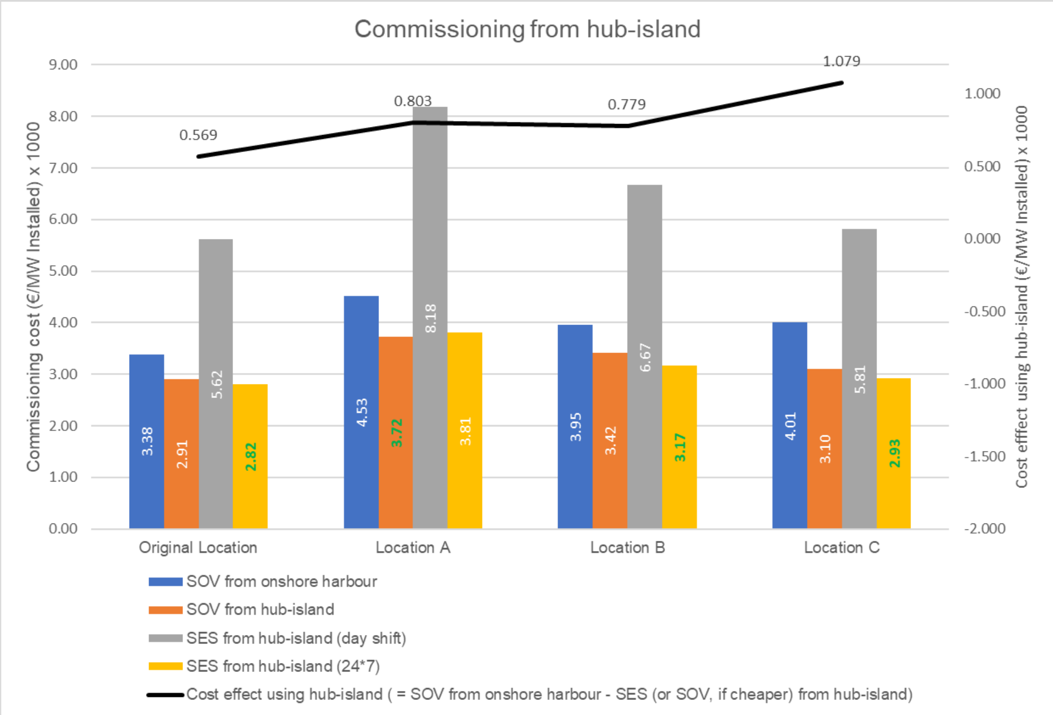


Figure 2 Costs comparison when performing commissioning from hub-island with different vessels (lowest value at each location in green)

Table 3 Estimate of the size of marshalling harbour needed on hub-island assuming 3.9 GW installed per year

Component	**Quantity (for one 0.975 GW wind farm)**	**% components stored on hub-island simultaneous (assumed)**	**Space needed on marshalling harbour (m^2)**	**Space needed on marshalling harbour (hectare)**
Foundations (Monopiles + transition piece)	65	75%	40,000 to 50,000	4 to 5
Wind turbines	65	50%	60,000 to 65,000	6 to 6.5
Overall			100,000 to 115,000	10 to 11.5

Table 4 Estimate of the size of warehouse for large spare parts[11] needed on hub-island

Dimension	**Value**	**Unit**
Floor area (est.)	7500 to 8000	m^2
Height	8	m
Volume of warehouse to store large spare parts	60,000 to 64,000	m^3

[11] The floor area for the warehouse is scaled from a reference warehouse at IJmuiden for Vestas spare parts and serving as a base for Prinses Amalia wind park. The above numbers in should be treated as best estimates based on TNO's previous experience.

