FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

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FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

PR36: ADVANCED MANUFACTURING OF SUBSTRUCTURE COMPONENTS

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Summary

This report summarises the work undertaken to assess advanced manufacturing technologies for floating offshore wind substructures. This project provided insight into the adoption of advanced manufacturing technologies for floating offshore wind substructure components. We:

- Identified and described state of the art technologies for manufacturing and assembling components for floating substructures. These should be either in use, at, or close to, commercial scale that could be applied to serial manufacturing.
- Determined the potential to reduce the cost of fixed and floating wind substructures by using advanced manufacturing technologies and design for manufacture strategies.
- Analysed the potential blockers to adopting advanced manufacturing technologies for floating substructures and suggested next steps for how these can be addressed.

The project was split into five work packages (WPs). This report outlines the work undertaken for all WPs and presents the key findings of the project. In:

- WP1 and 2 we identified the substructure typologies and advanced manufacturing technologies.
- WP3 we identified relevant manufacturing facilities who were then interviewed and visited to gather relevant information and understand state of the art practices.
- WP4 we performed detailed assessment of relevant advanced manufacturing and assembly technologies to determine the benefits, drawbacks and ease of adoption for series manufacture and assembly for floating offshore wind substructure components.
- WP5 we assessed the impacts of advanced manufacturing technologies on the cost of floating offshore wind substructures. This was done by breaking the CAPEX cost of different floating substructure designs into the categories which make up the total. The relative changes in these cost categories when advanced manufacturing technologies are used were then quantified based on the research undertaken in WP4. These cost changes were aggregated to provide a total. The combination of different technologies used on each substructure was chosen to provide an optimal result with the aim of reducing cost.

1. Introduction

This report summarises insights from the project on the adoption of advanced manufacturing technologies for Floating Offshore Wind (FOW). It identified advanced manufacturing technologies applicable to Floating Offshore Wind Turbine (FOWT) substructures, determined the potential cost savings and assessed barriers to their implementation. Throughout the process of the project the following reports were produced:

Table 1-1 Project work packages.

Work package number	Work package description	Deliverable number	Deliverable description
WP0	Project management, integration, and scoping, including planning for stakeholder engagement	D1a	Project delivery plan and stakeholder delivery plan and tracker
WP1 / WP2	Substructure typology, componentry and manufacturing assessments, including developing a manufacturing taxonomy review.	D2a / D2b	BVGA-16446-D2a Substructure assessment all typologies BVGA-16446-D2b Taxonomies component and process These reports identified the components and the manufacturing technologies expected to be assessed in WP3.
WP3	Manufacturing facility review	D3	BVGA-16466-D3-Manufacturing facility review This report provides an overview of the key facilities identified, their characteristics and a summary of the manufacturing and assembly technologies used.
WP4 / WP5	Advanced manufacturing methodologies. Impact of advanced manufacturing on LCOE	D4	BVGA-16446-D4 report This report describes the assessment of relevant advanced manufacturing and assembly technologies to determine the benefits, drawbacks and ease of adoption. It also presents the impacts of advanced manufacturing technologies on the cost of foundation substructures and the barriers to adoption of these advanced approaches.
WP6	Summary	D5	BVGS-16446-D5 Summary report (this report) Summarises the work undertaken and key conclusions.

2. Work packages 1 and 2: Identifying the substructure typologies and advanced manufacturing technologies

In WP1 and WP2 we identified and defined the substructure typologies and manufacturing technologies to be assessed in future work packages. Eight substructure typologies were selected to represent the range of options available and manufacturing technologies for FOW, as shown in Figure 2-1. Note, two of the typologies are from bottom-fixed offshore wind which have been included in the study as these have relevant learnings applicable for FOW.

