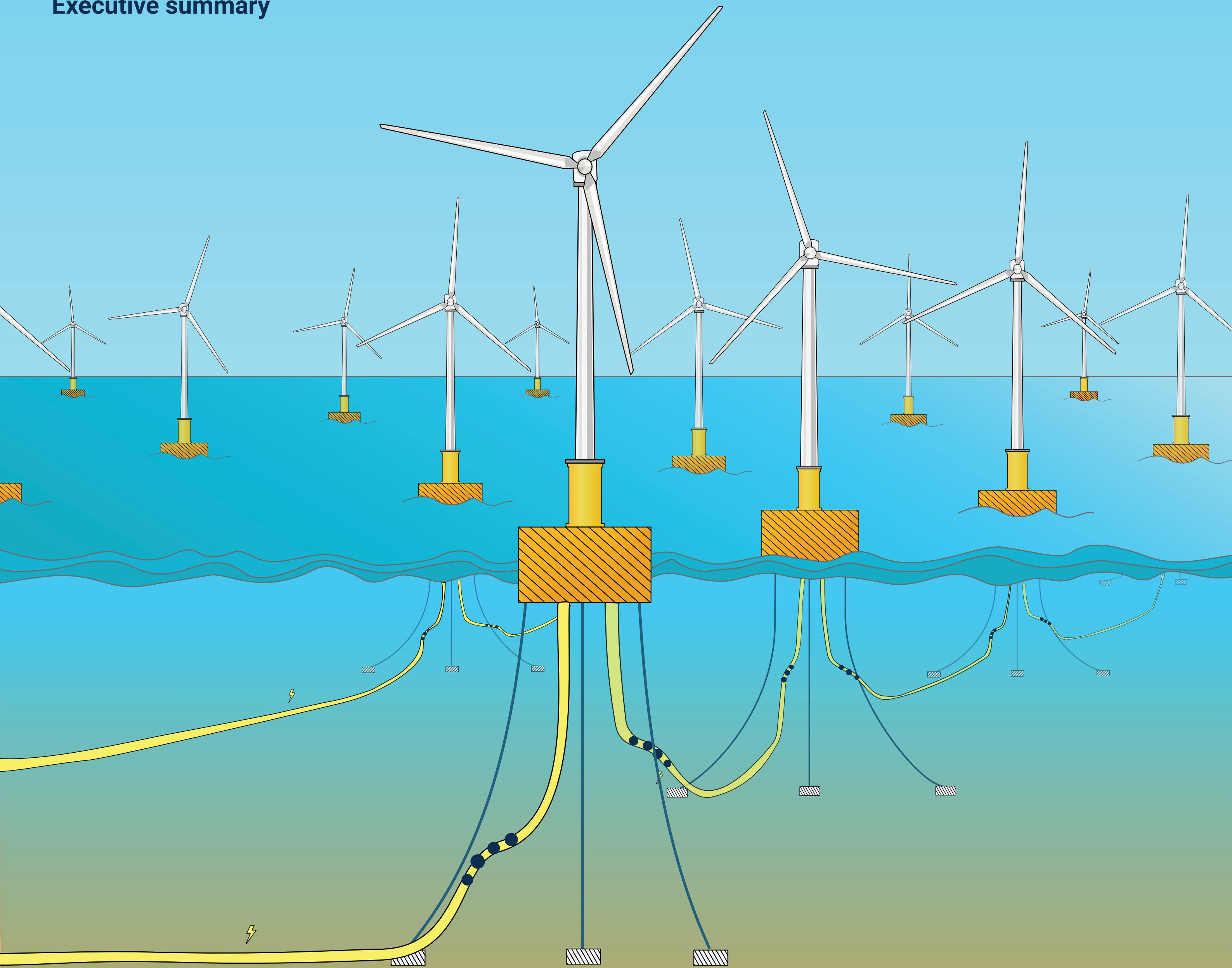
# 3D Printed Concrete Suction Anchor (3DSA)

Floating Wind Technology Acceleration Competition

**Executive summary**



June 2021

**Project funded by:**

Scottish Government
Riaghaltas na h-Alba
gov.scot

**Project co-led by:**

The Floating Wind Technology Company

**Acknowledgements**

This project has been supported under the Floating Wind Technology Acceleration Competition (FLW TAC) which was funded by the Scottish Government and managed by the Carbon Trust's Floating Wind Joint Industry Project (FLW JIP).

