Offshore wind industry review of GBSs

Identifying the Key Barriers to large scale Commercialisation of Gravity Based Structures (GBSs) in the Offshore Wind Industry

Prepared for the Scottish Government

November 2015

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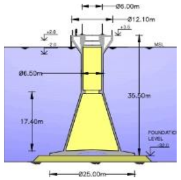
List of Abbreviations

Abbreviation	Meaning
AUV	Autonomous underwater vehicle
CAU	Consolidated anisotropic sheared un-drained test
CPT	Cone penetration test
DSS	Direct simple shear
DWT	Deadweight tonnage
EoS	Economies of scale
EPC	Engineering, procurement and construction contracts
FID	Final investment decision
GBF	Gravity based foundations
JUB	Jack-up Barge
LD	Liquidated damages
RNA	Rotor nacelle assembly
SIMOPS	Simultaneous operations
SLS	Serviceability limit state
SPMT	Self propelled modular transport
TIV	Turbine installation vessel
TSHD	Trailing suction hopper dredger
T & I	Transport and installation
ULS	Ultimate limit state
WTG	Wind turbine generator

Content

Industry view of Gravity Base Structures as foundation for Offshore Wind Turbines



Technology Review

- The number of GBS installations has decreased significantly over the last few years as the market has moved away from shallow-water GBS. New concepts for deeper-water conditions have not yet seen large scale deployment.
- To-date, full and partial scale demonstrations have not created sufficient industry confidence.
- The various foundation designs have been classified depending on transport (floated or lifted) and consider if the solution includes WTG or not.

Trends and Challenges

- There are some common trends, but there are also some discrepancies that generate a lack of confidence between clients (e.g. Offshore Wind Developers).
- Some overarching barriers need to be evaluated before pushing GBSs any further.
- A SWOT analysis has been developed considering the views from designers, developers and other industry stakeholders.

The future of GBSs

- Many challenges can be easily addressed through collaboration between concept designers, beyond the promotion of the use of concrete in the offshore wind sector.
- GBSs have potential to become a cost effective alternative WTG foundation in offshore wind.
- Designers, developers and governments could support the development of GBSs by sharing the benefits and creating win-win situations.

Content

2.1. Market Assessment - GBS Overview

Gravity based structures can be categorised in a number of ways. This study separates GBS into the following two classifications.

Firstly, by separating into two groups based on the mode of transportation to the installation site:

Float-out-and-sink concepts – "Floated"
These concepts use large geometric volumes and result in the production of self-buoyant structures, meaning tugboats can be used to transport to the offshore site and no heavy-lift vessel is required. Once at the site, an injection of water ballasts the structure to the seabed and a permanent ballast is then provided by sand or aggregate.

Lifted Concepts
These systems benefit from being smaller (usually requiring less concrete), however investments into transportation vessels are higher as they require mobilisation with a combination of auxiliary; heavy lift crane, and/or transportation vessel or barge.

GBS can also be distinguished by their approach to installation of the foundation and Wind Turbine Generator (WTG) to the Offshore Wind Farm (OWF):

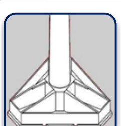
Foundation only
Just the foundation is transported to the OWF.

Integrated transportation
Foundation, tower and rotor nacelle assembly (RNA) are erected onshore and transported to OWF together.

The figure opposite illustrates the classification system used in the remainder of this report based on these key identifiers.

Note: The designers stated in each category reflect current and past concepts developed or executed

2.1. Market Assessment - Designers that have provided input to the analysis

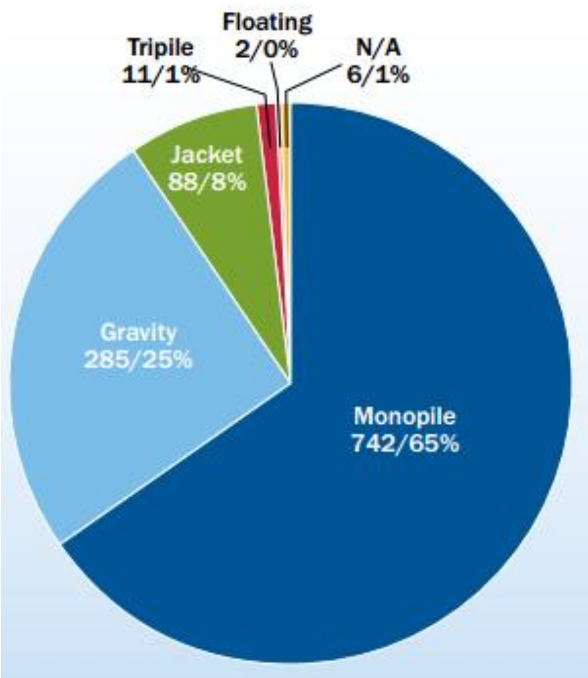
Diagram	Company	Description	Primary Contact
	Van Oord bam	**Bam & Van Oord GBS Consortium** •Crane free gravity base comprising a concrete shell around a steel monopile. •Seabed preparation is required to place gravel bed and no skirts are required.	**BAM Nuttal Ltd,** T: +44(0) 1276 63484 E:Gavin.Gerrard@BAMNuttall.co.uk E:Arthur.costerus@vanoord.com
	SKANSKA Boskalis Offshore Grontmij	**JV - Boskalis, Grontmij & Skanska GBS** •Self-buoyant hybrid concrete/steel GBS with a flat base and no skirt. •GBS sits on a pre-prepared, level gravel bed. •No heavy lift equipment is required offshore.	**Boskalis Offshore** Bart van Schooten, Manager Renewables E: Bart.van.schooten@boskalis.com T: +31 78 696 8626
	GRAVITAS OFFSHORE HOCHTIEF / COSTAIN / ARUP	**Gravitas (JV between Hochtief, Costain and Arup)** •Concrete gravity base structure requiring no skirt. •Limited seabed preparation required as the foundation is designed to accommodate existing seabed slopes and surface sediment.	**GRAVITAS Offshore Ltd,** Gordon Jackson, Director E: gordon.jackson@arup.com T: +44(0)207 755 2289
	seatower	**Seatower** •Crane free Gravity foundations are self-buoyant, hybrid steel/concrete structures. •No dredging is required and no specialised vessels are required for installation. •Shallow steel skirts are used for final penetration.	**Seatower AS,** Petter Karal, CEO E: petter.karal@seatower.com T: + 47 480 111 99
	Ocean Resource Ltd	**Ocean Resource – Sea Breeze** •Sea water ballasted, self-buoyant, re-deployable concrete gravity base foundation. •Fully assembled foundation with turbine tower, nacelle and blades and commissioned onshore before being tugged to site.	**Sea Breeze Ocean Resource** Dr Lewis Lack, Director E: lewislack@oceanresource.co.uk T:+44 (0)1291 430 841
	GBF Gravity Base Foundations	**GBF (Ramboll, BMT Nigel Gee, Freyssinet Consortium)** •Concrete gravity base using an integrated approach to onshore construction, transportation and offshore installation. •A lifted design using a specialised semi-submersible Transportation and Installation Barge; the turbine and tower can be pre-installed onshore if required.	**Ramboll** William Brook-Hart,Technical Director E: William.Brookhart@ramboll.co.uk T: 023 8081 7548
	STRABAG Boskalis Offshore	**Strabag and Boskalis Offshore Consortium** •A lifted design using a floated crane. •Pre-stressed concrete is used and small skirts may be required depending on soil conditions. •Integrated footing plates are used for load transfer from concrete to soil and to avoid gaps between concrete and soil and developing of scour.	**Strabag Offshore Wind GmbH** Jens – Peter Grunau E: jen-peter.gruanu@Strabag.com T: +49 7117883 9727

Note: From the different GBS designers approached, none from the L-FO group accepted to fully participate in the study, but the report has used existing literature instead.
Other designers have replied to specific queries.

2.2. Current Installations - GBS Commercial Experience, from 2010 to today

2010

GBS as a turbine substructure made up 25% of the foundation market, with Thornton Bank (Phase 1) 6 foundations fully commissioned along with an additional 279 shallow L-FO GBS foundations already in the water.

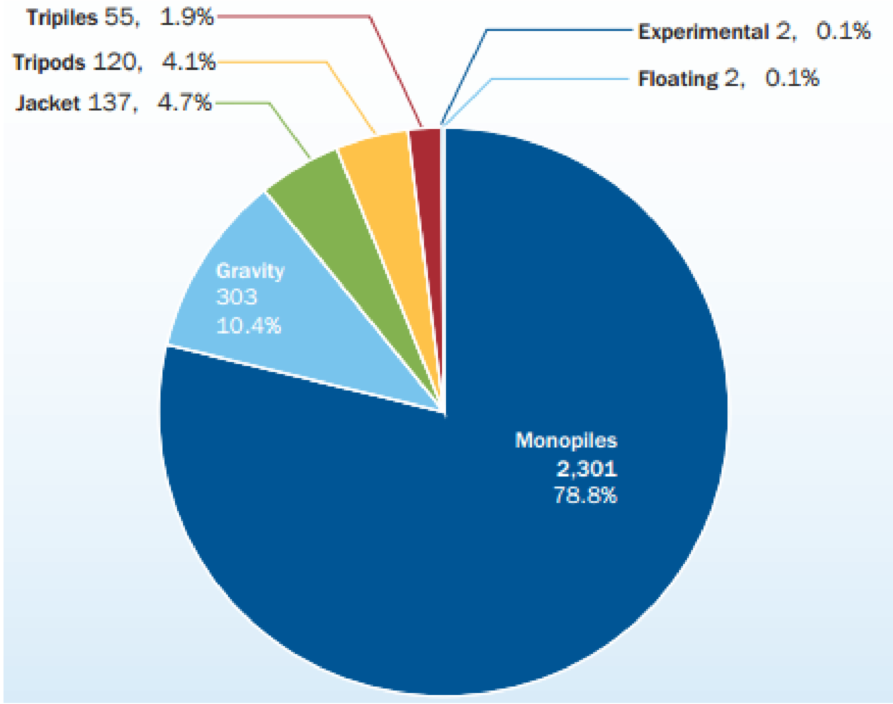


The possible justification behind the reduction in market share for GBSs could be the fact that over the last few years the market has moved away from shallow waters, and that it is only now moving to water depths and turbine sizes where the new GBS concepts will be competitive.

2015

However, since then, the market share of GBS has decreased to only 10.4% in 2014, falling to below 10% when considering current installation. This equates to, an overall increase of only 18 units, all of them in Baltic waters.

Monopile installation tripled, however GBS installations have only increased by 6% between 2010 and 2014.