3. Re-run scenarios for O&M cases

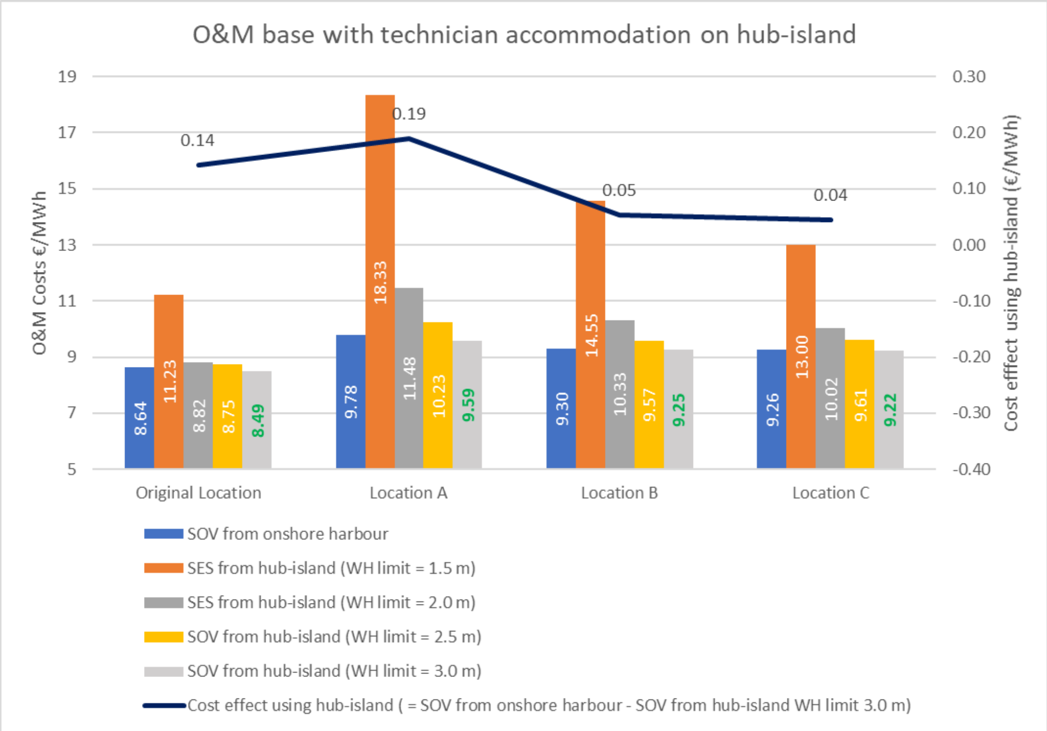


Figure 3 Costs comparison when using hub-island as an O&M base for technician accommodation with different vessels (lowest value at each location in green)

4. Installed capacity scenario (tipping point: Dist. from hub-island to WF)

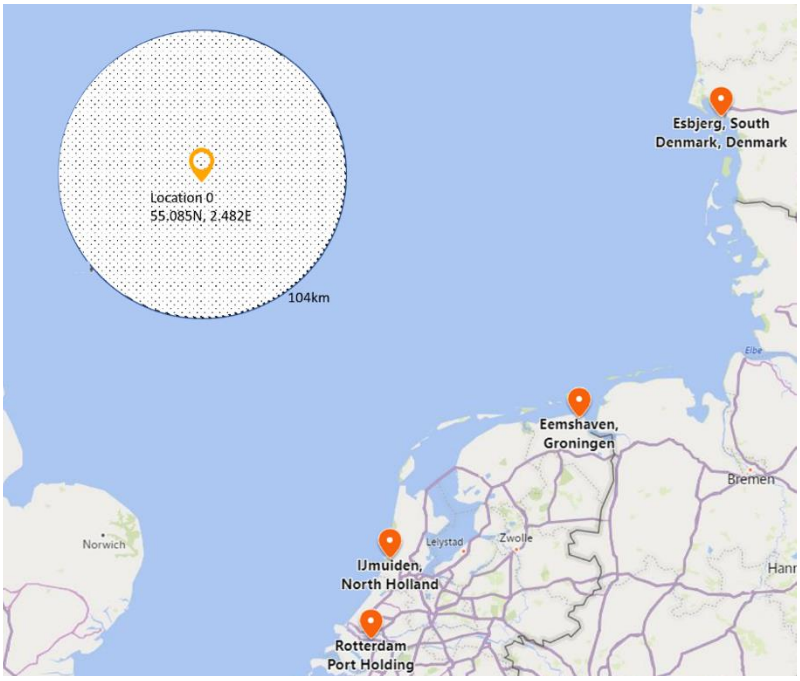


Figure 4 Tipping point and zone favouring installation from hub-island (Location 0)

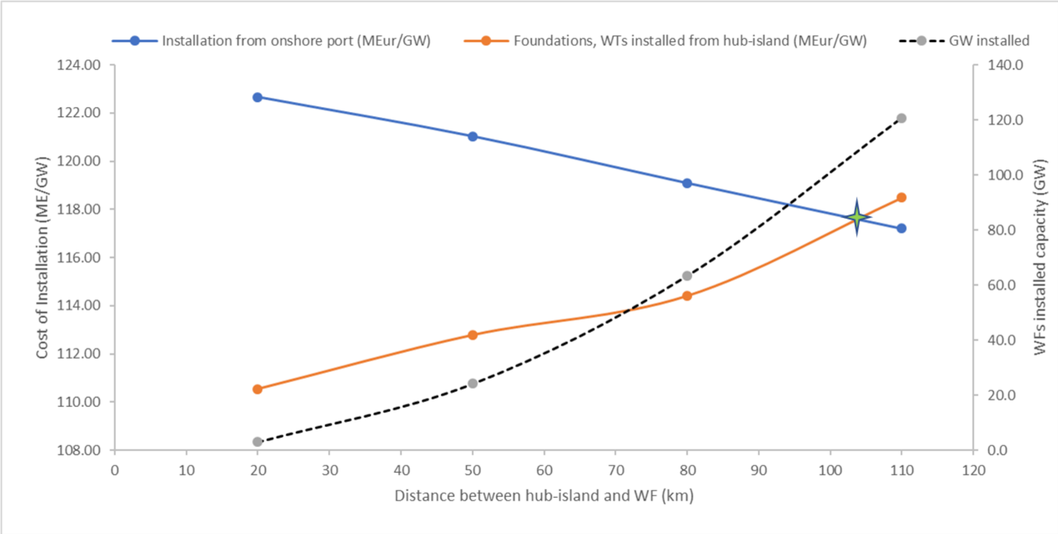


Figure 5 Installation Costs from hub-island (Location 0) v/s onshore fabrication ports with tipping point at 104km (or 108GW)