FLW JIP, formed in 2016, is a collaborative research and development initiative between the Carbon Trust, and fifteen leading international offshore wind developers: EDF Renouvelables, EnBW, Equinor, Kyuden Mirai Energy, Ocean Winds, Ørsted, Parkwind, RWE, ScottishPower Renewables, Shell, SSE Renewables, TEPCO, TotalEnergies, Vattenfall, and Wpd.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Published in the UK: 2021

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The project team would like to thank the following organizations for their input and collaboration:

- The Scottish Government and The Carbon Trust for funding and guiding this research;
- Members of the Floating Wind Joint Industry Project for providing feedback and revisions to the report;
- Purdue University for guidance on concrete printing matters.

# Executive Summary

Among the floating offshore wind plant components, the anchors are the most expensive to manufacture and deploy after turbine and substructure. The typical drag embedment anchor, for example, may cost up to £350,000 to manufacture and deploy. Steel suction buckets are often the preferred anchoring solution for floating offshore wind turbines as they can withstand omnidirectional loading and be installed with high location accuracy and minimum noise and seabed disturbance. Steel suction anchors make use of imported steel in many countries that do not have the necessary domestic supply chain. Therefore, an opportunity exists for new anchor designs and manufacturing technologies that reduce costs and increase domestic economic benefits.

In this study, we assessed the geotechnical, structural, manufacturing, and economic viability of a 3D-printed concrete (3DCP) suction anchor, or 3DSA, for offshore wind applications. This included:

- Defining the environmental conditions for the 3DSA design.
- Designing the 3DSA and carrying out sensitivity analysis on the design for different soil conditions and water depths.
- Assessing the feasibility of wet-towing the 3DSA to the installation site.
- Carrying out a proof-of-concept 3D printing for components of the 3DSA and defining the key manufacturing processes.
- Assessing the cost and Levelized Cost of Energy (LCOE) associated with the 3DSA, compared to conventional steel suction-installed anchors.

The anchors were designed to moor a 10-MW system comprised of the DTU 10-MW turbine mounted on the OO-Star Wind Floater. Both a catenary and a semi-taut mooring layout were analyzed to provide more information on the sensitivity of the applicability of the 3DSA to different sea-keeping systems. Results were further upscaled to include the impact of 15-MW systems on the anchor technology and to arrive at cost estimates.

### *Defining Environmental Conditions*

The anchor designs were based on realistic environmental conditions. These allowed predictions of the installation, operational, and removal loads. The selected metocean and soil conditions reflect sites around Scotland that are identified as suitable for floating offshore wind, i.e the Draft Plan Options (DPOs) (The Scottish Government, 2019a). In particular, DPOs NE7 and NE6 (Figure 0-3) were chosen as representative deployment sites for a typical floating wind plant making use of suction-installed anchor technology, with the Port of Peterhead as the relevant marshaling site. The soil at NE7 is primarily characterized by clay, whereas NE6 soil is mostly composed of sand. A 100-m water depth was assumed as representative of both sites.

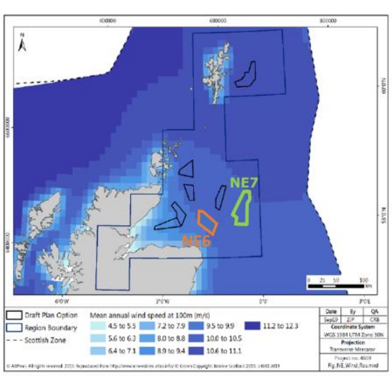


*Figure 0-1. Mean annual wind speeds offshore Scotland, and DPOs selected for this feasibility study (The Scottish Government, 2019).*

In-service loads were attained by numerically simulating specific turbine and environmental conditions (operational and parked/idling cases) based on a relevant subset of design load cases prescribed by current practice standards (DNVGL-ST-0437 and DNVGL-ST-0119).

Annual Energy Production estimates (53.5GWh and 80GWh for 10 and 15-MW systems, respectively) were also derived from numerical simulations, the site-specific wind speed probability distributions, and by assuming realistic park availability and losses.

### *Designing the 3DSA*

By considering two sites (NE7 and NE6), two offshore wind turbine systems (10 and 15-MW), and two mooring configurations, this study yielded eight designs for the conventional steel suction-installed caissons (baseline) and eight for the 3DSA (new technology).

Key geometry and mass parameters for the steel designs are given in Table 0-1.