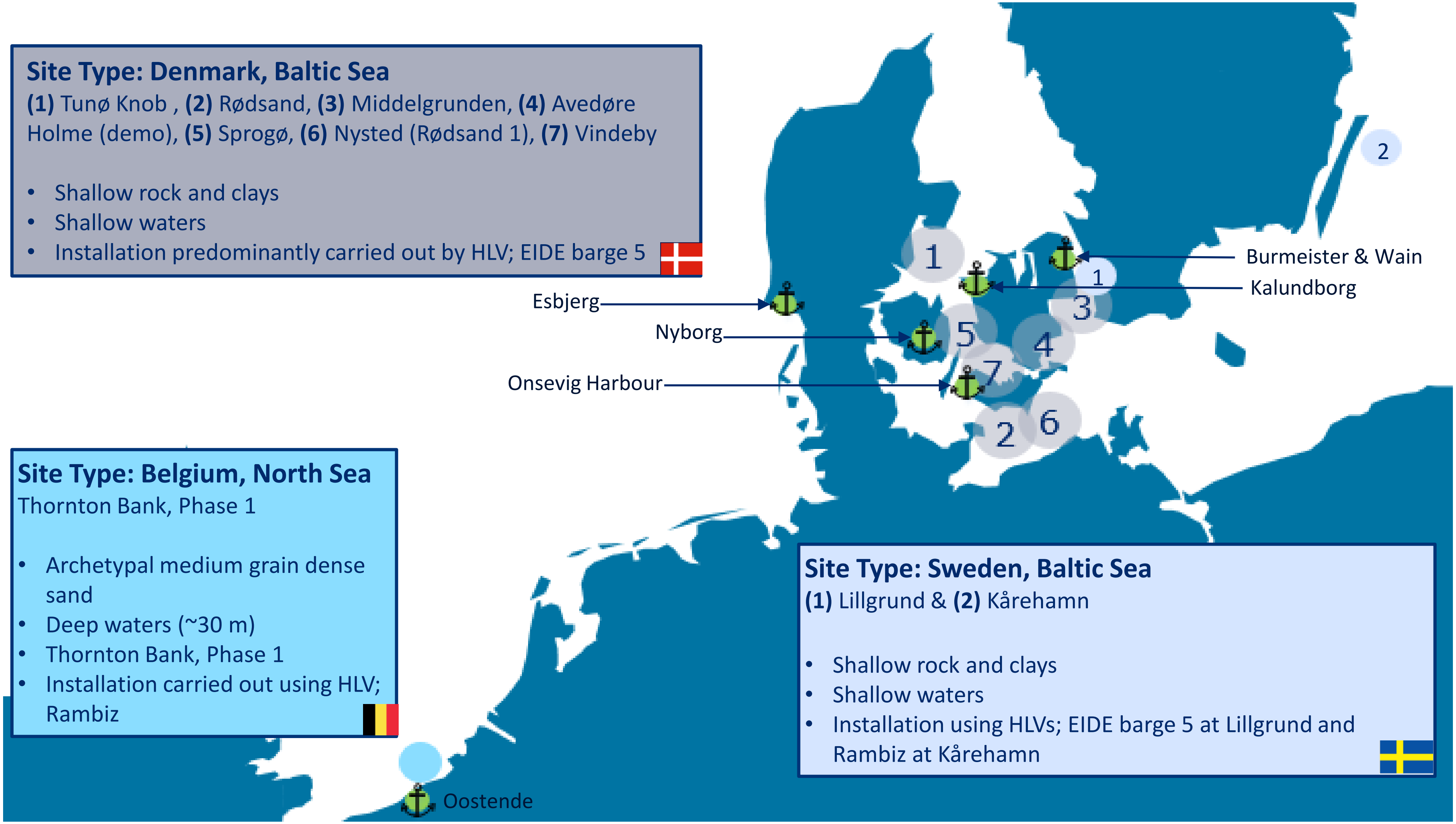
Ref: EWEA Key trends and statistics 2010. http://www.ewea.org/fileadmin/files/library/publications/statistics/20110121_Offshore_stats_Full_Doc_final.pdf

Ref: EWEA: The European offshore wind industry - key trends and statistics 2014. http://www.ewea.org/fileadmin/files/library/publications/statistics/EWEA-European-Offshore-Statistics-2014.pdf

2.2. Current Installations - GBS commercial experience in the Baltic & North Seas

Conventionally, GBSs have been installed at shallow depths in the Baltic Sea using heavy lift vessels (HLV).

A number of principal manufacturing ports exist in Denmark, however these have been used to fabricate comparatively small GBS.



Site Type: Denmark, Baltic Sea

(1) Tunø Knob , **(2)** Rødsand, **(3)** Middelgrunden, **(4)** Avedøre Holme (demo), **(5)** Sprogø, **(6)** Nysted (Rødsand 1), **(7)** Vindeby

- Shallow rock and clays
- Shallow waters
- Installation predominantly carried out by HLV; EIDE barge 5

Site Type: Belgium, North Sea

Thornton Bank, Phase 1

- Archetypal medium grain dense sand
- Deep waters (~30 m)
- Thornton Bank, Phase 1
- Installation carried out using HLV; Rambiz

Site Type: Sweden, Baltic Sea

(1) Lillgrund & **(2)** Kårehamn

- Shallow rock and clays
- Shallow waters
- Installation using HLVs; EIDE barge 5 at Lillgrund and Rambiz at Kårehamn

2.2. Current Installations - Details of site and installation approaches

Country	Project	Inst. Date	Dist. from shore	WTG Rating	Number of GBSs	Water Depth	Designer	Port	Vessel type
Belgium	Thronton Bank Phase 1	2009	27 km	5.0 MW	6	30m	COWI	Oostende	HLV
Germany	Arkona-Becken Südost	2006	35 km	Metmast	1	24m	Züblin AG (Strabag)	Lubmin	HLV
Denmark	Vindeby	1991	1.8 km	0.45 MW	11	2 – 4 m	MT Højgaard	Onsevig Harbour	HLV
	Tunø Knob	1995	5.5 km	0.5 MW	10	4 – 7 m	Skanska	-	HLV
	Middelgrunden	2000	4.7 km	2.0 MW	20	3 – 6 m	MT Højgaard	Burmeister & Wain's dry dock	HLV
	Nysted (Rødsand 1)	2003	10.8 km	2.3 MW	72	6 -10 m	COWI	Nyborg	HLV
	Avedøre Holme (demo)	2009	0 km	3.6 MW	3	2 m	Arkil A/S	-	HLV
	Sprogø	2009	10.6 km	3.0 MW	7	6 – 16 m	NIRAS	Kalundborg Port, DK	HLV
	Rødsand 2	2010	9 km	2.3 MW	90	4 – 10 m	COWI	Nyborg,	HLV
Sweden	Lillgrund	2008	11.3 km	2.3 MW	48	4 – 8 m	COWI	Nyborg	HLV
	Kårehamn	2013	3. 8 km	3 MW	16	8 – 20 m	COWI	Esbjerg	HLV
France	Fecamp (demo)	2015	15 km	Metmast	1	30m	Seatower	Le Havre	Cranefree

Site details for GBS installations in the Baltic and North Seas

Lifting of GBS for Thornton Bank installation

www.scaldis-smc.com

RAMBIZ, Scaldis

Maximum Draft: 5.6 m

LOA: 85 m

Berth: 44 m

Lifting Capacity: 2 cranes with 1600 T and 1700 T respectively. Total: 330T.

Installation of GBS at Nysted 1.
Photo courtesy of DONG energy

EIDE barge 5

Maximum Draft: 3.615 m

LOA: 76 m

Berth: 37 m

Lifting Capacity: 1.450 T

2.2. Current Installations - Current foundations installed in the Baltic, Irish and North Seas

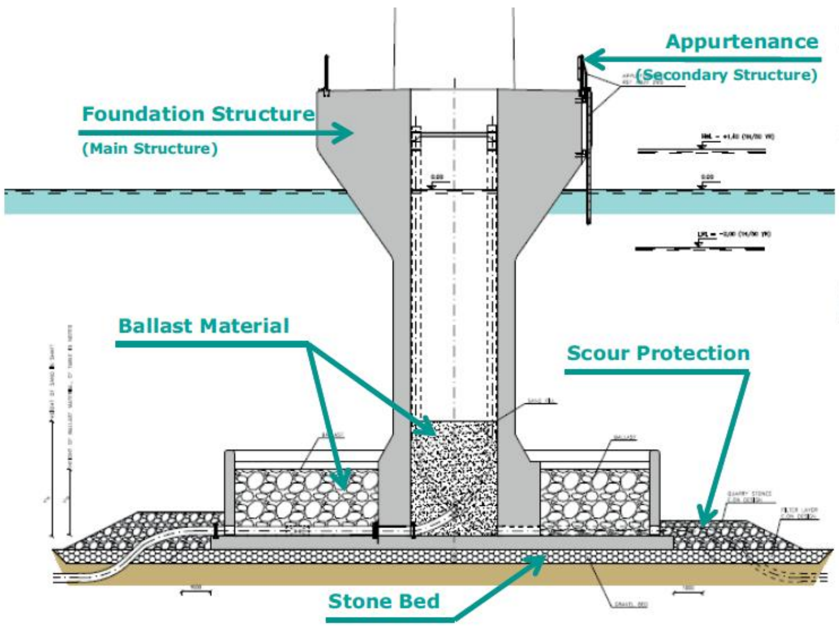
2.3. GBS Design Evolution of L-FO concepts installed with a WTG

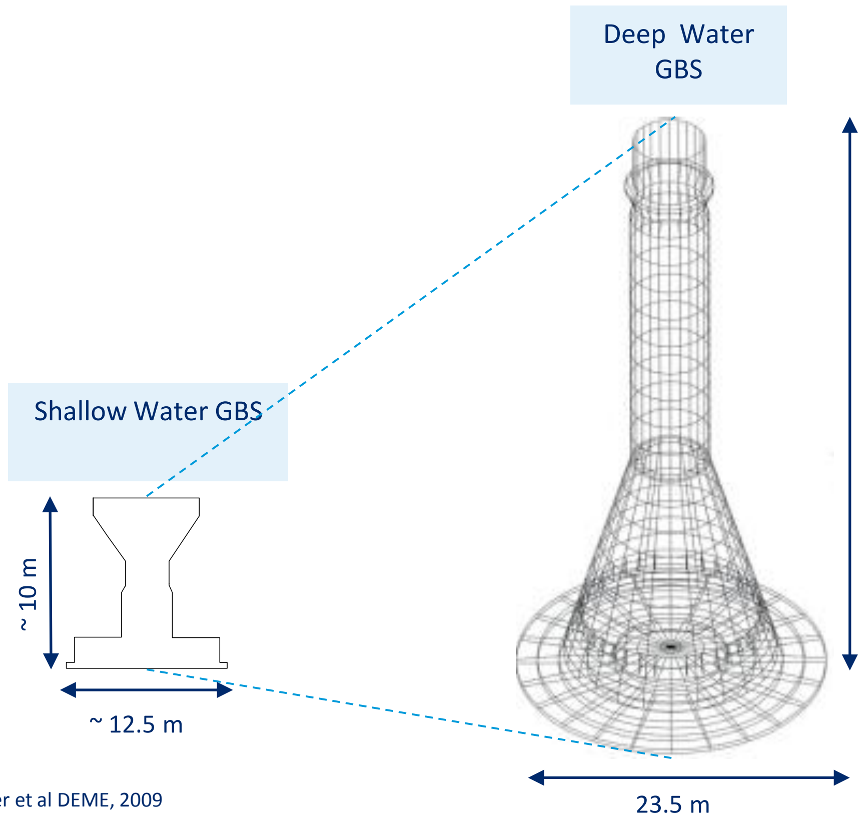
Shallow Water GBS – Baltic sites

- Installation between 2001 and 2010.
- Shallow waters (up to 12m).
- Low interface level above MSL (not significant wave loading but strong ice loading, hence requirement to have an ice cone).
- Designs for 2.3MW WTGs.
- Installation by a purpose built system on EIDE barge 5.

Deep Water GBS – North Sea

- Installation in 2009.
- Deep waters (up to 30m).
- High interface level above MSL (significant wave loading but no ice loading, hence no ice cone required).
- Designs for 5 MW WTGs.
- Installation by a Rambiz heavy lift barge.





References:

Gravity Based Foundations, Structure Aspects of offshore Wind Turbine Foundations, COWI, 2010.

Gravity Base foundations for the Thornton Bank Offshore Wind Farm, Dredging International, Kenneth Peier et al DEME, 2009

Offshore Wind Turbine Foundation s – The COWI Experience. Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering, OMAE 2007, Jørn H. Thomsen, Torben Forsberg, Robert Bittner, P.E.