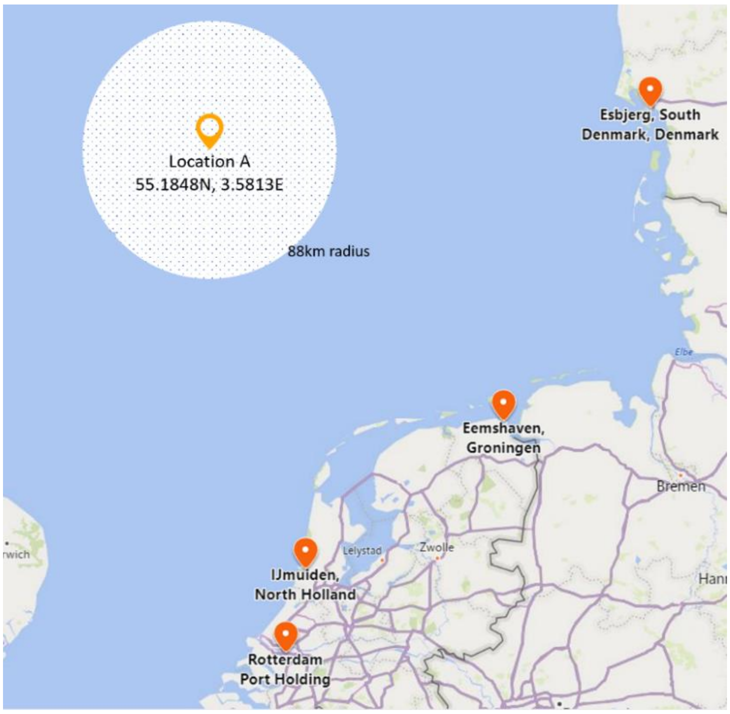


Figure 6 Tipping point and zone favouring installation from hub-island (Location A)

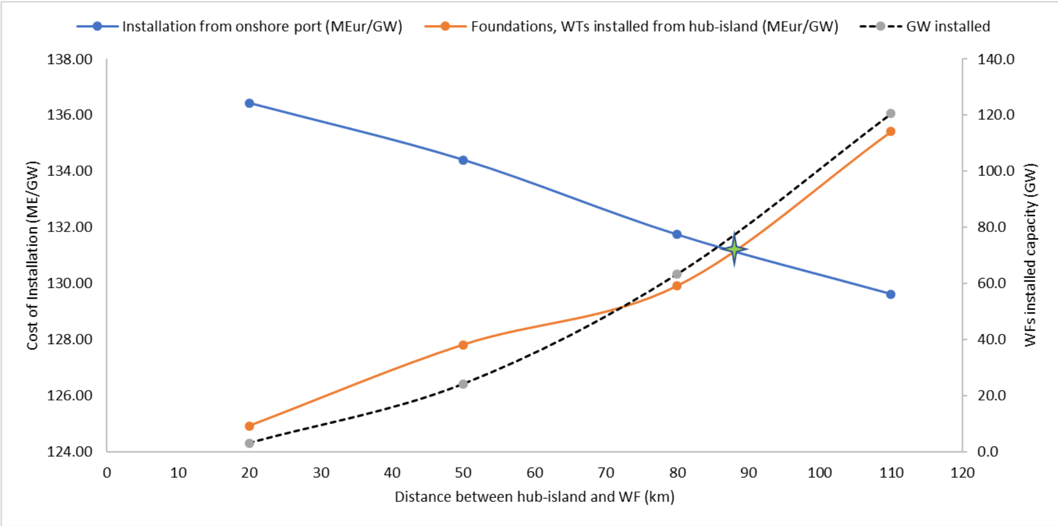


Figure 7 Installation Costs from hub-island (Location A) v/s onshore fabrication ports with tipping point at 88km (or 77GW)

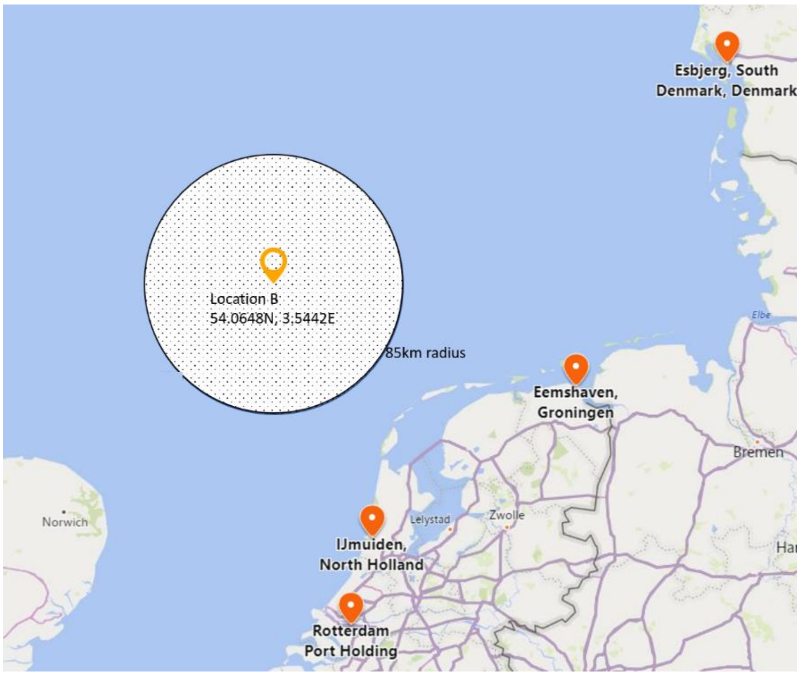


Figure 8 Tipping point and zone favouring installation from hub-island (Location B)