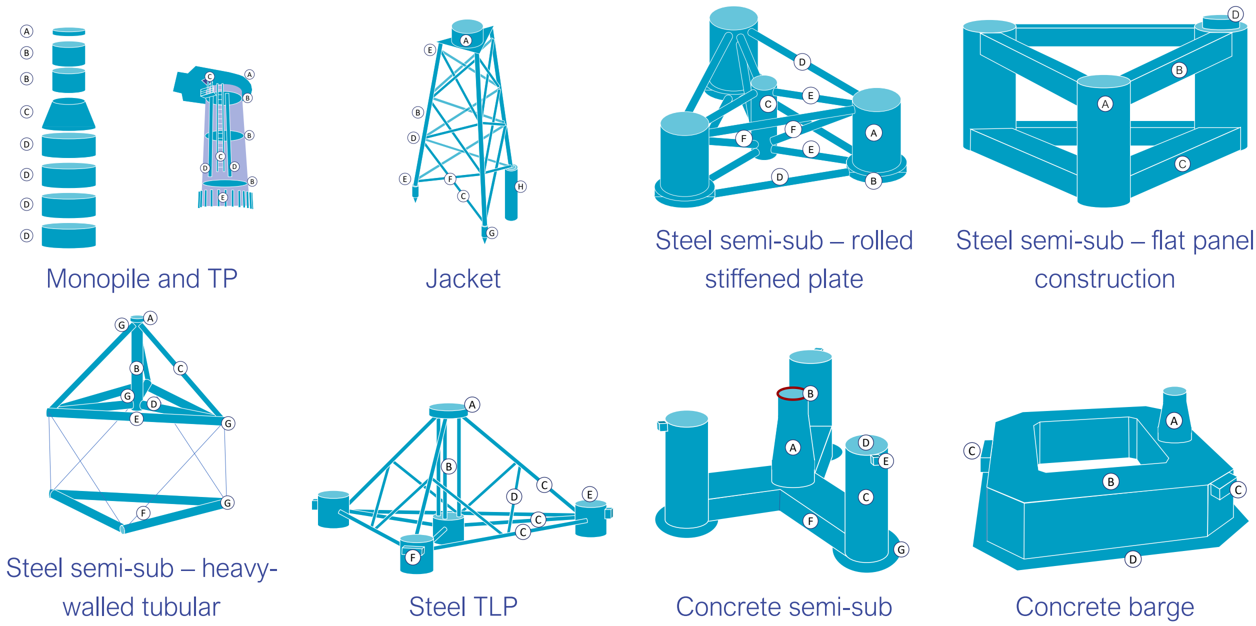

Figure 2-1 Representative fixed and floating offshore wind turbine substructures.

We identified the major components and their expected dimensions, mass and other important characteristics, such as materials, for designs that support 15 MW turbines.

We then identified and described the state of the art, or “advanced”, technologies for manufacturing and assembly of components for floating substructures, either in or close to commercial use, that could be applied to serial manufacturing of FOW substructures. This assessment revealed the technologies and classifications in Figure 2-2.