2.3. GBS Design Evolution - Main executions to-date (Foundation for WTG only)

Shallow water lifted design (Bilfinger Aarslef, Cowi and others, using EIDE barge 5;) [Rodsand 2 (2010) as example, 2000 to 2010]

Shallow water lifted design (Jan De Nul, Cowi and others, using Rambiz 2) [Kårehamn, 2013]

Deep water lifted design (Deme, Cowi and others, using Rambiz) [Thronton Bank phase 1, 2009]

2.3. GBS Design Evolution - Main executions to-date (Met Mast only)

Lifted Met Mast (Zublin-Strabag) [Arkona-Becken Südost, 2006]

2x Float-out-and-Sink Met Mast (Drace) [Inch Cape, 2014]

Float-out-and-Sink Met Mast (Seatower + MTH) [Fécamp, 2015]

2.4. Stakeholder interrelationships

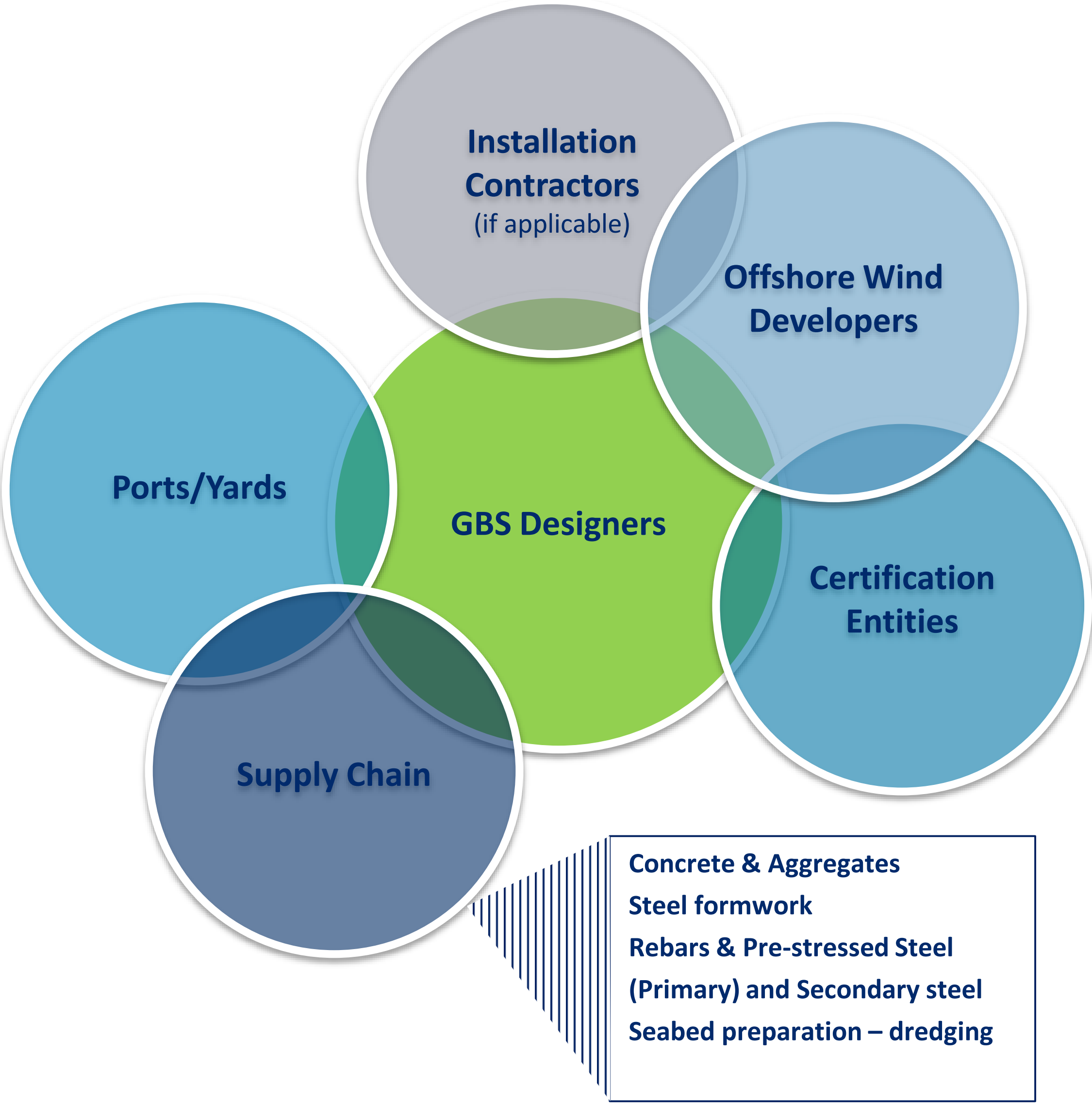
The figure illustrates the stakeholder interrelationships which have been identified with gravity base designers at the core.

This figure identifies the two key areas of development:

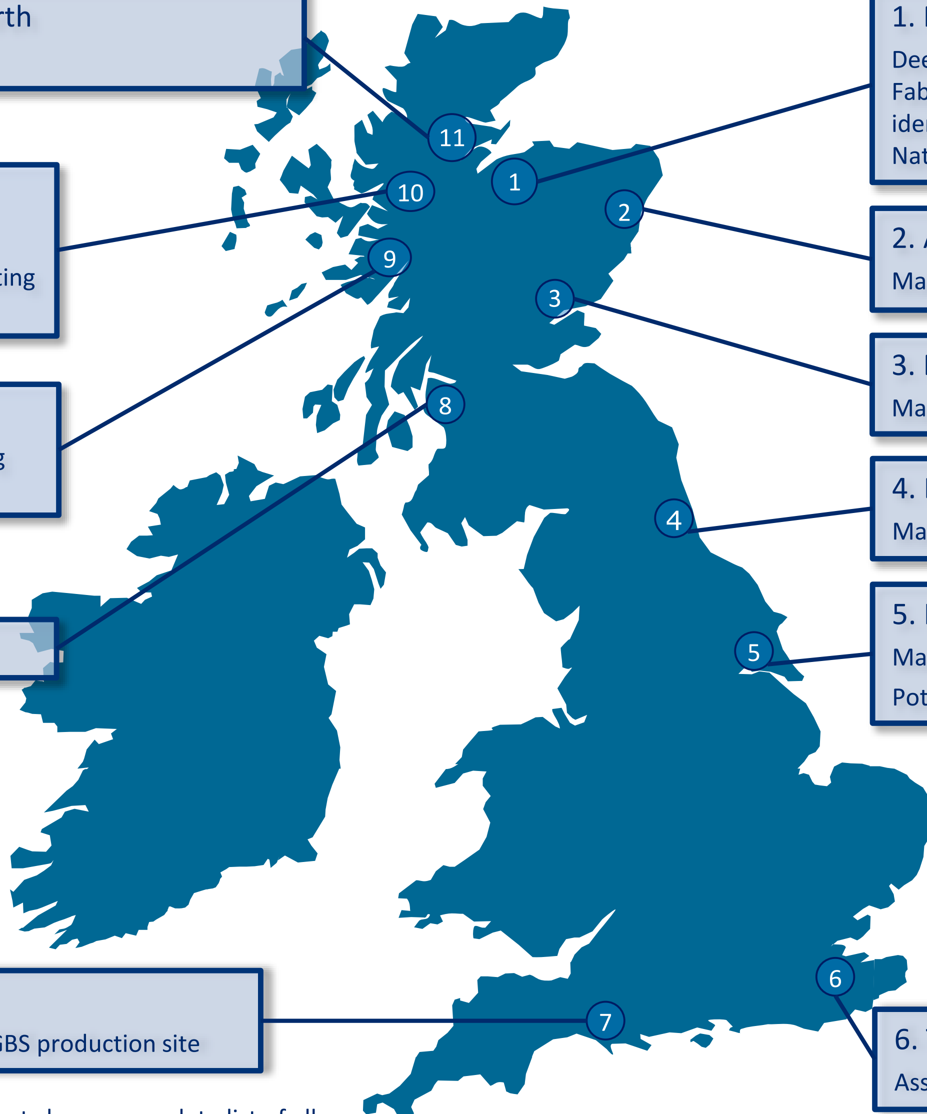
- Fabrication: Focusing on the early engagement between developer, port authorities, local government bodies and GBS designer.
- Installation: This focuses on site developer and their separate interactions with installation contractors and certification entities depending on the terms / type of contract in place:
    - Turn Key/EPCI Contracts.

  VERSUS

    - Separate design and build contracts.



2.4. Possible UK Ports that could host a GBS yard



11. Cromarty Firth

Nigg dry docks

10. Kishorn Port Limited

Maximum draft : 10-13 m.

On site quarry with concrete and aggregating producing facilities

9. Glensanda site

On site quarry with aggregating producing facilities

8. Clydeport (Hunterston)

7. Portland

Assessed as potential GBS production site

1. Port of Ardersier

Deep water port – former McDermott Fabrication Yard and O & G port. It has been identified within the Scottish Enterprises' National Renewables Infrastructure Plan

2. Aberdeen

Maximum draft: 13.6 m (Albert Basin)

3. Dundee (Forth Ports)

Maximum draft: 8.9 m

4. Blyth & Tyne

Maximum draft: (Blyth) 10 m

5. Humber / Hull

Maximum draft: 10.4 m

Potential WTG manufacturing site

6. Thamesport

Assessed as potential GBS production site

Note that the ~~ports~~ list~~ed~~ does not represent ~~show~~ a complete list of all suitable sites, but the ones identified by the participating designers.

Content

3.1. Design

Note: Only an indication of water depth (35m) was provided to the designers

Common Trends

Clear difference between lifted and floated designs:
- Floated designs with **base height** between 7m and 10m.
- Lifted designs with **base height** below 2m.
- Base diameters between 30m and 35m for all solutions except for F-IT solutions.

Concrete weight around 5000t in most cases.

Most designs use sand ballast on final position.

Main differences between designs

Different approaches regarding the use of pre-stressed steel:
- Some designers use only normal rebars for "easy use".
- Some designers use pre-stressed steel to increase durability (lower cracks) and reduce rebars needs

Large variation on steel to concrete ratios:
- Variation is not correlated with the use of pre-stressed steel.

Interface with WTG:
- Not well described and considered as potential risk by some.
- Vary between designers.
- Only some designers have fully designed the interfaces with the turbine (with selected turbine suppliers).

Foundation typology particularities

F-IT
- Large base diameter (largest from all solutions).
- Permanent ballast with only water.
- Significantly more concrete (>20%) than floated ones.
- Potential issues on achieving required WTG verticality.

F-FO
- Large number of different concepts available in the market.
- Large variation between concepts regarding the shaft design.
  - From full-concrete shafts to full-steel shafts (trade-off between cost of steel and cost of greater overall dimensions to achieve floating stability).
- Larger footprint than lifted concepts.

L-IT
- Tendency of using pre-stressed concrete.
- Potential issues on achieving required WTG verticality.

L-FO
- Solutions used historically in the Baltic sea (and in shallow areas).
- Deep water solutions not pushed anymore by designers.

3.2. Site - Water Depth and Geology

Common Trends

GBS are suitable for a wide variety of soil conditions.
- Except in unconsolidated and/or soft surface sediment (which can be dredged).

Variation of geometry depending on water depth:
- GBSs are seen as more competitive in deeper waters (beyond 35m).
- GBSs are seen as more competitive with larger diameter turbines (the designs are not highly sensitive to a WTG capacity increase).

Variation of geometry depending on soil conditions.
- Dimensions tend not to vary significantly depending on soil conditions.

Need of gravel bed between soil and structure in most instances.

Main differences between designs

Sea Bed Preparation needs/requirements vary significantly between designers.
- Dredging is considered by designers to different extents. Some state that it is not required (independently of the type of concept developed).

Use of Skirts *(Global perspective looking at all the concepts):*
- Lack of clarity between concept designers regarding skirt benefits and applicability in different soil conditions.
- [Most of the designers are convinced about the potential need of skirts for their own solution depending on the site conditions].

Need of Scour protection:
- Linked to the use of skirts, no clear consensus on when scour protection is needed.