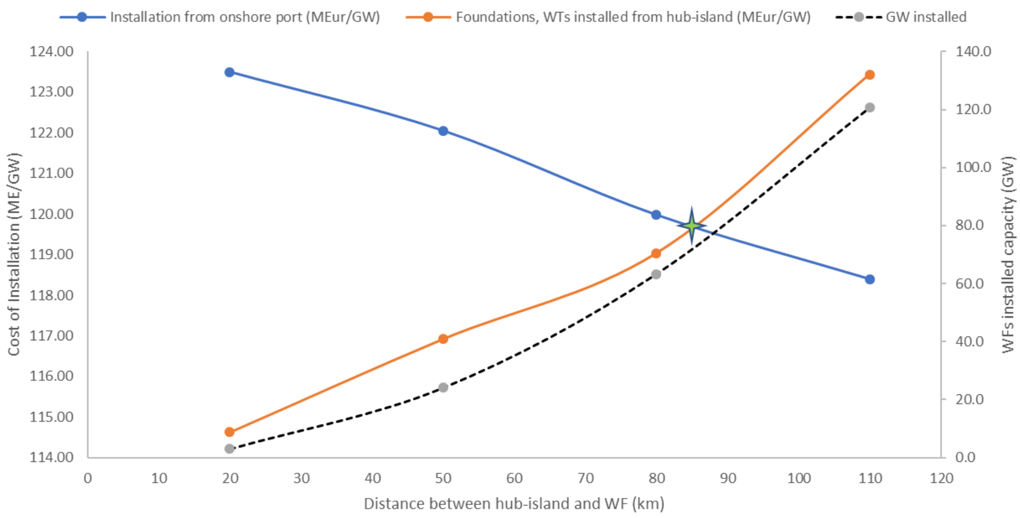


Figure 9 Installation Costs from hub-island (Location B) v/s onshore fabrication ports with tipping point at 85km (or 72GW)

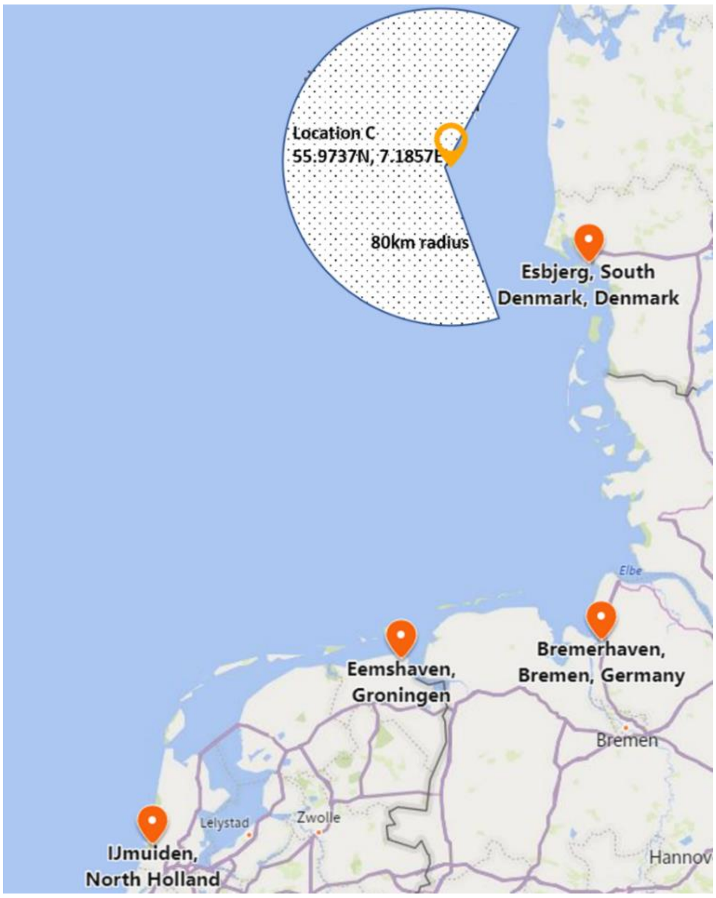


Figure 10 Tipping point and zone favouring installation from hub-island (Location C)

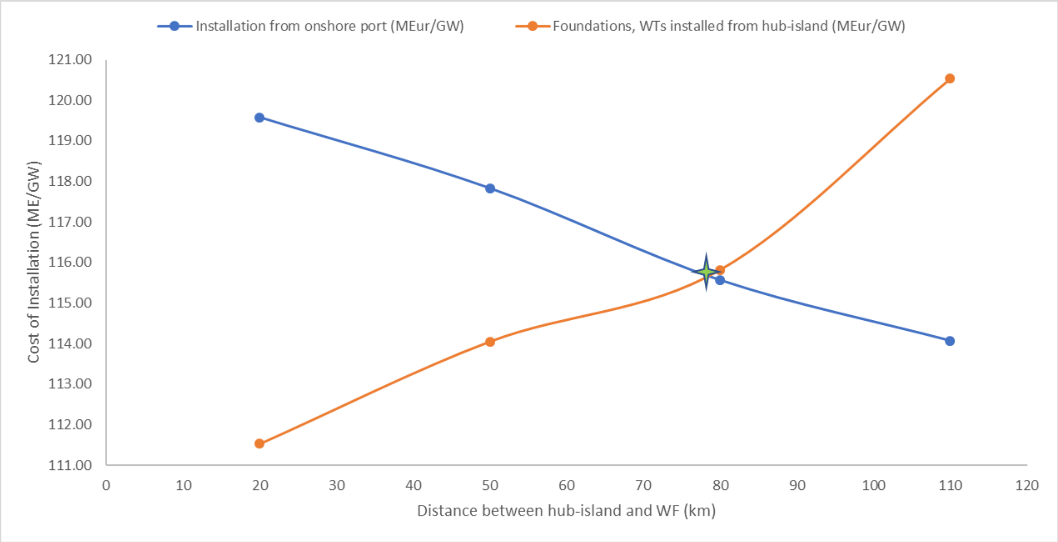


Figure 11[12] Installation Costs from hub-island (Location C) v/s onshore harbour with tipping point at 80km