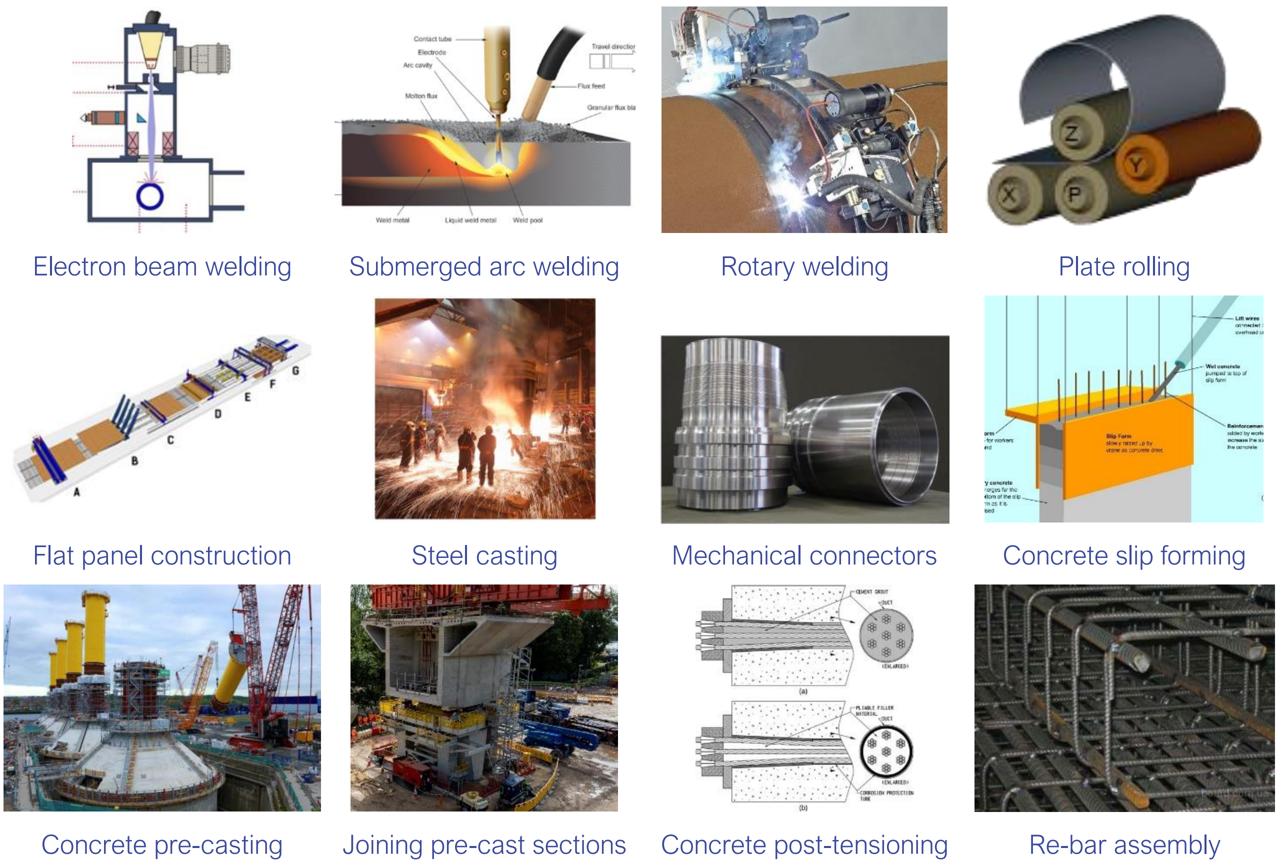

Figure 2-2 Advanced manufacturing technologies.

3. Work package 3: Identification of manufacturing facilities:

In WP3 we produced a list of the manufacturing facilities and fabricators that use the manufacturing technologies displayed in Figure 2-2. From this list we selected a representative sample for stakeholder engagement within WP4 in order to gain industry insights into the fabrication and assembly of FOWT substructures. The list of manufacturing fabricators contacted is displayed in Table 3-3, along with their relevant technologies, and the form of engagement carried out.

We engaged with the supply chain to understand its current facilities, manufacturing processes and the advanced manufacturing technologies it expects to use to manufacture and assemble floating substructures at a rate of about one per week.

This was carried out through 5 visits and 10 interviews for 15 facilities, chosen to represent the 12 advanced manufacturing technologies of interest.

For each identified fabrication facility, desk based research was used to investigate:

- Location of facilities, primary industries served and the potential for floating offshore wind component manufacture and assembly
- Advanced manufacturing and assembly technologies used
- Capabilities, including key equipment and tooling
- Dimensions of the components handled
- Handling of critical materials and components, production rates, advanced manufacturing of substructure components
- Dimensions of the facility, and
- Manufacturing strategy.

Findings were reviewed for gaps and the most valuable facilities to engage with were identified by assessing:

- Evidence of relevant advanced manufacturing and assembly technologies which merit deeper desk research and investigation, and
- Facilities which would provide the greatest benefit from engagement and visits.

Where interviews and site visits were carried out the following process was followed:

- Questions were prepared in advance to ensure focus on the key issues for each facility, including the identification of industry needs and challenges to the adoption of advanced technologies
- Interview notes were taken, complimented by taking photos where permitted, and
- Desk based research to complete understanding.

Table 3-3 Relevant manufacturing facilities and technology developers and record of engagement.