Foundation typology particularities

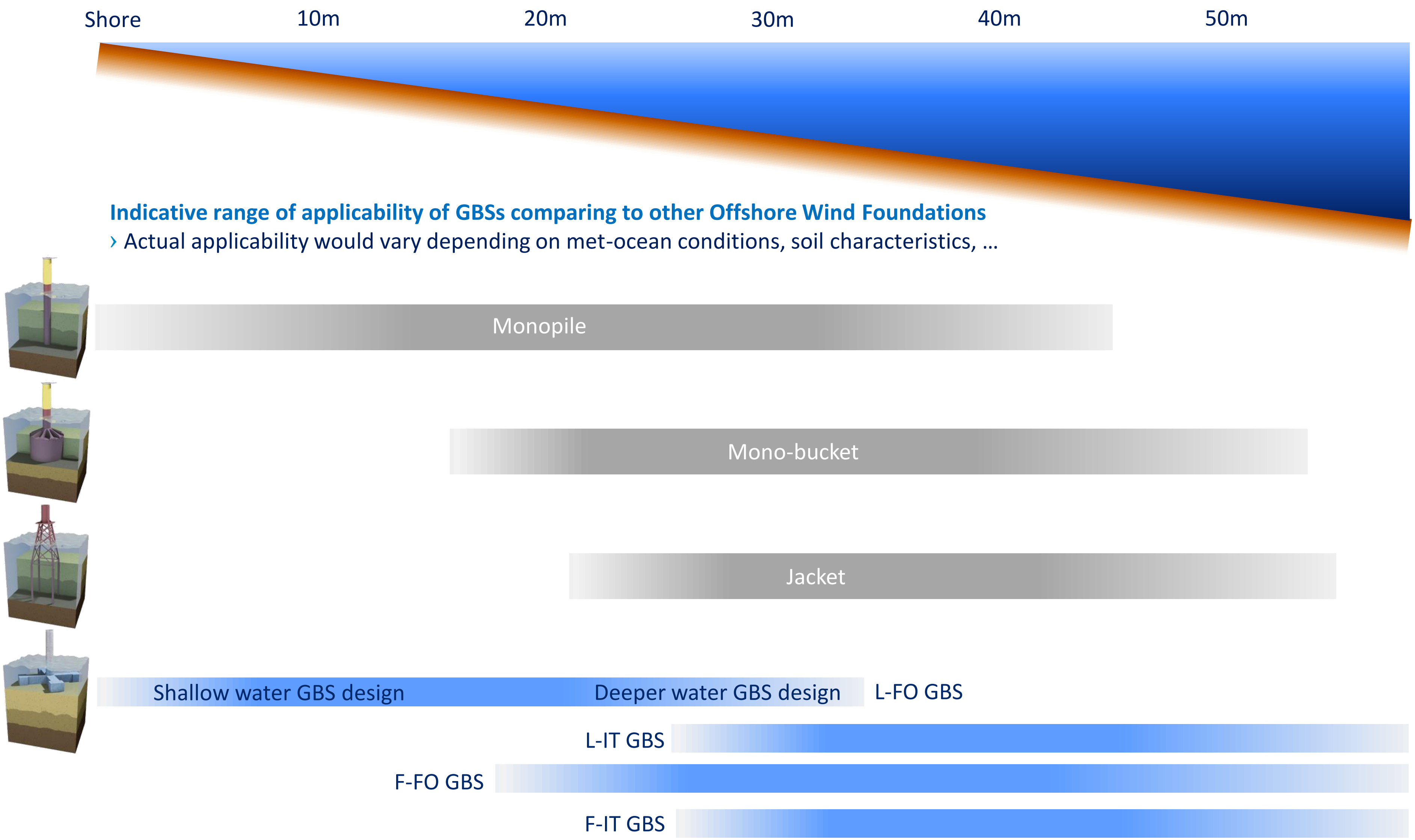
F-IT
- Dimensions driven by soil bearing capacity and floatability requirements.
  - Rocky soils may lead to a 15% weight reduction.

F-FO
- Dimensions driven by soil bearing capacity, resistance to sliding and floatability requirements.
- Tendency that "one fits all" with regards to the buoyant chamber, hence no big variation depending on soil conditions.
  - Main restrictions are linked to floatation/buoyancy and fabrication and supply chain needs (to achieve industrialisation).

L-IT
- Dimensions driven mainly by soil bearing capacity.
- Tendency that "one fits all" in varying soil conditions.
  - Main restrictions are linked to installation (linked to the installation vessel) and fabrication needs (to achieve industrialisation).

L-FO
- Dimensions driven mainly by soil bearing capacity.

3.2. Site - Use of GBSs in relation to depth



Images: tradyna.com

3.3. Supply Chain

Common Trends

One stop shop:

- In the majority of cases, design + fabrication + installation happens within the main concept developer.
- Most of the designers aim to follow an **EPCI approach** (vs Multi-Contract approach), including:
  - Engineering
  - Procurement
  - Construction
  - Assembly and Commissioning (in IT solutions)
  - Transport and Installation (including seabed preparation, tugging, lowering to the seabed and possible scour protection)
- The supply of WTG is always considered separately.

Main differences between designs

Spread of auxiliary equipment needed:

- Lack of alignment on which auxiliary equipment is needed (both for fabrication and for transport/installation despite all solutions being fairly similar (i.e. concrete gravity base foundations).

Foundation typology particularities

F-IT

- Need of cooperation of WTG supplier.
- Need for specialised flotation and stability aids.

F-FO

- No need for specialised installation equipment / installation vessels subject to supply chain bottlenecks and considered expensive.

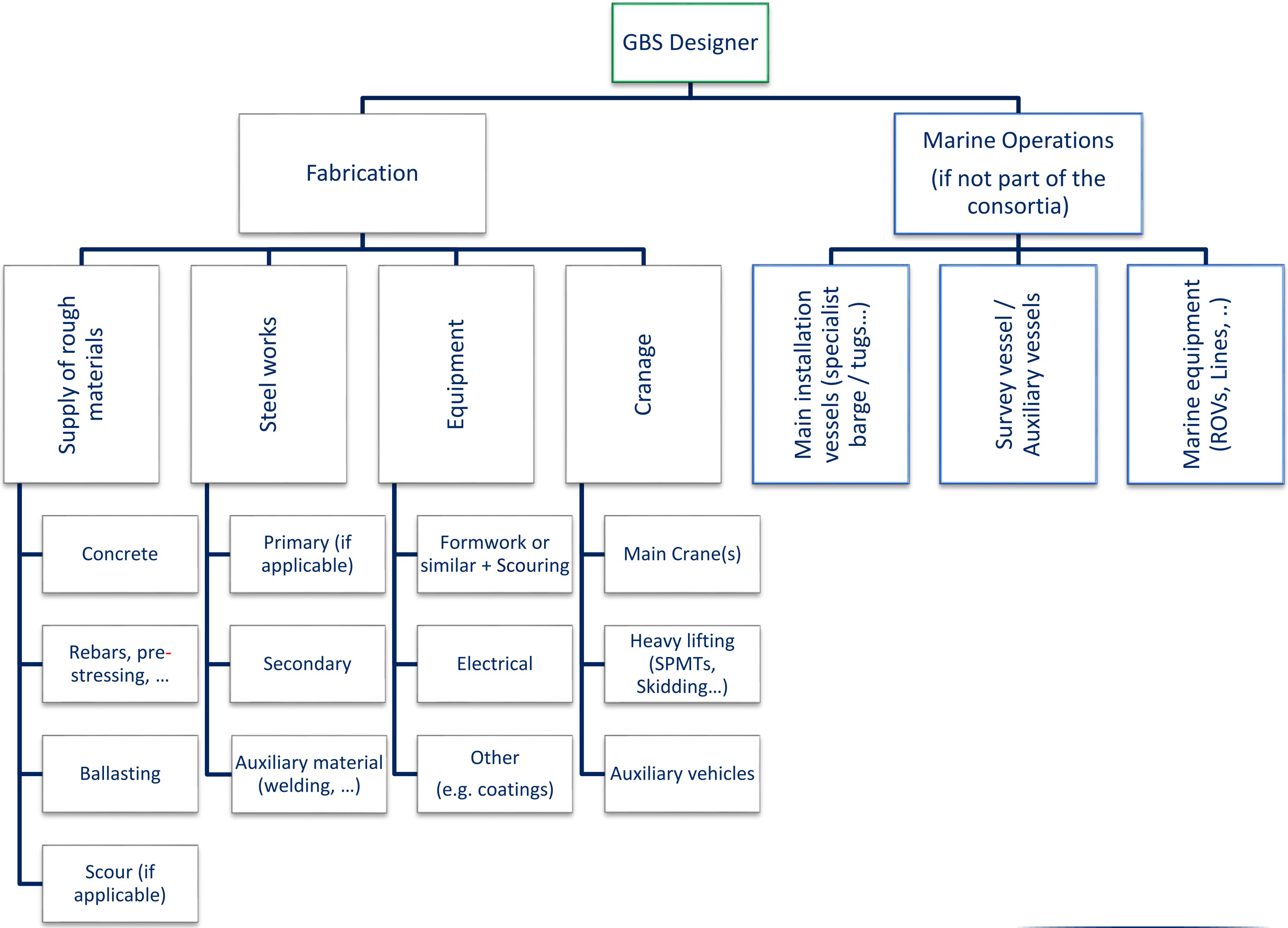
L-IT

- Need of cooperation of WTG supplier.
- Need for special marine installation equipment potentially linked to supply chain bottlenecks.
  - There would not be bottlenecks if the installation equipment is purpose built for the concept and project.

L-FO

- Need for special marine installation equipment potentially linked to supply chain bottlenecks.

3.3. Detailed supply chain map



3.4. Yard & Load-out operation

Common Trends

Fabrication yard should be close to the quayside:
- Suitable access from land and sea.
- Draft at harbour basin should be in excess of 10m (>12m often).

Quay should have sufficient bearing capacity.

Need of skidding systems / SPMTs:
- to transport heavy weights.
- for movements of heavy equipment (cranes, …).

Short/medium distance from offshore wind farm is advantageous.

Yard dimensions can be reduced significantly (~40%) if operations are carried out 24/7 (comparing to 12h/day operation).

Main differences between designs

Dimensions:
- Significant variation between designers (20ha to 50ha for a 500MW project), however most of the designers quote areas between 20ha and 25ha.

Different Load-out operations.
- However most of the floated solution providers state the option of using a semi-submersible barge.

Foundation typology particularities

F-IT
- Potential beam limitation due to large base diameter.
- Potential draft limitations and quayside and in the towing route.
- Special cranes to assemble WTG are required.
  - Need to reach Hub Height on top of the foundation height (130m+)
  - Potential to assemble tower and WTG in-shore (and only do the load out operation of the foundation).

F-FO
- Potential draft limitations and quayside and in the towing route.
- The higher the draft the easier the operations would be (ideally in excess of 12m, though some concepts require only >10m).

L-IT
- The facility can be placed further away from the offshore wind farm if capable & fast transport and installation vessels are considered.
- Special cranes to assemble WTG are required.
  - Need to reach Hub Height on top of the foundation height (130m+)
- Some concepts use installation equipment (mainly vessels) that allows yards to be far away from the fabrication yard.

L-FO
- The facility can be placed further away from the offshore wind farm if capable & fast transport and installation vessels are considered.

3.4. Yard & Load-out operation - Areas of a common GBS yard

Auxiliary yard areas & equipment

- Welfare facilities (staff offices, car parking)
- Equipment storage areas
  - Heavy lifting
  - Trucks
  - …
- Access control points
- Unloading areas for WTGs, Aggregates / Cements, …. (quayside)

Batching plants and aggregate storage areas

Reinforcement prefabrication

Foundation fabrication

- Pre-fabrication facilities (if applicable)
- Formwork / concrete assembly

Secondary Steel

Assembly of concrete foundation and secondary elements

Use of Heavy lifting equipment (SPMTs, Skidding,…) [*]

Foundation assembly

- Foundation erection and grouting of connections
- Electrical & Mechanical equipment fitting

[*]