*Table 0-1. Suction-installed steel anchor optimized designs.*

| Mooring Type | Turbine Size | Parameter | Clay | Sand |
|---|---|---|---|---|
| Catenary | 10MW | Diameter | 3.5m | 13.5m |
| | | Penetrated length | 12.5m | 6.5m |
| | | Estimated weight (dry) | 46te | 101te |
| Catenary | 15MW | Diameter | 3.5m | 14.5m |
| | | Penetrated length | 14m | 7.25m |
| | | Estimated weight | 52te | 117te |
| Semi-taut | 10MW | Diameter | 3.5m | 11.5m |
| | | Penetrated length | 10m | 5.5m |
| | | Estimated weight | 38te | 72te |
| Semi-taut | 15MW | Diameter | 3.5m | 12.5m |
| | | Penetrated length | 11.5m | 6.25m |
| | | Estimated weight | 43te | 86te |

For the 3DSA design, whereas the geotechnical loading capacity and soil failure modes were estimated as for the steel anchors, the structure had to be additionally verified accounting for the anisotropy and failure modes of the concrete. In particular, special provisions were made to mitigate the effects of tensile stresses due to overpressure at extraction and localized bending from in-service loads at the padeye.

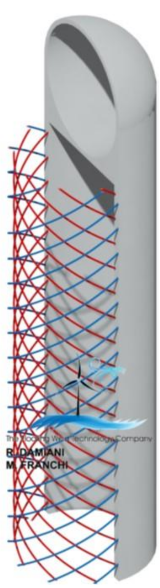


*Figure 0-3. Spiral Post-Tensioning (FWTC, patent-pending).*

Because of concrete's low tensile strength, reinforcement is necessary to mitigate these tensile stress states. The most viable reinforcement option for 3D printing is through post-tensioning, where steel tendons induce a general compressive stress state in the concrete. FWTC devised an innovative post-tensioning system for the 3DSA, denoted as spiral post-tensioning (Figure 0-4), that uses two counter-rotating rows of helicoidal prestressing tendons to generate a 'precompression' stress state in the structure. The precompression significantly reduces the final tensile stress generated

*Figure 0-2 Devised padeye solutions (FWTC, patent pending).*

by the external operational loads and extraction overpressure.

For the padeye mooring connection, several concepts were developed. Two solutions, devised by FWTC and denoted as ‘fixed’ and ‘flexible’ padeye connections (Figure 0-5), were selected for further engineering development.

Key geometry and mass parameters for the 3DSA designs are given in Table 0-2.

*Table 0-2. 3DSA main geometry and structural mass.*

| Mooring Type | Turbine Size | Parameter | Clay | Sand |
|---|---|---|---|---|
| Catenary | 10MW | Diameter | 4 m | 13.5 m |
| | | Wall thickness | 0.24 m | 0.3 m |
| | | Penetrated length | 15.5 m | 6.5 m |
| | | Concrete Mass | 153. 3te | 197.9 te |
| | | Steel mass including padeye | 28.8 te | 317.2 te |
| Catenary | 15MW | Diameter | 4 m | 14 m |
| | | Wall thickness | 0.24 m | 0.3 m |
| | | Penetrated length | 17.5 m | 7.25 m |
| | | Concrete Mass | 166.8 te | 229.1te |
| | | Steel mass including padeye | 30.2 te | 368.5 te |
| Semi-taut | 10MW | Diameter | 4 m | 11 m |
| | | Wall thickness | 0.24 m | 0.3 m |
| | | Penetrated length | 11 m | 5.5 m |
| | | Concrete Mass | 122.2 te | 136.8 te |
| | | Steel mass including padeye | 25.8 te | 187.6 te |
| Semi-taut | 15MW | Diameter | 4 m | 12 m |
| | | Wall thickness | 0.24 m | 0.3 m |
| | | Penetrated length | 13.5 m | 6.25 m |
| | | Concrete Mass | 139.7 te | 169.1 te |
| | | Steel mass including padeye | 27.5 te | 239.7 te |

With a rather slender anchor such as the 3DSA designed for clay soils (Figure 0-4), a buoyancy chamber placed on top of the suction skirt will help reduce the weight that must be supported by the installation crane (or winch) on the installation vessel. Additionally, the buoyancy chamber facilitates the towing and installation operations.

Sands are challenging environments for both steel and concrete suction anchors leading to large diameters, masses, and deeper waters required to meet installation and capacity demand. For applications in sandy soils, the calculated outer diameters are in excess of 11 m, and the anchor aspect ratio is about one half. A buoyancy chamber would not lead to an installation advantage in this case, and a flat steel lid is envisioned to replace the 3D-printed buoyancy chamber.