Table 5 Installation costs from onshore port and hub-island according to number of GWs around hub-island

	Location 0			Location A		
Sensitivity	**12 GW**	**36 GW**	**100 GW**	**12 GW**	**36 GW**	**100 GW**
Range of WFs around hub-island	36 km	60 km	100 km	36 km	60 km	100 km
Installation from onshore port (MEur/GW)	121.57	120.32	117.79	134.89	133.39	130.14
Installation from hub-island (MEur/GW)	112.15	113.06	116.59	127.01	128.08	132.75
Is tipping point reached ?	No	No	No	No	No	**Yes**
Tipping point for installation	**104 km (108 GW)**			**88 km (77 GW)**		

Table 6 Installation costs from onshore port and hub-island according to number of GWs around hub-island

	Location B			Location C		
Sensitivity	**12 GW**	**36 GW**	**100 GW**	**12 GW**	**36 GW**	**100 GW**
Range of WFs around hub-island	36 km	60 km	100 km	36 km	60 km	100 km
Installation from onshore port (MEur/GW)	122.47	120.94	118.92	118.64	117.07	114.56
Installation from hub-island (MEur/GW)	115.85	117.63	121.97	112.87	114.64	118.96
Is tipping point reached ?	No	No	**Yes**	No	No	**Yes**
Tipping point for installation	**85 km (72 GW)**			**80 km (or 40 GW)**		

5. Effective working time

Table 7 Assumptions for travel time of different vessels from O&M ports to hub-island (refers to technician available from only start of next shift due to obligatory resting time)*

	Original Location (dist from port)	**Location A**	**Location B**	**Location C**
Vessel type (Travel time)	**Seaton Able (UK) (220)**	**Den Helder (NL) (260)**	**Den Helder (NL) (150)**	**Esbjerg (DK) (100)**
Jack-up barge (100 MT)	10 h	11.5 h	7 h	4.5 h
Diving support vessel	8 h	8.5 h	5.5 h	3.5 h
Cable laying vessel	10 h	11.5 h	7 h	4.5 h
SOV	8.5 h	10 h	6 h	4 h
Daughter craft	0.5 h	0.5 h	0.5 h	0.5 h
tracker for SOV supply	-	-	-	-
SES (from island)	0.5 h	0.5 h	0.5 h	0.5 h
Fast Ferry vessel (25kts)	4.75* h	5.5 h*	3.5 h	2.5 h
Normal ferry vessel (12 kts)	10* h	11 h*	7 h*	4.5 h
Aircraft	2 h	2 h	2 h	2 h
Helicopter	2 h	2 h	2 h	2 h

[12] Due to a distance of only 60 km to the Danish coast from hub-island location C, trendline for WFs installed capacity (GW) is not shown in this graph. To calculate number of GW installed at tipping point distance, the shape in Figure 10 is considered.

Table 8 Hub-island based O&M costs plus additional technician yearly cost with different modes of transport

	Yearly O&M Costs (MEur/yr)			
OM Strategy	**Original Location**	**Location A**	**Location B**	**Location C**
Hub-island based O&M costs without tech transfer	158.83	179.32	172.94	172.37
Cost for technician transport (using aircraft)	**2.31**	**1.98**	0.62	1.25
Cost for technician transport (using helicopter)	3.54	3.39	0.97	2.04
Cost for technician transport (using fast ferry)	8.92	8.35	**0.61**	2.22
Cost for technician transport (using normal ferry)	6.98	7.26	5.27	**0.94**

Table 9 Effective bi-weekly technician working time (assuming 12-hour daily shift) using different transportation modes to hub-island

Effective bi-weekly technician working time (hours/two weeks)				
OM Strategy	**Location 0**	**Location A**	**Location B**	**Location C**
Aircraft for technician transport	**166**	**166**	166	166
Helicopter for technician transport	166	166	166	166
Fast ferry for technician transport	156	156	**164.5**	165.5
Normal ferry for technician transport	156	156	156	**163.5**

6. O&M beneficial scenario (tipping point: Dist. from hub-island to WF)

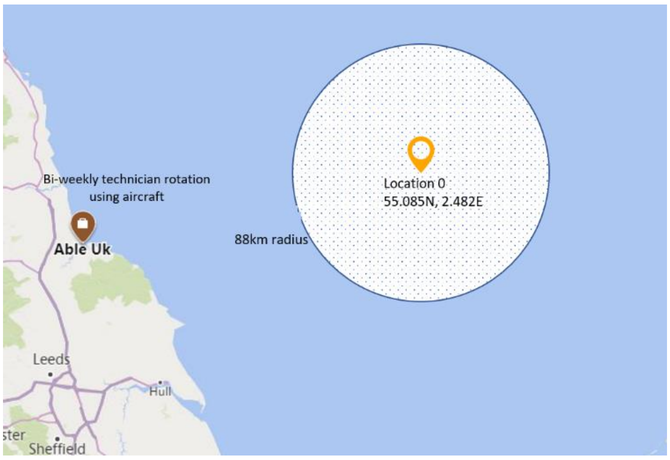


Figure 12 Tipping point and zone favouring O&M from hub-island (Location 0)