Example of SPMT equipment

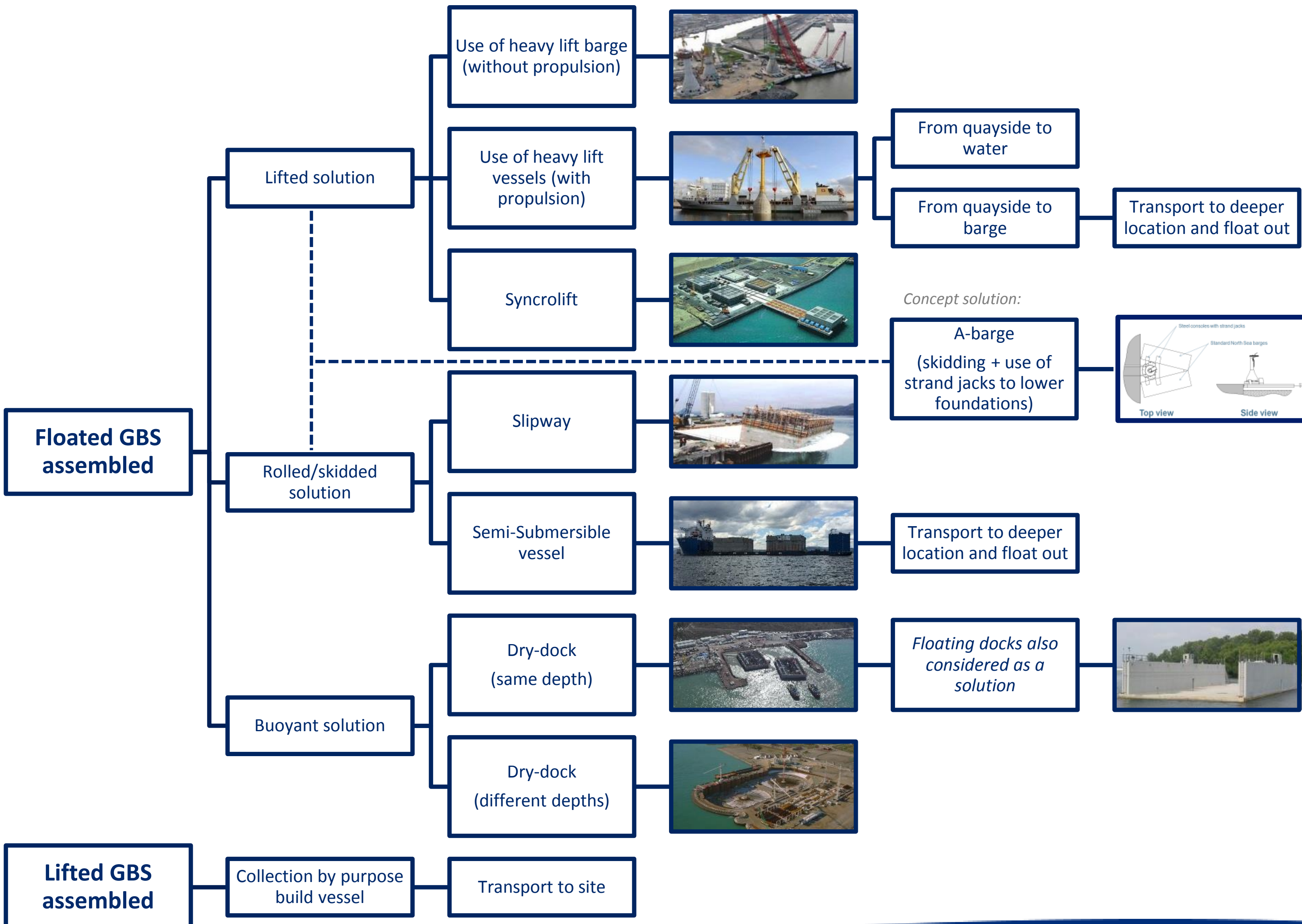
(source: Mamoet)

Example of rail skidding equipment

(source: Enerpac)

££
£10m to £100m+ is required to establish a yard *(depending on designer approach and/or existing infrastructure)*

3.4. Yard & Load-out operation – Existing Load out options

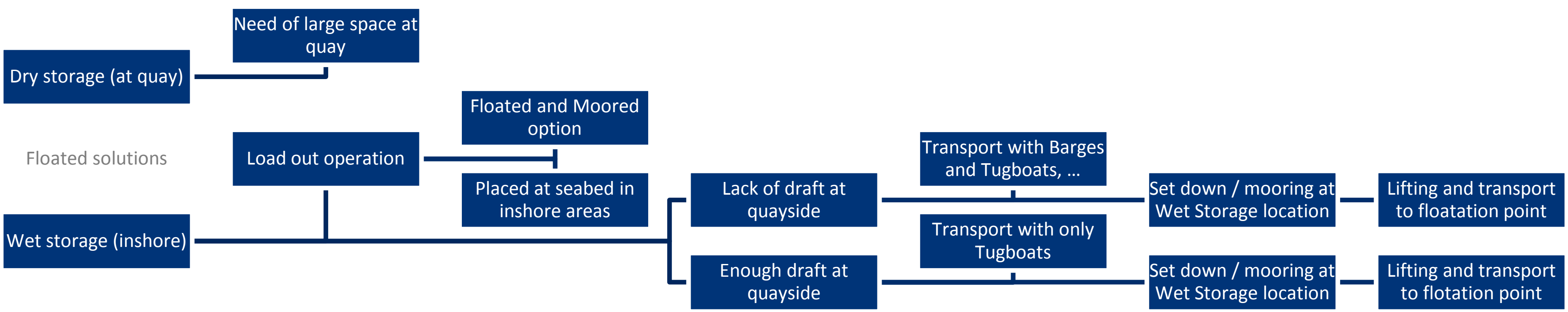


3.4. Yard & Load-out operation - Fabrication rates and storage

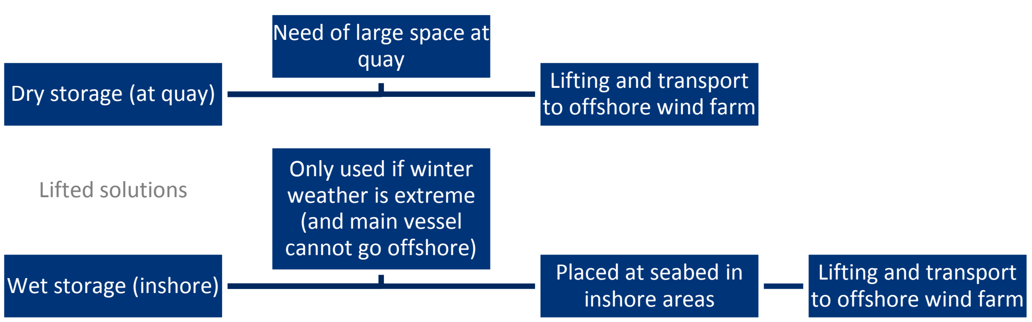
The issue of year-round fabrication

- Considering a ~500MW offshore wind farm and 6MW turbines, about 80 foundations would need to be manufactured, requiring a year-round fabrication schedule able to deliver more than one foundation per week.
- However, continued or serial installation during winter times may not be feasible, leading to an accumulation (and required storage) of foundations that are built during the winter time and need to be installed during summer time.

Floated solutions – Potential storage processes



Lifted solutions – Potential storage processes



3.4. Transportation & Installation - Process

Floated GBS foundations

Tow to site
- Use of conventional tugs (1 or 2 main tugs 60t~100t Bullard Pull and 1 or 2 auxiliary tugs ~50t BP).
- [High variation of Bullard pull required between designers].

[1]

Positioning
- Controlled positioning using 3 or 4 tugs (the same used during installation), potentially with Dynamic Positioning.
- Some F-IT require assembly of auxiliary buoyancy equipment.

Foundation lowering
- Lowering using controlled water ballasting.
- Potential under-base suction need if skirts are used [in certain soils].

Releasing for foundation
- Un-lashing of the connection lines between foundation and tugboats.
- Some F-IT solutions require removal of auxiliary equipment.

[2]

Sand Ballasting & Scour protection
- Ballasting with a slurry of sand to increase self weigh of the system.
- In some cases, high density material may be used.
- Placement of scour protection if needed.

Vessel Needs
- F-IT: 2 tugs + Auxiliary buoyancy equipment + anchor handler(s).
- F-FO: 3/4 tugs + anchor handlers.
- + 1 Control vessel. [*]

Lifted GBS foundations

Tow to site
- Use of transport barge/vessel (Vessel is a faster option).
- If barge is not self propelled, need of large tugboats (~200t Bullard pull).

[1]

Positioning
- Dynamic Positioning (DP) system.
- If the barge does not have DP, then use of mooring lines or tugboats is required, potentially with Dynamic Positioning systems.

Foundation lowering
- Use of crane on installation vessel/barge.
- Ballasting of installation barge to reach final depth.

Releasing for foundation
- Un-lashing of the connection link between crane/barge and foundation.

[2]

Sand Ballasting & Scour protection
- Ballasting with a slurry of sand or sand bags to increase self weigh of the system.
- Use of ballasting material / scour protection around the foundations.

Vessel Needs
- Main installation vessel (or)
- Barge with some tugs.
- + 1 Control vessel [if required].

[1] Sea Bed Preparation [Pre-Installation] vessel needs
- Dredger (mainly suction dredger proposed by designers)
- Fall pipe vessel (for gravel bed)
- Levelling tool

[2] Scour Protection [Post-Installation] vessel needs
- Fall pipe vessel
- Rock dumper

[*] Control vessel may not be required if the anchor handler plays its role

3.4. Transportation & Installation - Limitations

	Met-ocean Conditions		Limiting Factor			
	Transportation	Installation	Transportation	Installation	Range (Transit distance)	Weather Window [*]
F-IT	**2.5 m Hs** (Equating to ~ Beaufort scale 5 with moderate seas and sea states 3-4)	**2.5 m Hs**	20 knots wind (~10m/s) maximum for towing	*No information provided*	Providing a suitable weather window exists – in theory there is an unlimited range *(questionable, should be similar to F-FO)*	24h+ 8h for ballast
F-FO	**(3.0 m Hs)** Unrestricted conditions for towing, although it would be unlikely for a tow to take place in Beaufort Scales >6 (conditions with Hs >4 m and wind > 12 m/s) [Some designs limited to Hs < 2m]	Average limits at **1.5m Hs** and a **max.** limits at **2.5m Hs**, although larger tugs would provide greater stability if they are the limiting factor. Wave period could also be limiting.	Holding capacity of tugs in storm.	For all, ensuring a controlled GBS positioning, ballasting operation and stable ground contact is made. Also, the tugs itself can be a limiting factor.	100 nautical miles between safe havens. The range is theoretically unlimited if safe havens do exist. Economically this range would not exceed 150-300 nautical miles (depending on designer's view). *The cost of increased transits are lower for towed concepts*	In the region of 24h Some claim 12 hours
L-IT	**2.5 m Hs** (Equating to ~ Beaufort scale 5 with moderate seas and sea states 3-4)	Linked to the installation barge/vessel requirements (between 1.5m and 2.5m Hs)	Depending on solution: Transport by barge: Holding capacity of tugs in storm Transport by vessel: Vessel capabilities + Cost of the vessel/barge	Ballasting process – time constraints for touch down and disconnection of TIB / auxiliary vessel	Depending on solution: Transport by barge: **50 nautical miles** one barge Transport by vessel: up to **300 nautical miles** (due to increased transit speed)	2 days for barges 0.5-1 day for vessels
L-FO	**1.0 m - 2.5 m Hs** (limited to installation vessel / barge requirements)	**1.0 m - 2.0 m Hs** (limited to installation vessel / barge requirements)	Similar to L-IT	Similar to L-IT	Depending on solution, similar to L-IT	In the region of 24h

[*] Weather windows durations are only indicative and do not refer to any particular distance from shore

3.6. Operations & Maintenance

Common Trends

Less O&M requirement than steel structures:

- Very little maintenance demands.
  - Mainly linked to secondary steel (similar to steel structures demands).
- Regular crew transfer or survey vessels can be used to carry out maintenance checks.
  - Concrete has a longer marine lifetime than steel and specific transfers to the GBS will not be required - maintenance can be carried out during the WTG and turbine maintenance procedures (no more than annually for a visual check).

Main differences between designs

Type of monitoring needs vary depending on the designer:

- Some say that an annual visual check of post tensioning tendons and external concrete surface condition is sufficient.
- Others specify that only average maintenance checks every 2- 5 years for a 25-30 year operational lifetime of the turbine are required.
- Finally others state that concrete does not need inspection, but the monitoring should be focused on the wind turbine and secondary steel elements of the structure, and of scour and seabed morphology.

Foundation typology particularities

F-IT

No more than those already mentioned in the common trends.

F-FO

- There is potential for physical damage from vessel impact during turbine maintenance activities only on structures with steel shafts.
  - In concrete shafts the impact could affect the concrete cover and expose reinforcement to corrosion.
- Asset integrity for structures with steel shafts is similar to the monopile ones.

L-IT

No more than those already mentioned in the common trends.