Facility	Location	Submerged Arc Welding	Electron Beam Welding	Rotary welding	Plate rolling	Flat panel construction	Steel Casting	Mechanical connectors	Slip forming	Concrete Pre-casting	Jointing of pre-cast sections	Post tensioning	Reinforcement bar placement	Engagement
Acciona	Spain								✓	✓	✓	✓	✓	Video conference
Bam Nuttall	UK								✓	✓	✓	✓	✓	Video conference
Bygging-Uddemann	Sweden								✓	✓	✓	✓	✓	Face to face
Cambridge Vacuum Engineering	UK		✓											Site visit
Cammell Laird	UK	✓	✓			✓								Site visit
Chantiers de l'Atlantique	France	✓				✓								Site visit
Global Energy Group	UK	✓		✓	✓			✓						Video conference
GMC	UK							✓						Site visit
Lamprell	UAE	✓		✓	✓	✓								Video conference
Navantia	Spain	✓		✓	✓	✓								Video conference
OCERGY	USA				✓			✓						Video conference
CRC Evans (Pipeline Technique)	UK			✓										Site visit

Facility	Location	Submerged Arc Welding	Electron Beam Welding	Rotary welding	Plate rolling	Flat panel construction	Steel Casting	Mechanical connectors	Slip forming	Concrete Pre-casting	Jointing of pre-cast sections	Post tensioning	Reinforcement bar placement	Engagement
Sheffield Forgemasters	UK						✓							Video conference
Stiesdal Offshore	Denmark	✓			✓		✓	✓						Conference call
Vinci	France								✓	✓	✓	✓	✓	Video conference

4. Work package 4: Assessment of advanced manufacturing technologies and methods.

4.1. Advanced manufacturing technologies and manufacturing strategies

4.1.1 Overview and categorisation of methods

Thirteen advanced manufacturing and assembly technologies and manufacturing strategies were identified as being applicable to FOW. These methods are summarised in Table 4-1. It gives an overview of each manufacturing technology and strategy to align with the floating offshore wind substructure types identified in WP1. Table 4-2 categorises the strategies and technologies into high, moderate and low impact based on our assessment.

Table 4-1 Overview of identified advanced manufacturing and assembly technologies and strategies.

Number	Method	Overview
1	Electron beam welding	Welding through use of high-velocity electrons to fuse two materials
2	Submerged arc welding	Welding through formation of an arc between a continuously fed electrode and the workpiece
3	Rotary welding	Welding together of cylindrical sections using automated weld bugs on a guide band
4	Plate rolling	Forming flat steel plate into cylindrical sections
5	Flat panel construction	Assembly of a structure from stiffened flat panels
6	Steel casting	Construction of sub-components using hot liquid steel poured into moulds
7	Mechanical connectors	Joining cylindrical sections using mechanical connectors
8	Concrete slip forming	Continual process of casting concrete using sliding forms
9	Concrete pre-casting	Casting of individual concrete sections that are joined together
10	Jointing of pre-cast sections	Method of joining pre-cast concrete sections
11	Concrete post-tensioning	The use of tensioned tendons within cast concrete structures to improve the structural performance of the structure
12	Concrete reinforcement bar placement	The process of placing steel reinforcement bars within concrete as it is cast to improve its structural performance.
13	Advanced manufacturing strategies	Focused factories manufacturing components supplying local final assembly of substructures.

Table 4-2 Advanced manufacturing assembly technologies and strategies categorisation.

Category	Technology	Substructure typology where impact expected	Components where impact expected
A - high potential impact	Local vacuum electron beam welding	Steel semi-sub (heavy walled tubular), Steel TLP	Heavy walled tubular braces
	Rotary welding	Steel semi-sub (heavy walled tubular), Steel semi-sub (rolled stiffened plate)	Final assembly of tubular members
	Concrete Slip forming	Concrete barge, Concrete semi-sub	Components with uniform vertical section
	Flat panel construction	Steel semi-sub (flat panel construction)	Pontoons, columns
	Advanced manufacturing strategies	All steel and concrete typologies which include final assembly	
B- moderate potential impact	Plate rolling	Steel semi-sub (heavy walled tubular), Steel semi-sub (rolled stiffened plate), Steel TLP	Cylindrical columns, Tubular braces
	Mechanical connectors	Steel semi-sub (heavy walled tubular), Steel semi-sub (rolled stiffened plate)	Tubular braces for final assembly of the structure
	Submerged arc welding	Steel semi-sub (flat panel construction), Steel semi-sub (heavy walled tubular)	Tubular braces, jointing of plates on panel line
	Concrete pre-casting	Concrete barge, Concrete semi-sub	All components
	Jointing of pre-cast sections	Concrete barge, Concrete semi-sub	Assembly of all components
C – low potential impact	Concrete post-tensioning	Concrete barge, Concrete semi-sub	Assembly of all components
	Concrete reinforcement bar placement/tying	Concrete barge, Concrete semi-sub	All components
	Steel casting	Steel semi-sub (heavy walled tubular), Steel semi-sub (rolled stiffened plate), Steel TLP	cast steel nodes, Mechanical connectors

5. Work package 5: Cost analysis and barriers to adoption

5.1. Cost analysis

The objective of this work package was to understand the cost impacts of advanced manufacturing on FOWT substructures and the barriers to adoption of these advanced approaches. The method used to assess the impact on cost is shown in Figure 5-1.