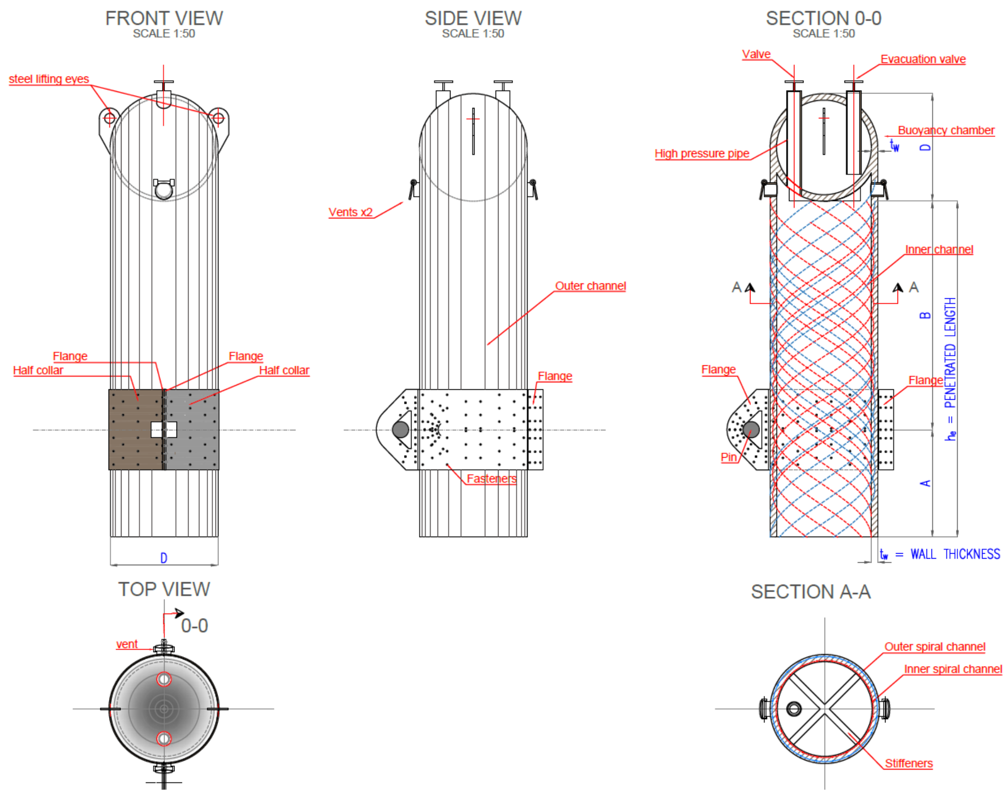


*Figure 0-4. Views and cross-sections of the 3DSA for clay soil applications.*

## *Sensitivity Analysis*

A thorough sensitivity analysis was carried out to assess the range of applicability across water depths and soil conditions that could make the deployment of the 3DSA viable (Figure 0-5). The results of this analysis showed that the 3DSA has a wide range of applicability.