L-FO

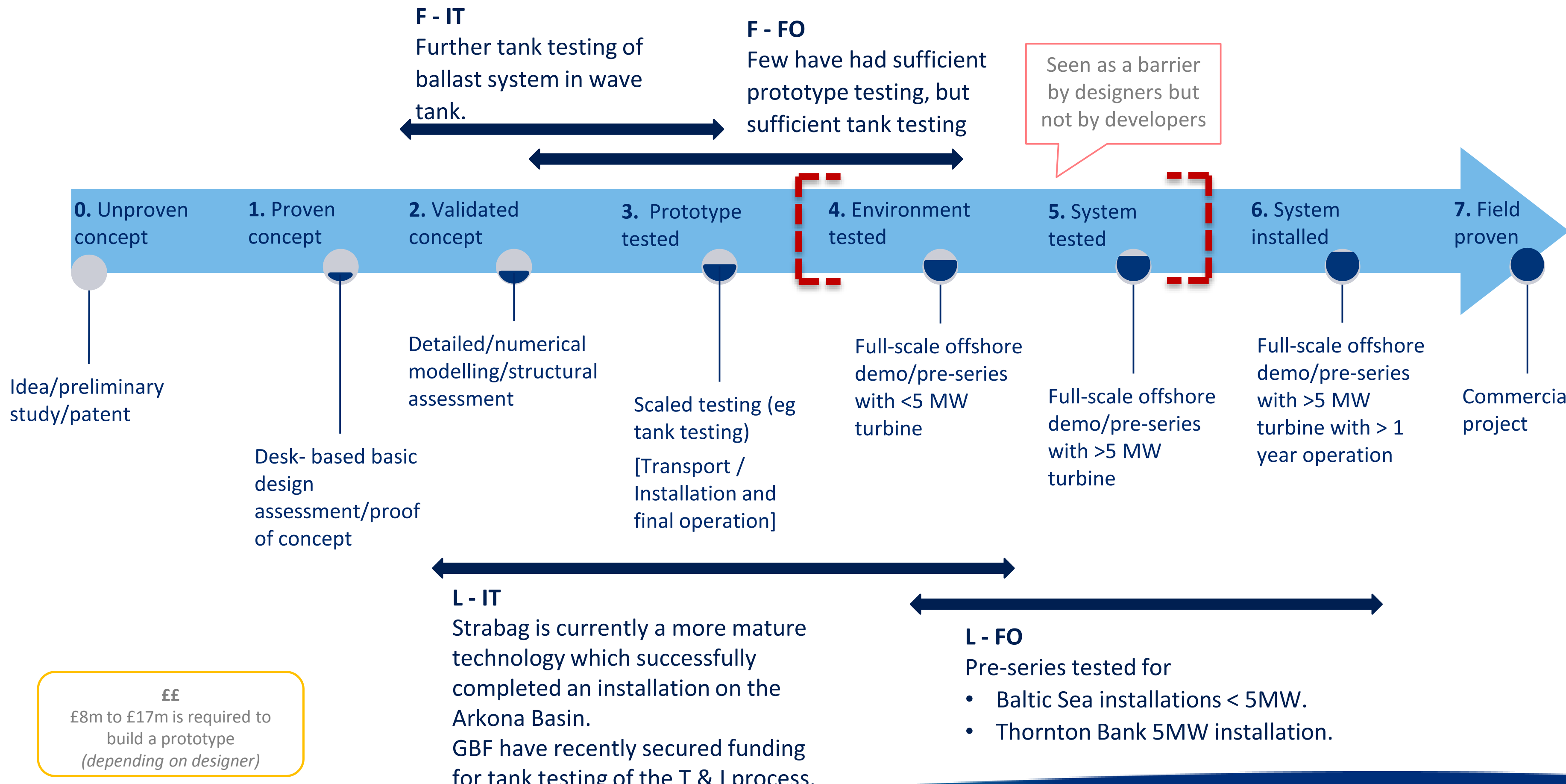
No more than those already mentioned in the common trends.

3.7. Technology Readiness Levels

Developers should ensure that lenders engineers are fully appraised on offshore concrete platform experience for the O & G and OWF industry.

A consensus amongst GBS designers is that Environment Testing (TRL 4) is a barrier to development and therefore the use of the conventional TRL sequence listed below impacts interest from developers and increases the risk of investment.

- The most common question raised regarding technology readiness relates to proving the mass logistics of transportation and installation.
- This can only be tested in full-scale commercial windfarms and hence designers should be able to leapfrog Environment Testing.



3.8. Optimal site conditions for GBS installations

Bathymetry and Geotechnical Conditions

Water depths greater than 30m and up to 60m

(considering current technology)

[35m+ according to developers]

Soil with a significantly **high shear strength** to resist the mass of the foundation. A larger base would be required in softer soils to distribute vertical loading

Soils that are problematic for pile driving –

Stiff clay /

Shallow bedrock

[but also applicable to other soil conditions]

Consolidated sediments in order to minimise seabed preparation. Similarly a flatter seabed would preclude the need to carry out extensive excavation of material (for those concepts that require excavation)

The North Sea is particularly suited to gravity base structures, where the cost competitiveness of monopiles and jacket foundations are being pushed to their limits. Strong currents associated with the Irish Sea and North Sea deeper waters with varying degrees of soil anisotropy could present complex environments for GBS installation. Site investigations and the increasing use of finite element modelling to fully comprehend the potential dynamic loading effects on foundations will all assist in increasing the confidence and ease of GBS installations.

General observations regarding geotechnical conditions

- The effect of vertical and cyclic loading on potential degradation and ground movement from storm loading is the main focus when assessing the feasibility of using a GBS as a foundation.
  - CAU (Consolidated anisotropic, sheared, un-drained shear strength) testing is used primarily to analyse the potential horizontal sliding capacity of GBSs at shallow depths.
  - Computational checks regarding the bearing capacity of the subsoil should be proven through ultimate limit state (ULS) analysis and the durability and strength of the system must be checked for a range of loads against the serviceability limit state (SLS).

Number of foundations

- A minimum number of foundations are required to break-even the investment on the fabrication yard.
  - Designer’s view: between 40 units and 100 units. 40 units is feasible (to recover port infrastructure investment) however 100 is preferred. Large number of units (100+) are required for Lifted solutions with bespoke vessels.
  - Developer’s view: 100 units +, but some solutions may be feasible with 60 units.
- The larger the WTG, the more cost-effective GBS are compared in to steel structures.

3.9. Cost competitiveness

Floated

- No use of heavy lift vessels [*]
- Same installation method independently of foundation size
- Simple decommissioning

Integrated Transport

- Few number of operations need to happen offshore
- No interface risks
- Potential earlier revenue

Foundation Only

- De-coupling of WTG installation of foundation installation (investment more spread during construction)

Lifted

- Faster installation (higher weather windows)
- No need of Heavy lifting cranes onshore (already on the vessel in some designs)

Centre:

- Construction based on mass production techniques (which improves with economies of scale)
- No requirement for skilled labour
- Concepts scales with increasing depth and larger WTGs
- Minor O&M activities

Floated / Integrated Transport:

- No need for specialist vessels

Floated / Foundation Only:

- No need for foundation installation vessels

Lifted / Integrated Transport:

- No need for separate turbine installation vessels
- More and potentially longer weather windows for transport and installation (depending on vessel used)

Lifted / Foundation Only:

- Potential fabrication in barges

[*] Reduced risk/cost of waiting for weather and reduced risk for vessel availability

Content

4.1. Design and Site conditions – General Challenges

✓ Existing Challenge // × Perceived Challenge

General Challenge	D	C	Proposed Mitigation
Novelty of the solution [See also additional note next page]. ▪ Some designers consider current steel foundation to be categorised as "novel" as well.	×	✓	▪ Influence / Educate Client's procurement processes. ▪ Collaboration with fit-for-purpose risk allocation (create relationship based on trust between designers, EPCI and client).
Lack of **confidence in concrete** as a solution for offshore wind due to fabrication times.	×	✓	▪ Designers believe that the proven ability of GBS in the O&G industry / bridge engineering should be drawn upon (in terms of fabrication rates) to increase industry confidence.
Verticality during installation need to be achieved. ▪ Some designers consider that this is not an issue at all.	×	✓	▪ Use of accurate dredging techniques or levelling solutions. ▪ Use of special equipment/wedges to achieve verticality at tower bottom.
Applicability in variable **soil conditions.** ▪ Thick layers (>2-3m) of unconsolidated and soft surface sediment is unfavourable for placing a concrete gravity foundation		✓	▪ Design fit-for-purpose soil-structure interaction. › Dredging the loose surface sediment until a consolidated layer or bedrock is reached. Precise soil preparation or execution of a gravel layer on top will provide suitable conditions for firm and stable contact between the base and ground. › Other solutions will use larger skirts to penetrate through the overlying soft sediment to provide extra support without the need for dredging.
Need of **sea bed preparation.**		✓	▪ Optimise sea bed preparation. › Precise soil preparation, use of gravel bed & scour protection req. › Use of skirts (?) [variable answers depending on designers].
Quality of **geotechnical information.**	✓		▪ Clients should undertake quality Soil Investigation in every location.
WTG **tower** to GBS **connection** (*only for immature designs*).	✓		▪ Further development of the design in collaboration with OEMs.
Need for a full-scale **demonstration** of the marine operations and for some structural elements.	×	✓	▪ Combine forces between designer to prove that technology works, involving support from clients.
Cost Effectiveness.		✓	▪ Performing comparison studies (piled vs GBS) under the same conditions, including details on the hypotheses and methods used.

D Designer // C Client-Developer

4.1. Design and Site conditions – Concept Specific Challenges

✓ Existing Challenge // × Perceived Challenge

	General Challenge	D	C	Proposed Mitigation
F-IT	Requirement of large volumes of grout to ensure contact between the base and the sea bed.	✓		▪ Potential use of OPC grout.
F-IT	High concrete volume only used for the float-out operation.		✓	▪ The additional concrete my compensate the use of HL vessels.
F-FO	High concrete volume only used for the float-out operation.		✓	▪ The additional concrete may compensate the use of HL vessels ▪ Detailed comparison between concrete designs.
F-FO	Buoyancy leads to high areas exposed to wave loading (mainly in soft clay sediments, where large bases may be needed).	✓	✓	▪ High dead weight (+ ballast), dredging and/or use of skirts may compensate the wave induced horizontal sliding.
L-IT	Lifting points during transport and installation.			▪ Careful design should be considered.
L-IT	The overturning moment of the turbine and foundation would cause soft clays to extrude beneath the foundation.			▪ Design of base dimension should be wide enough to avoid this phenomena happening.
L-FO	Lifting points (not as critical as in L-IT).			▪ Careful design should be considered.
L-FO	The overturning moment of the turbine and foundation would cause soft clays to extrude beneath the foundation.			

Additional comments from the designer community	Proposed Mitigation
Novelty of the solution (Currently there are many GBS deployed in O&G) ▪ For steel structures, there is a big difference between O&G and offshore wind, because the WTG loads are primary for the design. For GBS, the wave loads are primary, and those are the same in O&G as in offshore wind.	▪ Disseminate information about old and recent GBS projects, such as Kårehamn and the Fécamp demonstration.
Applicability in variable **soil conditions** ▪ Applicability of GBS is similar to those of piled concepts: › Piled concepts struggle with pile penetration in certain circumstances. › GBS struggle with some, particularly thick, soft top layers.	▪ Improve industry dissemination with regards to the applicability of GBS in offshore wind site conditions.