Equipment costs are included in the cost analysis. CAPEX is amortised across the substructures produced over one year, and annual equipment OPEX is calculated as a proportion of CAPEX. As the production rate will increase because of introducing new advanced technologies, equipment costs are split across more substructures than in the base cases, essentially reducing the cost per substructure.

Select a baseline substructure to compare against
- Select one steel and one concrete substructure type for cost anlaysis
- These substructures are the basis for comparison to the others
- This ensures major cost assummptions are kept consistent for all substructures

↓

Create a breakdown of costs
- Industry reports are used to gather cost information on the foundation baselines
- These are used to break down the total cost into relevant categories

↓

For every substructure being assessed, the cost change for each of these categories was quantified

↓

Aggregate the changes to give a total cost increase for each foundation from the baseline
- Combine the changes in each category to get a new total cost and percentage breakdown

↓

The technologies which should be used on each substructure are then agreed
- Selection aims to reduce the time and cost of production.
- When multiple technologies can be applied to the same area, the technology which has the best cost and time improvement is selected

↓

The improvement made by the combined technology selection to the cost categories identified is then quantified
- Percentage inprovement in each category is assessed based on reasearch done in WP4 and presented in Section 2

↓

These improvements are then aggregated to find a total cost saving when the optimum combination of advanced manufacturing technologies are used.

Figure 5-1 Cost impacts method.

5.2. Manufacturing strategy

Based on the knowledge gained through assessment of the advanced manufacturing technologies and engagement with industry we assessed the optimum manufacturing strategies for different substructure types. Our assessment is summarised in Table 5-1. Multiple specialised factories with local assembly is the preferred option for steel typologies, while a “concrete travelling factory” is the preferred option for concrete typologies.

Table 5-1 Summary of assessment of manufacturing strategies.

Advanced manufacturing strategy	Steel typologies	Concrete typologies
Option 1: Single location fabrication, local - all fabrication and assembly of the substructure at a single local location	A fabrication and assembly facility that only supplies local floating projects is unlikely to be successful as there is a low chance of sufficient floating projects being located in the vicinity of the port, or continuity of workload, to enable effective fabrication. Further, if the fabrication and assembly facility did not already exist, it would require an investment of several hundred million GBP for a single project, or small number, of local projects..	Is the default option being considered. The civil construction industry is used to working on one off or low volume projects with limited off-site prefabrication due to the mass of components involved.
Option 2: Single location fabrication, remote - all fabrication and assembly of the substructure at a single remote location, with transport to the local integration port	Is known to be under consideration by some developers, however, if fabrication is based abroad it will make it somewhat challenging to meet UK local content lifecycle requirements of 50%, increasing to 60%. Fully assembled substructures are also generally very large and expensive to ship: substructures take a lot of deck space and are unlikely to fit through the Suez or Panama canals (maximum vessel widths of 50.0 m and 51.25 m respectively)	Will be very challenging for the same reasons as steel typologies. Additionally it is even more expensive to transport due to its mass being around five times heavier.
Option 3: Multi-location – substructure components are fabricated at specialist suppliers then transported to a local port for final assembly	The primary benefit of this option is to have a large enough pipeline to invest in industrialisation at multiple specialised fabrication facilities which can deliver at scale to projects at a variety of local ports. Continuity of fabrication enables learning and improvement to take place. It also increases supply capacity and makes best use of local port space. This strategy relies on effective design for final assembly.	As the cost of moving concrete makes it prohibitive this option is defined as moving the concrete manufacturing equipment from local project to local project as a travelling concrete factory. The primary benefit is to enable learning and improvement from project to project, and reuse of some expensive elements of bespoke equipment, such as moulds and skidding systems.