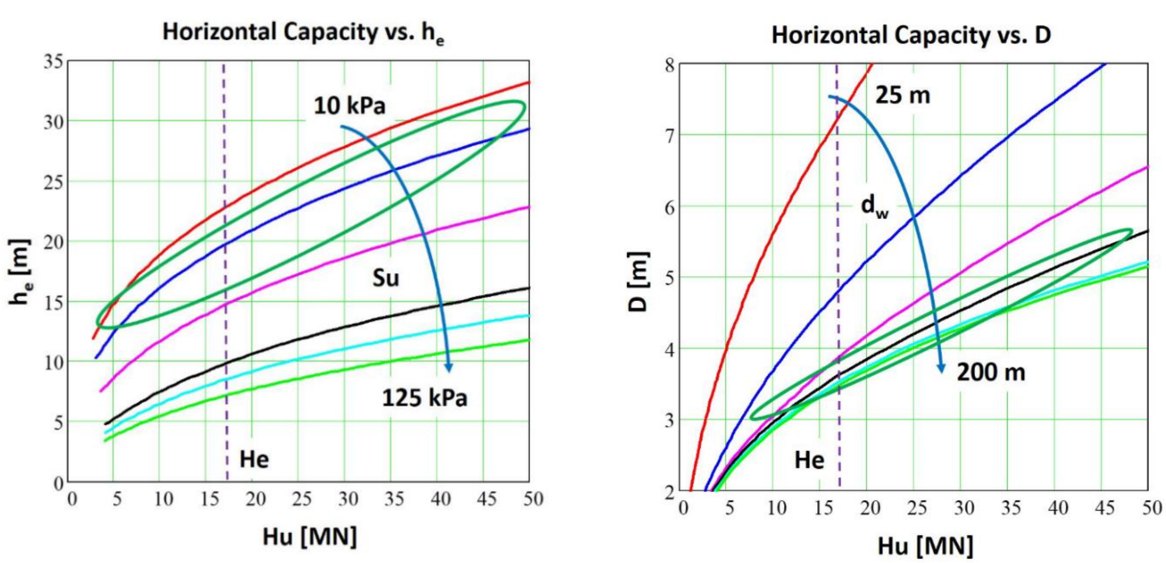


*Figure 0-5. Ultimate horizontal capacity (Hu) of the 3DSA as a function of penetration depth ($h_e$) and outer diameter (D), for various clay undrained shear strengths ($S_u$) and water depths ($d_w$). Green ellipses indicate the conditions encountered at DPO NE7.*

In clay soils, where suction anchors excel, the concrete suction anchor can be safely applied in varying stiffness stratigraphy. For water depths of 100 m, a maximum soil undrained shear strength of 125kPa can be assumed as the upper bound to the safe installation and operation of the *optimal* size 3DSA. In shallower waters, a minimum deployable water depth of approximately 30 m was found.

In sands, even at water depths greater than 100 m, large diameters and relatively shallow embedments are necessary to prevent piping soil failure. In shallow waters, the penetration resistance in sands is so large that the available hydrostatic pressure at depths less than 75 m makes the ability to use the 3DSA difficult to confirm analytically. The large mass associated with diameters in excess of 10 m for the mooring loads calculated in this study further complicate handling of the anchor at sea and its installation. Dedicated embedment tests will be necessary to further assess the viability of the 3DSA in sands.

The many variables and design considerations (e.g., load demand, water depth, stratigraphy, concrete strength, manufacturing constraints, logistics constraints) make the generalization of the 3DSA design quite difficult; the anchor will need to be specifically optimized and verified for each individual deployment site.

### *Installation Process*

Besides material and fabrication costs, expenses associated with the installation and transportation operations are important drivers of the offshore wind LCOE. Reduced vessel requirements such as crane capacity and deck load, as well as high operability in severe wind and wave conditions are desirable. A study was carried out to assess the 3DSA floatation stability and wet-towing feasibility. Towage was envisioned from the marshalling port to the deployment site by Anchor Handling Tug Vessels (AHTVs) with moderate crane capacity, thereby avoiding using larger vessels and reducing the number of offshore lifts for the anchor installation.

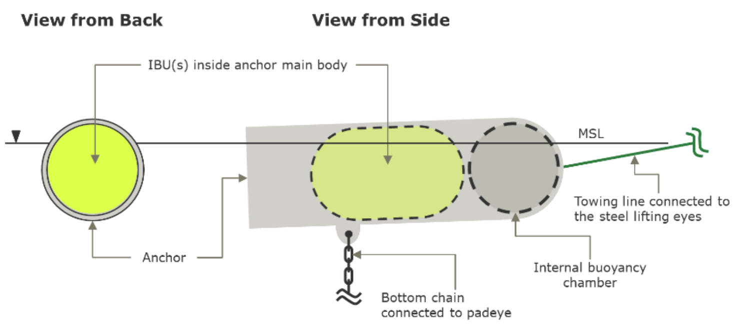


*Figure 0-6. Sketch of IBUs inside the main body of the clay design of the 3DSA for towage.*

The 3DSA for clay applications can be sealed at its bottom via inflatable buoyancy units (IBUs), partly submerged in a horizontal position, and towed with a moderate pitch (nose-up of 5 degrees, Figure 0-8). The displaced volume of the anchor body including the evacuated buoyancy chamber, as well as additional buoyancy units result in a reduced net weight during the upending operation of the anchor, reducing the demand on the crane to 100 tons.

Because of the reduced aspect ratio, and the lack of an upper buoyancy chamber, the anchor for sand applications would be towed upright for increased stability. This layout, however, requires additional buoyancy and will increase handling costs and work at sea.