D Designer // C Client-Developer

4.2. Yard and Load-out operation – General Challenges

✓ Existing Challenge // ✗ Perceived Challenge

General Challenge	D	C	Proposed Mitigation
Early engagement with developers [*] ▪ Procurement teams from the developers should be aware of time scales needed to set up a GBS facility. ▪ Current project timelines induced by development auction processes may be challenging to set up GBS fabrication yards.	✓		Potential engagement with other industries (e.g. O&G): ▪ Early engagement with port authorities to initiate yard strengthening and/or dredging before securing any project. ▪ Seek for early collaboration with developers. ▪ Engagement of public entities or secure government support.
Find suitable construction and assembly yards, which should: ▪ Be as close as possible to Offshore Wind Farms (Except for L-IT with transport and installation using a purpose built vessel). ▪ Have enough space with high bearing capacity to set up a facility. ▪ Have enough draft and area for marine operations, including wet storage space (if required). ▪ Have suitable load-out systems or allow construction of them › Suitable load-out systems are not required in the harbour if the installation vessel is equipped with a suitable loading system.	✓ & ✗	✓	Areas that can be easily prepared to host a GBS yard: ▪ Design and planning of load-out systems that do not require high investments, re-utilisation of existing infrastructure or leverage of new systems with other sectors (e.g. naval). ▪ Commitment from developers when defining supply chain plans to support a given geography / local content.
Achieve required production rates. ▪ No production line developed and already tested. ▪ Lack of confidence that construction yards proposed are achievable (except when experienced construction companies back a concept).		✓	▪ Extensive planning and logistic exercises. ▪ Early engagement with supply chain including the development of innovative construction techniques and materials. ▪ Removal of key elements from the critical path by use of pre-fabrication etc. ▪ Draw on experience from large-scale mass production of concrete in other fields such as bridge elements.
Link production to weather windows. (if project timescale require faster installations rates and installation system is not robust enough [i.e. cannot be utilised in rough weather])	✗	✓	Better planning and yard sizing to ensure that installation can happen with available weather windows (e.g. summer).
Limitations of auxiliary equipment onshore (e.g. cranes) considering the large weight of GBSs.		✓	Develop a detailed market assessment of existing heavy lifting solutions (e.g. SPMTs, cranes…).

[*] Only applicable to those concepts where the facility setup is not in the critical path.

D Designer // C Client-Developer

4.2. Yard and Load-out operation – Concept Specific Challenges

✓ Existing Challenge // × Perceived Challenge

	General Challenge	D	C	Proposed Mitigation
F-IT	Assembly of tower and TWG on-shore (high Hub Height [HH]).	✓	✓	▪ Development of methods that allow WTG installation in high HH.
F-IT	Development of robust load-out systems (see L-IT).	✓		
F-FO	*No more than those already mentioned in the general section.*			
L-IT	Sufficient navigational width and draft for Installation vessels.		✓	▪ Modification of harbours at additional cost.
L-IT	Load-out of foundation together with pre-installed tower and turbine.	✓	✓	▪ Collaboration between designer and WTG supplier. ▪ Assessment of cost-effective solutions or consideration of installing tower and WTG once foundation is on the vessel/barge.
L-FO	*No more than those already mentioned in the general section.*			

D Designer // C Client-Developer

4.3. Transport and Installation – General Challenges

✓ Existing Challenge // × Perceived Challenge

General Challenge	D	C	Proposed Mitigation
Weather Windows: ▪ Planning and operations of transport and installation are constrained by the available weather windows. There needs to be an adequate cycle time for the transport of GBS to sea. ▪ Logistical difficulties – Simultaneous Operations & planning voyage routes [+ potentially, but very unlikely, lack of tug availability].	✓	✓	Weather Windows: ▪ Ensure more GBSs are ready for transport than plan requires to increase flexibility of weather windows. ▪ Assess optimum size of the foundation storage. ▪ Thorough analysis assessing transportation/installation and construction site limitations to establish a feasible and economical voyage route.
Smooth Ballasting Operations during installation. ▪ Ensuring safe and stable lowering/ballasting operations (including touch down), where pumping system should be reliable. ▪ Installation is limited by lower sea stated than transport.	✓	✓	Specific studies: ▪ Wave tank testing to assess the optimal configuration of tugs and ballasting method. ▪ Optimise logistics so that all floating equipment is used efficiently utilising weather windows, considering bottlenecks. ▪ Disseminate information about old and recent GBS projects experiences, such as Kårehamn and the Fécamp demonstration.
Sufficient ground contact and stability of GBS on sea bed – particularly in assuring skirt penetration is adequate.		✓	Geotechnical site surveys and thorough laboratory testing to ascertain the variability of soil across the site.

D Designer // C Client-Developer

4.3. Transport and Installation – Concept Specific Challenges

✓ Existing Challenge // × Perceived Challenge

	General Challenge	D	C	Proposed Mitigation
F-IT	Dynamic behaviour of turbine and foundation during transportation (+ Challenges of F-FO).		✓	Parametric studies to demonstrate real suitability of foundation to towing, plus validation through tank testing.
F-IT	Purchase of turbine and foundations simultaneously.	✓	✓	Align procurement teams and assess project cash needs carefully.
F-IT	Behaviour and stability of GBS in the water.	×	✓	Same as F-FO, but including wind effects due to Integrated Trans.
F-IT	Sinking of the foundation during transport.	×	✓	Testing of ballast system in-shore. Strong QA.
F-FO	Slower transport than some L-FO that could require longer weather windows (despite having high survival conditions, limited by tugs).	✓	✓	Flexible logistical planning supplemented by good weather forecasts + Start towing in expectation of favourable weather conditions during installation (critical stage), and return to port as contingency.
F-FO	Behaviour and stability of GBS structure during towing and installation in variable conditions. ▪ Limitation could be restrictive.	×	✓	Parametric study to demonstrate the suitability of the substructure design + tank testing using a scale model to assess: ▪ Drag forces on the GBS at various tow speeds in calm water. ▪ Motion behaviour of the GBS structure in different sea conditions covering both transport and installation. ▪ Influence of the temporary water ballast on the motion behaviour of the GBS (if applicable).
F-FO	Sinking of the foundation during transport.	×	✓	Testing of ballast system in-shore. Strong QA.
L-IT	Single point of failure (1 installation vessel/barge).		✓	Consider procurement of 2 or 3 barges on large projects.
L-IT	Expensive upfront investment (even for low # of units).	✓	✓	Depreciation with other sectors (O&G, bridges, …).
L-IT	Control of the disconnection of the GBS from the vessel.		✓	Further design refinement of ballasting mechanism, installation of fenders and using stricter met-ocean constraints.
L-IT	Purchase of turbine and foundation simultaneously.		✓	*(see F-IT)*
L-FO	Single point of failure (1 installation vessel/barge).		✓	Consider procurement of 2 or 3 vessel/barges on large projects.
L-FO	Expensive upfront investment (even for low # of units).	✓	✓	Depreciation with other sectors (O&G, bridges, …).
L-FO	Control of the disconnection of the GBS from the vessel.		✓	Design refinement of ballasting mechanism, less critical than L-IT.

D Designer // C Client-Developer

4.4. Market Barriers

✓ Existing Challenge // × Perceived Challenge

	Barrier	Description	D	C
Concept	Knowledge	Technical teams from clients do not fully understand or are comfortable with concrete structures.	✓	
	Number of designs developed	The presence of different design concepts and no consensus on which is the best method presents little confidence to developers on which concept to invest in. Better convergence of opinion on material, strength selection, usage of pre-stressing and whether dredging or other sea bed preparation is necessary.	✓	✓
	Previous installations	There is considerable perceived risk, particularly following Thornton Bank and the lack of commitment to the GBS foundation. Between other factors, the time for installations did not remain on track.	✓	
Fabrication	Number of foundations	Increase in WTG size and decrease in capacity of offshore wind farms that receive funding has meant that the total number of foundations that need to be installed has decreased significantly, hence it is difficult to justify the investment in a new yard or the competitiveness of concrete solutions for a single project.		✓
	Supply Chain	Non-exist supply chain and a long time to mobilise one. Previous installations have favoured monopile supply chain, allowing it to mature.	×	✓
Risk	Bankability	*[For far offshore and deeper water]* Risk aversion by developers and banks/lender engineers (staying with familiar technologies) due to long term uncertainty in industry, leads to consideration of known solutions.	✓	✓
	Scale	Lack of confidence that large scale marine operations (number of foundations) can be carried out.		✓
Costs / Financing	CAPEX	Perception of a very high upfront cost to develop a GBS production facility or transport & installation equipment [depending on the approach selected] (+ large disparity between designers, leading to industry confusion).	✓ ×	✓
	EPCI approach	Developers would benefit from instigating a design draw up and procuring a build cost of the structure from the market rather than going directly to consortia to use profit-driven designs.		✓
	Demo.	Cost of a demonstration may be too high.	✓	✓
Policy	Uncertainty	No clear policy of support for offshore wind beyond 2020 in some countries, and this reduces appetite of developers to make the level of investment required to construct an edge-of-shore facility.	✓	✓
	Auction processes	Timelines linked to auction process, limit the time available prior to FID, which tends to lead to adopt a “design then build” approach, favouring generic technologies such as monopiles or jackets..	✓	✓

D Designer // C Client-Developer

4.5. Market view of GBS as an alternative to monopiles and/or jackets

Quotes from industry stakeholders [*]:

Monopiles / Jackets

"The areas of interest in the North Sea currently benefit from consolidated glacial derived thickly bedded sediments. This are optimal for pile driving."

"Monopiles are a simple and known entity." (but "XL Monopiles are not a proven solution")

"Finding an alternative solution where sufficient experience has not been accumulated is unnecessary when a known solution already exists."

"The steel industry has enhanced its monopile solution such that is effective in deeper waters."

"Political importance in certain markets of steel industry."

GBSs

"The are advantages of GBS in shallow rock sea beds such as those West of Scotland, Ireland and France."

"Whilst GBS designs are likely comparable in suitability in certain areas, a risk assessment would clearly point in favour of using a known foundation such as monopile or jackets instead as these are known entities."

"Lack of long term market confidence prompting risk aversion."

"Lack of full scale demonstration, large investments for installation and fabrication."

"Schedule risk when no existing supply chain."

"Too much focus on bespoke float out concepts."

Designer's views / Developer's views

[*] These quotes do not reflect the views from all the designers / developers.
The section simply aims to show some of the current beliefs/thoughts from the industry.

Content

5.1. STRENGTHS (Internal positive factors)

- GBSs are particularly **cost effective** in **deeper waters** (beyond 30m) and larger WTGs.
- **Longevity of a GBS** is high due to concrete being an extremely durable material in the marine environment:
  - Reduced maintenance is required and solutions with low sensitivity to fatigue.
  - Exploit the fact that OpEx cost could be significantly reduced, lowering the overall LCOE.
  - There is potential to extend lifespan of GBS for repowering scenarios (lasting 100 years) without major investments.
- GBS are **suitable in environments** which are otherwise **unfavourable for piled foundations or bucket foundations** (shallow rock) as well as being suitable in other soils (sands, clays, …).
- **Reduced price volatility** and therefore risk of price escalation, given the reliance on concrete over steel commodity.
  - Also concrete is considered to be less costly than steel.
- Potential use of a **supply chain** without bottlenecks and possibility of high **local content** (and implementation practically anywhere).
- **No need of transition pieces** (avoiding grouted connections / hammering in flanges issues).
- Tolerances are not as strict as steel fabrication, enabling faster fabrication and mass production without skilled labour.
- Very **good environmental credentials** – in particular; no piling noise during installation and low carbon footprint across the supply chain.
- GBSs could be **easily removed** during wind farm decommissioning (particularly floated solutions).

Foundation typology particularities

F-IT
- Commissioning onshore reduces vessel numbers offshore reducing costs and HSE risk during offshore operations.
- No need of separated WTG installation vessel and low interface risk.

F-FO
- No specialised installation vessels required (HLV or JUV).
- Possibility to have parallel installation (by mobilising cheap tugs).
- Increased weather windows: some concepts show installation weather windows of 12 hours (max 24 hours) in waves up to 3m Hs.

L-IT
- Smaller base diameter for lifted design.
- Commissioning onshore reduces vessel numbers offshore reducing costs and HSE risk during offshore operations.
- More weather windows due to Transp. & Inst. vessel capabilities.
- No need of separated WTG installation vessel and low interface risk.

L-FO
- Long track record in the Baltic sea (shallow waters).
- Smaller base diameter for lifted design.
- (if large vessels are used) potential larger weather windows.