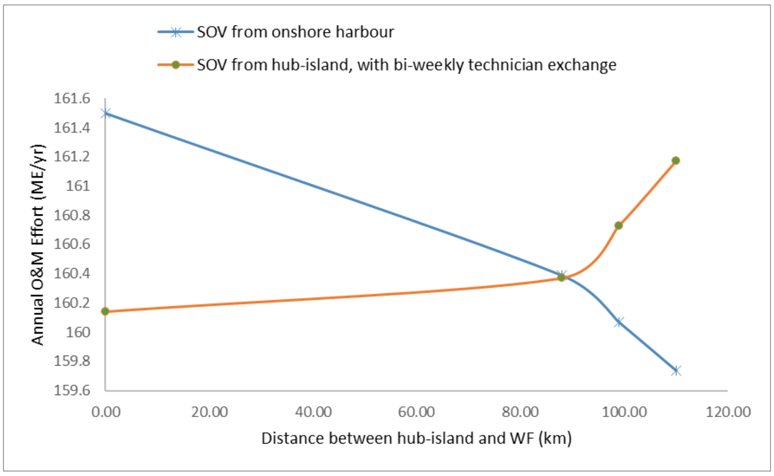


Figure 13 O&M Costs from hub-island (Location 0) v/s onshore O&M port

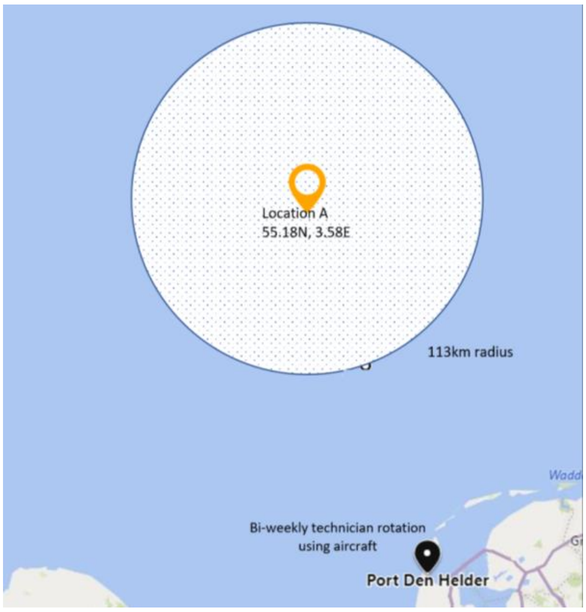


Figure 14 Tipping point and zone favouring O&M from hub-island (Location A)

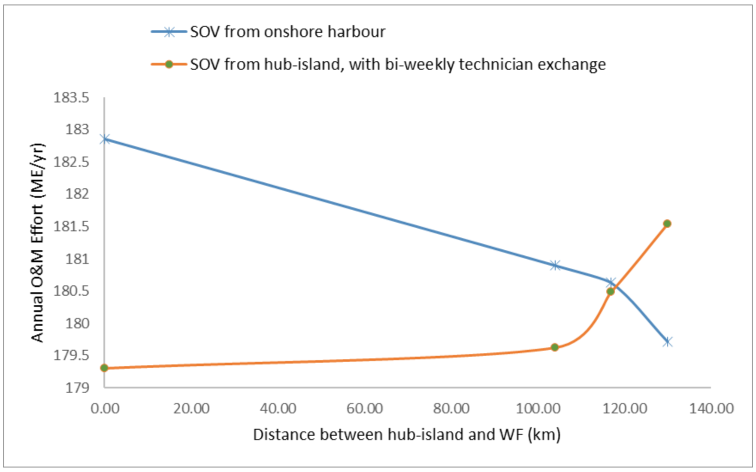


Figure 15 O&M Costs from hub-island (Location A) v/s onshore O&M port

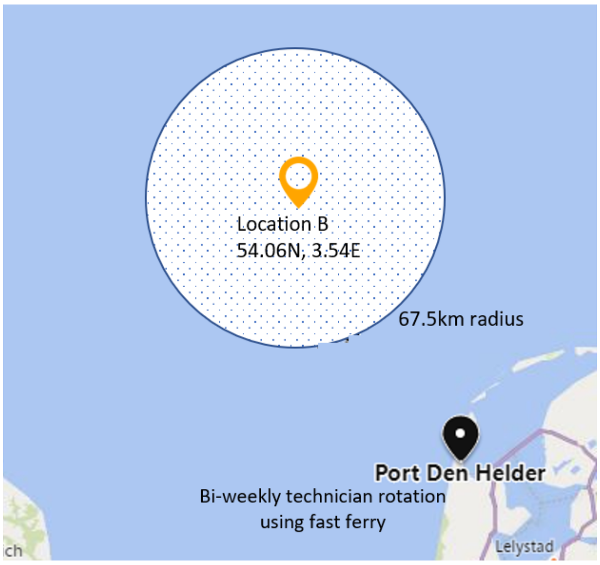


Figure 16 Tipping point and zone favouring O&M from hub-island (Location B)