### *3D-Printing Feasibility*

Research was conducted on the manufacturing process and strategy culminating in a proof-of-concept 3D printing of anchor components/segments at various scales (Figure 0-7), including a cylindrical skirt at 1:17 scale, a cylindrical segment at 1:5 scale, a dome at 1:5 scale, and 1:1 scale wall segment with a curvature matching the full-scale cylindrical skirt with post-tensioning channels. The team also performed 3D concrete printing experiments at up to full scale to test and prove the ability to print spiral post-tensioning ducts, prove the potential of 3DCP as a production method, and test the buildability requirements. The experiments demonstrated that:

- a predictable, uniform, constant diameter duct can be attained using 3D printing;
- 3DCP is a technically viable production method for manufacturing the anchor walls quickly without collapsing the structure;
- printing can be performed with only two people, demonstrating the potential for leanly staffed production.


*Figure 0-7. Examples of 3D printed sub-scale components of the 3DSA.*

The key steps involved in the anchor 3DCP manufacturing process (Figure 0-8) were defined together with specifications for printer, pump, concrete-mix properties, concrete curing, reinforcement placement, and fitting of pneumatic components for the 3DSA configurations.

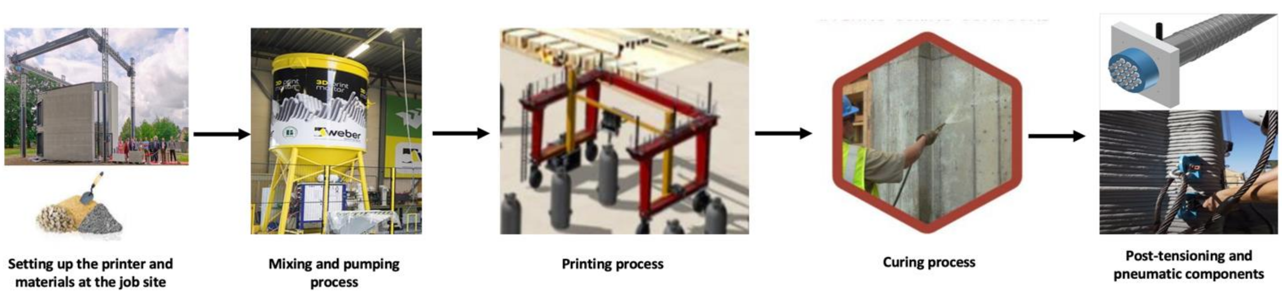


*Figure 0-8. Manufacturing Phases for the 3DSA.*

An assessment of the feasibility of 3D concrete printing of the 3DSA at quayside in Scottish ports, with specifications for indoor and outdoor space requirements was performed. RCAM projects achieving printing rates at Peterhead Port of up to 4 anchors per 8-hour shift using 4 printers simultaneously once the 3DSA technology is fully developed. At full production, a 1GW wind plant consisting of 66 turbines and 200 anchors could be manufactured in as little as 50 days thus leveraging the best weather windows at Peterhead Port.

### *Cost Analysis*

A detailed cost analysis for the manufacturing, launching, towing or alternative transportation, and installation was conducted for all the 3DSA designs.

To offer a financial comparison between the application of conventional suction-installed anchors and of the 3DSA technology, RCAM estimated the levelized cost of energy (LCOE) of an offshore wind farm composed of 66 15-MW turbines moored at the two sites examined in this study using either steel or 3DSA anchors. 3DSA anchors are estimated to reduce manufacturing costs by approximately 75% compared to steel anchors. The total wind plant CapEx savings amount to approximately £75,000,000 for a representative 1 GW wind farm, yielding a 1.2-2.1% reduction in LCOE depending on the details of the deployment site and wind plant (Table 0-3).

*Table 0-3. LCOE reduction achieved with the use of 3DSA anchors.*

| | Anchor Type (15 MW) | Baseline LCOE (£ / MWh) | % LCOE Reduction with 3DSA (Deck Deployment) | % LCOE Reduction with 3DSA (Wet Tow) |
|---|---|---|---|---|
| Clay | Catenary | 75.67 | 1.8% | 1.5% to 2.1% |
| | Semi-Taut | 74.38 | 1.5% | 1.2% to 1.7% |
| Sandy | Catenary | 78.33 | 1.3% | - |
| | Semi-Taut | 76.26 | 1.2% | - |

This project found that the 3DSA is a viable solution for floating offshore wind in a large number of environmental settings and turbine and substructure configurations. Some technical aspects, however, will need to be further developed and validated through further design, analysis, and testing. Most notably, post-tensioning details and efficacy will need to be verified with structural tests as will the anchor-padeye connection to address static and fatigue issues. The manufacturing production rates will need to be verified at full-scale, and the operations near the quay and at sea need to be demonstrated. The operability of buoyancy chamber and IBUs and embedment should be verified with dedicated tests.