5.2. WEAKNESSES (Internal negative factors)

- Very **high investment** during initial phase (mainly for manufacturing yard) [Not applicable to all solutions].
  - Substantial upfront investment in order to achieve cost-effective economies of scale production is against the current economic situation.
  - Smaller projects will not realise the true capital cost benefits and may be comparably costly. This can only realistically be mitigated by providing a low risk, long-term pipeline of projects for GBS.
  - For cost effective serial production, a sufficient **quayside** (expensive) **facility needs to be constructed**.
- **Unaligned approaches** from expert engineers – disparity in design concepts creates a higher uncertainties for developers.
- Concepts are still considered **low maturity TRLs** as there are a few large scale deployment examples, particularly using floated concepts which designers are tending towards.
  - Lack of **size demonstration** projects. Thornton Bank is seen as a barrier to development rather than a positive milestone.
- The **variability of seabed preparation methods** depending on geology and designer increase uncertainties to end clients.
  - Inconsistency between designers on the requirements and needs linked to the seabed preparation.
  - Lack of understanding of which are the potential issues if verticality is not achieved.
- Potential constraints when assessing winter **storage** if installation cannot happen year-round.
  - Not applicable if a robust installation solution and a sufficient storage has been planned.

Foundation typology particularities

F-IT

- Concept transportation/installation in harsh environments still not proven – no past experience of floated devices installed far offshore.
- Large dimensions to ensure floatability of the entire system.
- Requirement of an auxiliary system during lowering/installation.

F-FO

- Concept transportation/installation in harsh environments still not proven (or sufficiently spread in the offshore wind industry) – no past experience of floated devices installed far offshore.
- The hybrid solutions vary, however some designs still need to establish a low-risk, well proven, durable connection between steel elements and concrete elements.

L-IT

- Initial additional investment for special purpose vessels.
  - Difficult to justify in small-scale project and potentially limiting in large scale projects (where more than 1 unit would be beneficial).
- Need of large draft for some special barges (>15m draft during transport).

L-FO

- (if crane barges are used, which has been common practice) potential smaller weather windows.

5.3. OPPORTUNITIES (External positive factors)

- **Collaboration** (e.g. Concrete Centre's Interest Group for Gravity Foundations) will help to increase awareness of GBSs and cope with common challenges. This could help to increase industry knowledge in:
  - Soil – structure interaction (seabed preparation, need of gravel beds, need of skirts, …).
  - Marine operations (e.g. tugging operations, ballasting operations,…).
  - Time frames / common project schedules required in planning and pre-FID stages, as well as from FID to actual construction.
- **Successful installation** of Seatower's floated concept off the coast of France in February and the met mast installed in Moray Firth and Inch Cape should increase confidence in the industry, there is less risk associated with these designs than previously thought.
  - O&G, bridge and tunnelling engineering success experience as in harsh marine environments should be drawn upon to increase industry confidence.
- Strong **fabrication track record** port infrastructures (caissons built on a production-line basis) and bridge building engineering.
  - Socioeconomic benefits and opportunities for local employment are sizeable.
- A number of **suitable size dry docks** and **yards** with sizeable hinterland have been identified in the UK and Scotland. Early engagement between offshore wind developers and port authorities could facilitate the use of GBS as offshore wind foundations.
- Potential wide **applicability** of GBSs in different soil conditions (disagreement with developers).
- New generation GBS solutions are early in their life cycle, so the **potential** to find big **cost savings** and **optimisations** is much larger than for existing solutions.

Foundation typology particularities

F-IT

- Integrated designs should encourage collaboration across the supply chain between turbine manufacturers, foundation designers, contractors and developer.
- Potential to follow "plug and play approach", pre-laying the electrical/cable infrastructure and allowing direct generation after WTG installation.

F-FO

- Independence of O&G market dictating vessel prices (also F-IT).
- WTG investment not required early in the project (better distribution of cash needs).

L-IT

- Potential earlier revenue (see F-IT).
- Potential depreciation of the large investment in marine equipment (transport and installation vessel/barge) considering other sectors like O&G decommissioning projects.

L-FO

- WTG investment not required early in the project (better distribution of cash needs).

5.4. THREATS (External negative factors)

- General consideration from the developer and investor community that GBS are "**novel**" concepts without a ready supply chain Unpredictable **pipeline** from the UK Government (or other European governments).
  - Currently, there is no foreseeable support beyond 2020, therefore developers are unlikely to invest in higher risk, innovative solutions.
- **Procurement** measures currently in place:
  - Turnkey / EPCI contracts obligates contractors to commit to firm price commitments in relatively short periods of time. This promotes the use of foundations based on vessel availability rather than supporting innovative cost effective solutions.
  - The "design then build" approach (due to budgetary controls prior to the FID) further discourages a collaborative relationship with contractors.
- It is estimated that an ideal **implementation scenario** would consist of an order of between 80 – 100 GBSs if a large upfront investment is required [Not applicable to all solutions, since some claim ~50 GBSs]. (It is considered that collaboration between developers is unlikely).
  - The time to develop this may not fit with the pipeline of work for Round 3 sites or the UK CfD allocations, or for other European auction processes.
- Given the North Sea harsh environment and potential for weather window instability, there is a **lack of confidence** in the operability of GBS installations with sufficiently low risk and high volume of annual deployment.
- The **fast-rate development of XL monopiles** for suitability in deeper waters, and it's existing supply chain comparing to the GBS one.
- **Port constraints** – bearing capacity for material loads, access systems for delivery of materials (steel works and concrete)…, needs to be sufficient. Also, transportation of foundation requires significant **navigational draft** (ideally upwards of 15m to be cost competitive).

Foundation typology particularities

F-IT

- Perhaps considered the most innovative and least mature design – the greatest threat is that it is too innovative for consideration on a large scale deployment. More demonstrations are required to prove the transport and installation capability of the foundation
- Dimensions may be too big for find suitable port facilities

F-FO

- Potential bathymetry limitations in towing routes force longer transport times and require larger weather windows.
- *This solution is more flexible against volume of annual deployment, since more tugs can be used if needed without causing bottlenecks*.

L-IT

- Higher costs compared to floated designs as a result of TIB usage instead of tugs (if project-by-project approach is considered and not a long-term view)
- The availability of TIBs are limited and may require procurement of bespoke TIB vessel for a project

L-FO

- Industry believes that the experience in the 6 demos of Thornton Bank was not positive

5.5. SWOT ANALYSIS - Summary

Offshore Wind GBS SWOT

Strengths

- GBSs are particularly cost effective in deeper waters (beyond 30m) and larger WTGs.
- Low O&M requirements and easy decommissioning.
- Suitability in environments where piled foundation are not suitable. Good environmental credentials – no piling noise, low carbon footprint.
- Potential use of a supply chain without bottlenecks and possibility of high local content.
- Reduced price volatility.
- No need for transition pieces.

Weaknesses

- High investment during initial phase (mainly for manufacturing yard).
- Un-aligned approaches which decreases developer confidence and leads to risk aversion.
- Transport and installation methods are still not considered fully proven for deeper waters – particularly for floated designs.
- Potential constraints for storage (if not properly planned).

Opportunities

- Collaboration between designers to overcome uncertainties.
- Leverage in previous success stories.
    - Concrete in marine environments.
    - Fabrication of large number of units.
- Potential applicability in different soil conditions.
- Potential to find big cost savings and optimisations is much larger than for existing solutions.

Threats

- Considered a “novel” foundation.
- Lack of knowledge among certain decision-making staff.
- Unpredictable pipeline and required number of foundation to depreciate the yard/vessel.
- Existing procurement practices and timelines.
- Existing port constraints.

Content

6.1. Main Conclusions

The Market

There are certain hurdles that need to be addressed before GBSs can be widely implemented in the offshore wind industry

Current lack of market clarity is considered a large barrier to enable implementation of GBSs due to the investments required in the fabrication yard and/or special vessels [for some GBS concepts].	Current auction processes do not allow sufficient time to plan or prepare the required infrastructure considering existing approaches.

The opportunities

How to turn the table

GBSs should document an attractive cost reduction comparing to current foundation typologies in order to gather interest form developers.	There are many perceived or existing challenges that can be easily addressed through coordination and joint effort from the designers (see next section).

The success

GBS appear to have high potential in becoming an alternative that is considered in parallel to monopiles / jackets, once the opportunities are addressed

GBS designers should focus to optimise the areas that address the market barriers (e.g. fabrication timelines) to enable the implementation.	Increased market understanding and confidence could enable GBSs to be considered by developers in earlier stages.

6.2. Recommendations

GBS Designers

- Collaborate to provide responses to the key discrepancies (e.g. use of skirts).
- Focus on optimised fabrication to move away from capital intensive yard setups and be able to fit into current project development schedules.
- Increase confidence in transport and installation processes and fabrication rates.
- Consider taking ownership of certain risks, like risks that are understood by the designer but not so much by the clients (e.g. potential waiting on weather).
- Seek wider EU support as an industry to jointly push GBSs.

Offshore Wind Developers

- Run detailed (FEED) comparison studies between steel and concrete foundations considering balance of plant, transport, installation and lifetime operation.
- Consider GBSs when developing supply chain maps given its benefit to local areas.
- Request designers to move from EPCI model to separate design and build contracts - offer license fees to cover development costs.
- Assess potential collaboration with other developers to justify use of GBSs.

Governments and public bodies

- Map potential locations where GBSs could be built and consider potential support for implementation in collaboration with designers.
- Support supply chain to be ready for GBSs “just in case” rather “just in time”.
- Assess whether the geologies and environmental conditions were arguably best suited to GBS foundations.
- Consider potential advantages of Repowering to assess GBSs potential.
- Undertake detailed socioeconomic benefits.

Need for :

Coordination across the different work-streams

+

Leverage more from other sectors experience (e.g. O&G, Bridges…)

+

Share benefits if a new cost-effective solution is implemented (i.e. all parties should see benefits)

6.3. The need for a demonstration - Proof of concept

General view

Need for a large-scale project developed on time and within budget to increase belief in GBS as an alternative foundation for offshore wind farms:

- **Design** and **operation** do not need proof of concept (40 years + of concrete history in marine environments can be drawn upon).
- **Transport** and **installation** do require proof of concept [variable views between designers in this aspect].

Floated concepts

2 Met-Mast scale installations have happened over the last year:

- Inch Cape and Moray Firth Met Masts.
- Fécamp Met Mast: Seatower demo.

In addition, designers have undertaken thorough design desk-based and tank testing studies, including HAZIDs and HAZOPs involving experts from design, construction, transportation, installation and marine warranty in many cases, as well as third party consultancies or certification bodies.

However, some clients feel that there is a need to demonstrate (from the client's perspective) that full-scale marine operations can be undertaken in a sequential way and in harsh met-ocean conditions (not in calm seas, when the Met Mast were installed).

Potential collaborative project with designers, EPCI contractors, developers and government could help unblock the technology:

- Trial installation campaign of one floating GBS at > 5-10 locations far offshore to understand the real weather limitations during transit and installation.
- Full scale demonstration of the fabrication processes.
- Need to deliver on budget and on time.

Lifted Concepts

Demonstration of L-IT solutions are more complicated because of the need for the installation vessel even for a small number of units.

However, tank testing of the vessel/barge should provide enough confidence to the designer to accept potential weather risks.

6.4. Areas of potential collaboration between designers

Designers should not only collaborate for lobbying purposes but also collectively **address key common challenges** and **educate** the industry about the advantages of concrete GBSs and the mitigation of potential issues.

The main areas that GBS designers should address include:

Design

- Rationale for using simple rebars or pre-stressing steel, defining Pros and Cons.
- Alignment in steel/concrete ratios.
- Monitoring requirements for concrete structures and OpEx costs clarity.

Soil

clarify best practices in each soil typology (Sand, Clay, Rocky soils…), covering

- Standard recommendations to clients regarding geotechnical investigations and testing.
- Benefits of using skirts.
- Sea Bed Preparation [Pre-Installation] needs.
- Scour Protection [Post-Installation].
- Situations where dredging of the upper layers may be required.
- Long term performance of GBS and assessment of potential settlements.

Fabrication and **yard**

- Dimensions of the yard required for a certain number of structures.
- Auxiliary equipment needs (and pros & cons for each solution).

Transport and **Installation**

- Requirement of number of tugs to tow a floated structure considering Marine Warranties Surveyor requirements.
- Installation in a cyclic approach and in rough conditions.

Offshore wind industry review of Gravity Base Foundations (GBSs)

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