6. Conclusions

6.1. Findings – advanced manufacturing strategies and technologies

We have investigated and described manufacturing strategy for FOWT substructures along with seven steel and five concrete manufacturing technologies selected at the end of WP3, see Section 4.1. We have used an iterative combination of desk research, interviews and visits with previously contacted firms and some additional parties. The draft steel and concrete sections have been reviewed by TWI, and contractors BAM and Acciona, respectively. We found that:

- In steel fabrication, the majority of advanced manufacturing technologies are proven in other industries, where their use is justified by the scale of production. As several tens of millions of tonnes of steel per year is fabricated for industries including shipbuilding, oil and gas, chemical process plant, civil-engineering and wind energy, this is not entirely surprising. There is no fundamental reason that they will not be adopted for FOW substructures but fabricators need the confidence to invest in them through visibility of a pipeline of sufficient firm orders and clarity of which substructure typologies will be used in future.
    - Electron beam welding has the potential to speed up the welding process very significantly and save large amounts of energy from pre-heat and welding. Faster welding also makes better use of equipment, labour and space. Although it has been demonstrated for longitudinal welds in monopiles, it remains to be certified for FOW.
    - Mechanical connectors are critical for an effective "make anywhere, assemble locally" approach to accelerate manual or rotary welding at final assembly. Some connections have been demonstrated at smaller scales including Steisdal's pinned connections and GMC's hydraulic tubular joints. We believe there is the opportunity for further innovation and design optimisation to address practical tolerance issues and site conditions. Mechanical connectors are also expected to need certification for use in FOW.
- For concrete manufacturing the same broad findings apply to most of the technologies investigated – advanced technologies are all established in different areas of the civil construction industry and are expected to be adopted when the civil engineering contractors have the confidence to invest in them.
    - One area where automation could be applied, but has not been, is in the placement and tying of steel reinforcement. This remains a largely manual process. We think this is because it uses relatively low-skilled labour and the nature of the material would make it a challenging process to automate. Labour makes up approximately 24% of concrete substructure costs, reducing reinforcement placement time could help to lower this, but will only be beneficial if the equipment required costs less than the labour savings. We do not believe this is likely in the near future.
- For advanced manufacturing strategies we recommend the following options should be seriously considered to accelerate learning and cost reduction at this early stage of the industry:
    - For steel, we recommend a "multi-site fabrication with local assembly" approach. This relies significantly on the use of effective joint designs. It is improved if the combination of foundation designer, EPCI, module manufacturer and port can have sufficient continuity of work to invest in industrialisation and continuous improvement in each area of the supply chain.
    - For concrete, we recommend a "travelling concrete factory" variation of the project-focused approach that is traditionally used by the civil engineering industry for major projects. This involves the foundation designer, civil engineer and key construction equipment suppliers working together collaboratively over sufficient successive projects to enable the capture of learning and the continuous enhancement of their utilisation of high-value site equipment, such as gantry slip forms and high-capacity skidding systems.

6.2. Findings – cost impact

We have estimated the impact of adopting advanced manufacturing technologies, by defining a scenario for each substructure typology using a complementary combination of advanced manufacturing technologies. The base cases for the analysis assumed a small batch of 5-10 substructures was being manufactured using appropriate established processes and technologies.

The combination of technologies used versus substructure typologies is shown in Table 6-1 for steel and Table 6-2 for concrete. For each technology we identified the areas where it could be applied and the percentage of the total fabrication this made up. For example, 30% of the welds in a steel semi-sub with rolled stiffened plate are seam welds, where electron beam welding could be used.

Table 6-1 Technology combinations selected for substructure types – steel.

Technology	Semi-sub, steel: rolled stiffened plate	Semi-sub, steel: flat panel construction	Semi-sub, steel: heavy walled tubular	TLP, steel
Electron beam welding	Seam welds and circumferential welds for rolled plate. Tubular braces. 30% of the welds	-	Seam welds and circumferential welds for rolled plate. Tubular braces. 40% of the welds	Seam welds and circumferential welds for rolled plate. Tubular braces. 60% of the welds
Submerged arc welding	Used for welding some stiffening plates that can't be done by EBW. 30% of the welds.	Flat panel construction. (Included in panel line)	Used for some stiffeners that can't be done by EBW. 20% of the welds.	-
Rotary welding	Used for some stiffeners that can't be done by EBW/SAW. 20% of the welds.	-	-	Used for some stiffeners that can't be done by EBW/SAW. 20% of the welds.
Plate rolling	Column shells - improvement to established plate rolling process	-	Already considered in base case. No improvements	Already considered in base case. No improvements
Flat panel construction	-	Column shells, braces and pontoons.	-	-
Steel casting	-	-	Used for joints (as part of mechanical connectors)	-
Mechanical connectors	-	-	Use for remaining connections of tubular braces (replaces 20% of welds)	-