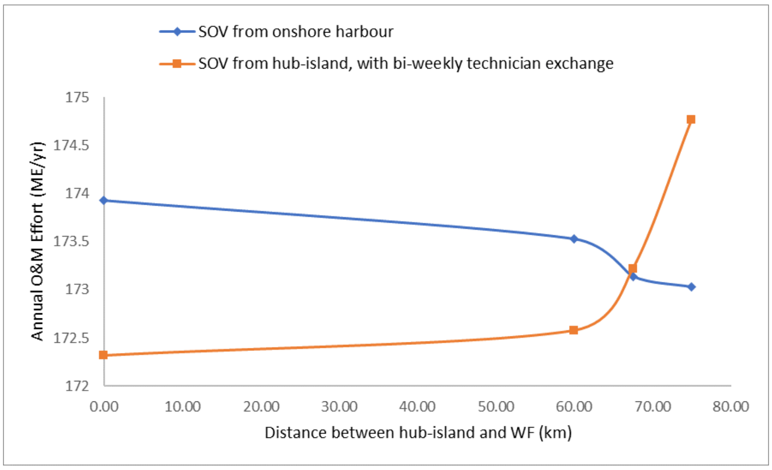


Figure 17 O&M Costs from hub-island (Location B) v/s onshore O&M port

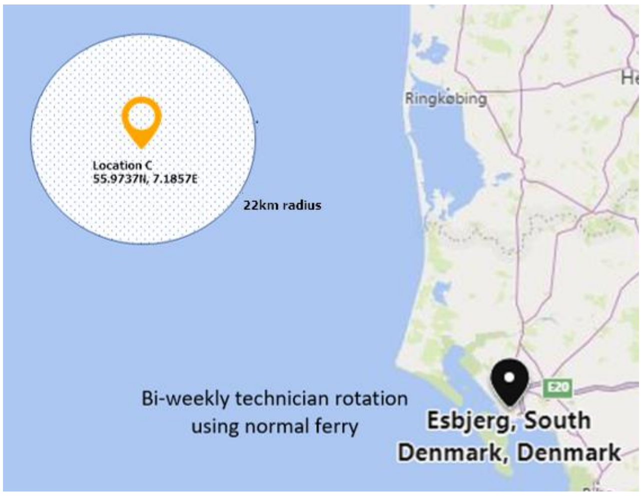


Figure 18 Tipping point and zone favouring O&M from hub-island (Location C)

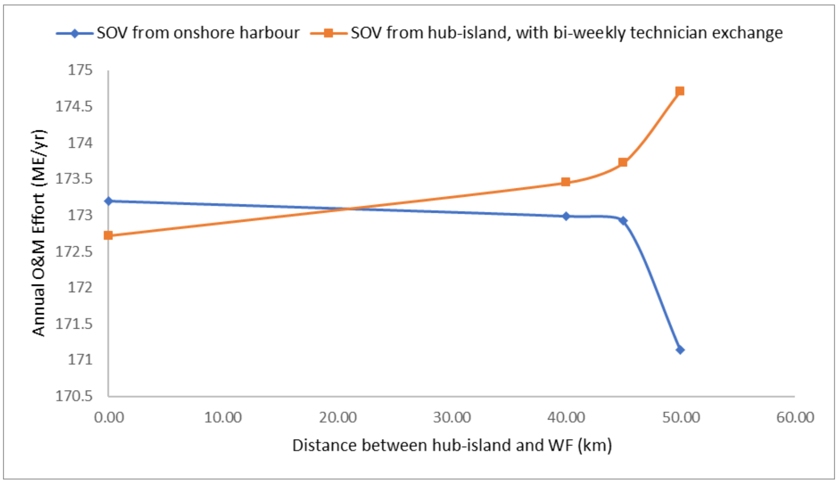


Figure 19 O&M Costs from hub-island (Location C) v/s onshore O&M port

7. WT deterioration (% difference in OM Effort (M€/yr) from original failure rates)

Table 10 Default failure frequencies for different maintenance categories (MCs)

Sequence name	Maintenance Category (MCs)	Failure frequency (/yr/turbine)
Corrective maintenance	Remote reset	5
	Inspection/repair inside	2.5
	Inspection/repair outside	0.5
	Small replacement	1.5
	Large replacement	0.1
	Infield cable replacement	0.005
Preventive maintenance	Annual Campaign	1
	Foundation inspection and repair	1

Table 11 Equipment and repair time for different maintenance categories (MCs)

Sequence name	Maintenance Category (MCs)	Equipment	Repair time (h)
Corrective maintenance	Remote reset	-	2
	Inspection/repair inside	Access vessel	4
	Inspection/repair outside	Access vessel	8
	Small replacement	Access vessel	8,16,24
	Large replacement	Jack-up barge	24,40
	Infield cable replacement	Cable laying vessel	24
Preventive maintenance	Annual Campaign	Access vessel	24
	Foundation inspection and repair	Access vessel	24

Table 12 WT deterioration (Sensitivities 1 and 2) for Locations 0 and A

# Scenario	# Case	Description	Location 0 (OM Costs MEur/Yr)				Location A (OM Costs MEur/Yr)		
			Original failure rates (no bathtub)	Sensitivity 1 failure rates	Sensitivity 2 failure rates		Original failure rates (no bathtub)	Sensitivity 1 failure rates	Sensitivity 2 failure rates
Scenario 4	Case 1	SOV from onshore harbour	161.5	161.96	166.46		182.86	182.53	188.27
	Case 2_SOV_2	SOV from hub-island (WH limit = 3.0 m)	158.83	160.22	163.99		179.32	179.77	185.11
	Case 2_SES_2	SES from hub-island (WH limit = 2.0 m)							
Scenario 5	Case 1	No warehouse for large spare parts	158.83	160.22	163.99		179.32	179.77	185.11
	Case 2	Warehouse available for large spare parts on hub-island	158.93	159.60	163.88		178.65	178.81	184.35
Scenario 6	Case 1_Sens_1	Jack-up barge from onshore harbour (no day-rate reduction)	158.83	159.97	164.53		179.35	179.89	185.12
	Case 1_Sens_2	Jack-up barge shared from onshore harbour (33% day-rate reduction)	150.37	151.13	155.12		170.53	169.93	175.35
	Case 2	Jack-up barge operated from hub-island (33% day-rate reduction)	147.64	148.11	151.89		166.99	166.99	171.81
		Percentage change from original failure rates case		-0.57	3.19			-0.051	3.08

Table 13 WT deterioration (Sensitivities 1 and 2) for Locations B and C

# Scenario	# Case	Description	Location B (OM Costs MEur/Yr)				Location C (OM Costs MEur/Yr)		
			Original failure rates (no bathtub)	Sensitivity 1 failure rates	Sensitivity 2 failure rates		Original failure rates (no bathtub)	Sensitivity 1 failure rates	Sensitivity 2 failure rates
Scenario 4	Case 1	SOV from onshore harbour	173.93	173.36	178.90		173.2	173.43	178.71
	Case 2_SOV_2	SOV from hub-island (WH limit = 3.0 m)	172.94	172.70	178.29		172.37	173.39	177.99
	Case 2_SES_2	SES from hub-island (WH limit = 2.0 m)							
Scenario 5	Case 1	No warehouse for large spare parts	172.94	172.70	178.29		172.37	173.39	177.99
	Case 2	Warehouse available for large spare parts on hub-island	170.34	171.99	176.23		172.56	172.37	177.77
Scenario 6	Case 1_Sens_1	Jack-up barge from onshore harbour (no day-rate reduction)	173.25	172.10	177.54		172.83	173.18	177.76
	Case 1_Sens_2	Jack-up barge shared from onshore harbour (33% day-rate reduction)	163.23	163.16	167.57		162.82	163.46	167.63
	Case 2	Jack-up barge operated from hub-island (33% day-rate reduction)	159.15	160.33	164.44		159.13	160.45	164.66
		Percentage change from original failure rates case		-0.056	2.99			-0.38	3.14

8. CO2 reduction estimation

Table 14 Total CO2 emission reduction from installation scenarios at all hub-island locations

Installation of 3.9 GW		Emissions (CO2) TTW (tonnes/year)			
Scenario	**Description**	**Location 0**	**Location A**	**Location B**	**Location C**
1	Common Vessels	1166.4	1616.95	1113.5	1059.5
	Installation from onshore port	7563.1	6783.5	5376.3	6136.2
	Foundations, WTs installed from hub-island	4987.8	4559.8	3728.9	4103.2
	Savings (tonnes CO2)	2575.3	2223.7	1647.4	2033
2	Common Vessels	8729.5	8400.45	6489.8	7195.7
	Commissioning with SOV from onshore harbour	1.3	1.7	1.1	0.6
	Commissioning from hub-island	0.3	0.4	0.3	0.1
	Savings (tonnes CO2)	1.0	1.3	0.8	0.4
	Total installation savings (tonnes CO2)	**2576.3**	**2225.0**	**1648.2**	**2033.4**

Table 15 Total CO2 emission reduction from O&M scenarios at all hub-island locations

O&M of 3.9 GW		Emissions (CO2) TTW (tonnes/year)			
Scenario	**Description**	**Location 0**	**Location A**	**Location B**	**Location C**
4	SOV from onshore harbour	5.4	6.9	4.9	3.2
	SOV from hub-island + biweekly technician transfer	10.8	12.2	4.8	2.2
	Savings (tonnes CO2)	-5.4	-5.3	0.1	1.0
6	Jack-up barge shared from onshore harbour	12.7	17.3	11.0	5.8
	Jack-up barge operated from hub-island	6.7	9.2	5.8	3.1
	Savings (tonnes CO2)	6.0	8.2	5.2	2.7
	Total OM savings (tonnes CO2)	**0.6**	**2.9**	**5.2**	**3.7**

Table 16 Frequency and movement of installation vessels at onshore harbour and hub-island per year

	Installation of 3.9 GW/year			
Scenario	**Vessel type**	**No of vessels**	**No of round trips from port (per vessel)**	**No of round trips from island (per vessel)**
Foundations, WTs installed from hub-island	Scour Protection Vessel	2	10	0
	Jack-up vessel (foundations)	3	1	29
	Jack-up vessel (WTs)	3	1	29
	Cable laying vessel	4	7	0
	Cable burying vessel	4	7	0
	Grapnel run vessel	4	7	0
	Crew transfer vessel	4	7	0
	Barge-foundations	2	26	26
	Barge-WTs	**2**	26	26

Table 17 Frequency and movement of O&M vessels at onshore harbour and hub-island per year

	O&M of 3.9 GW/year			
Scenario	**Vessel type**	**No of vessels**	**No of round trips from port (per vessel)**	**No of round trips from island (per vessel)**
SOV from hub-island + biweekly technician transfer	SOV	1	2	26
	Jack-up barge	1	17	0
	Cable laying vessel	1	5	0
	Aircraft/Ferry (for technician transfer)	1	26	26
	Helicopter (for technician transfer)	5	26	26