Table 6-2 Technology combinations selected for substructure types – concrete.

Technology	Concrete semi-submersible	Concrete barge
Concrete slip forming	-	Used for main walls of structure
Concrete pre-casting	Used for main pontoons and towers	Used for top sections
Jointing of precast section	Included in pre-casting process	Included in pre-casting process
Concrete post tensioning	Considered as part of base case - little room for improvement	Considered as part of base case - little room for improvement
Concrete reinforcement bar assembly	Automated re-bar quite immature so not included in mid-point assessment	Automated re-bar quite immature so not included in mid-point assessment

The cost reductions identified are shown in Figure 6-1.

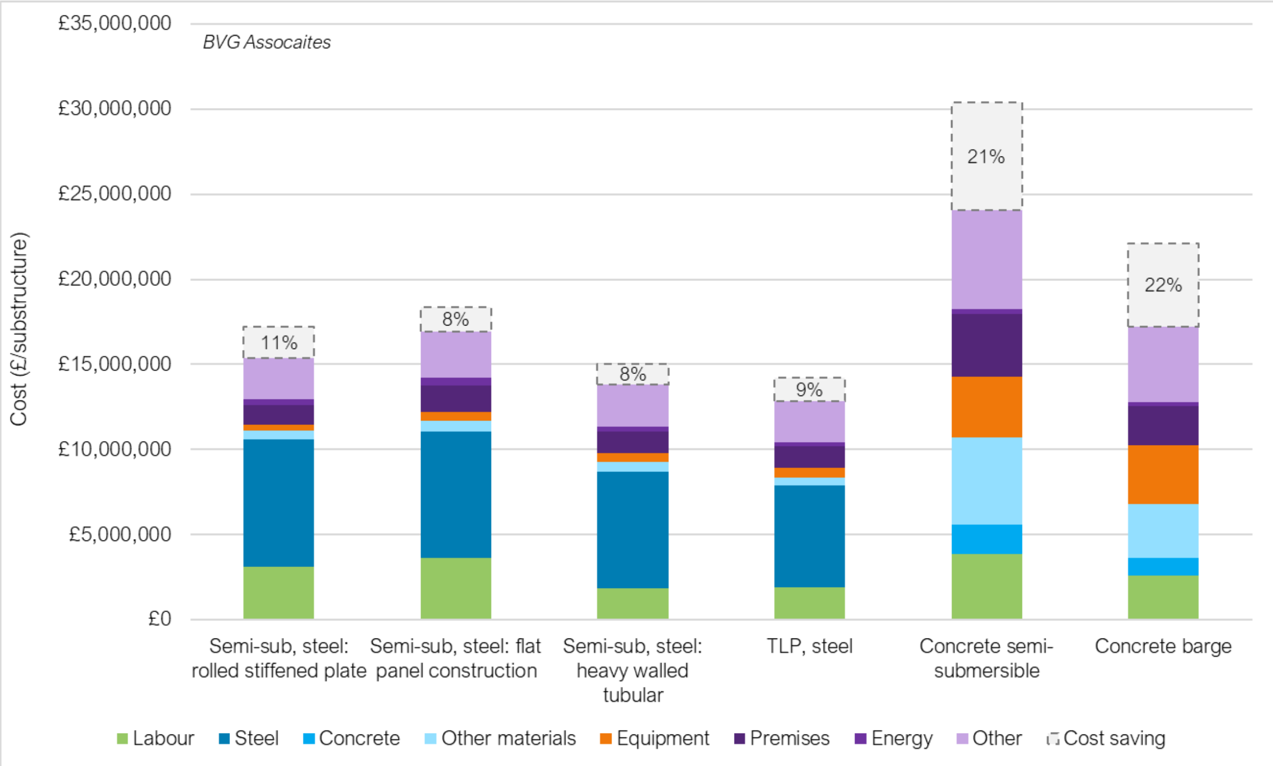

Figure 6-1 Costs per unit for each substructure typology before and after the application of advanced manufacturing technologies.

The cost reduction for the steel typologies ranged from -8% to -11% and for the concrete typologies from -21% to -22%.

The percentage improvement is the key finding from this work. No significance should be placed on the relative cost of the substructures as the work did not begin with a set of substructure designs optimised for the exact same metocean conditions and turbine. The cost estimations are, therefore, high level only and attention should be focused on the percentage improvements.

Note, these are the benefits of adopting only the specific technologies identified. Further benefit should be achieved through addressing other elements of the cost stack, for example optimising the design of substructures and their integration with the turbine and mooring system, challenging some of the oil and gas design standards, optimising cost elements not examined in this study such as transporting substructures within a manufacturing site and into the water, or benefits of scale such as increased purchasing leverage hence lower unit cost rates for e.g. materials.

6.3. Findings – barriers to adoption

The key barriers to adoption and their suggested mitigations are shown in Table 6-3.

Table 6-3 Key barriers to adoption and recommended mitigations.

Barriers	Recommended mitigations
Visibility and confidence of the order pipeline, firm and conditional, against which the supply chain is prepared to invest	Developers should make capacity commitments (in advance of project final investment decisions) with the highest levels of their supply chains, whether EPCIs or major manufacturers. Developers should collaborate with each other on project delivery dates to make shared use of supply chains and enable their investment in industrialisation.
Uncertainty of substructure design, with over 100 variants being promoted, and substructure scale	Steel fabricators should industrialise the fabrication of building blocks across different substructure designs that share a common process ("process standardisation"), for example flat panel corner columns or cast mooring connectors. Civil engineering contractors and ports should focus on industrialising specific aspects of concrete manufacturing.
Maturation of electron-beam welding	Innovators and enabling industry organisations should support certification of longitudinal thick-walled tube welds, and further process innovation to address additional component and weld geometries.
Maturation of mechanical jointing technology	Innovators and enabling industry organisations should seek certification of novel mechanical jointing techniques for FOW, and further process innovation to address the practical challenges of scale and alignment accuracy.

7. Recommendations

To translate the findings of this project into sustainable benefits for the FOW industry we recommend:

1. **EB welding:** OREC should support the further development, testing and certification of electron beam welding for longitudinal and circumferential welding of thick-walled tubulars. This is of greater benefit to fixed offshore wind for the fabrication of monopiles than for FOW, but it is important nevertheless. The objective is to reduce the lead time and cost, and increase the output rate, of these challenging welds.
2. **Joints:** OREC should support further design, testing and certification of final assembly joints for steel fabrications, including the practicalities of jointing with the dimensions required. The objective is to enable design anywhere – assembly anywhere supply chain strategies.
3. **Collaboration between engineers and fabricators:** OREC should foster a deep level of technical communication between engineers and fabricators to share good practice between them. Also, to standardise on elements of their structures where they do not need to be in competition. This could be achieved through the creation of a working group comprising of engineers and fabricators who meet to discuss challenges and potential solutions. One working group could cover both steel and concrete substructures. The objective is to accelerate the benefits from industrialisation and encourage the innovation of specialists to address specific elements shared across concepts.
4. **Concrete manufacturing costs:** OREC should commission an independent report to describe a model of the processes, equipment and people needed to manufacture concrete substructures. This should illustrate the differences between concepts and the adoption of more, or fewer, advanced technologies in line with foreseen production rates and total numbers. The objective is to encourage more civil contractors to consider entering the industry and build a conversation and consensus around accelerating cost reduction for concrete substructures.

What we don't recommend is encouraging the development of further novel substructure concepts as clients do not want them at this stage in the evolution of the industry. Rather, they seek a reduction in the number of concepts and continuous development, testing and improvement of the remaining concepts.

About BVG Associates

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- Our highly experienced team has an average of over 10 years' experience in renewable energy.
- Most of our work is advising private clients investing in manufacturing, technology and renewable energy projects.
- We've also published many landmark reports on the future of the industry, cost of energy and supply chain.

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