CREATE

Concrete as a Technology Enabler

Public Report

WES Structural Materials and Manufacturing Processes Stage 3

WES-ARP-MT31-D11

ARUP

WES-ARP-MT31-D11: Public Report

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Author: Karoline Lende

The Concrete as a Technology Enabler (CREATE) project aims to demonstrate the potential of concrete to enable cost reduction in Wave Energy Converters (WECs). The CREATE project has been commissioned by Wave Energy Scotland (WES) and is led by Ove Arup and Partners Ltd (Arup).

ARUP

Contents

1. Project Introduction

Project Summary

The Concrete as a Technology Enabler (CREATE) project aims to demonstrate the potential of **concrete** to enable **cost reduction** in Wave Energy Converters (WECs).

CREATE Stage 1 outcomes:

- Benefit of traditional concrete technology demonstrated for four WEC devices.
- Accurate quantification of cost reduction through pre-FEED level design of the Carnegie Clean Energy CETO 6 submerged pressure differential device.
- Identified opportunity for precast construction of concrete WECs.

CREATE Stage 2 outcomes:

- FEED level design of CETO 6, targeting key risks for concrete devices, including areas of high localised loading and technical viability of precast construction.
- Full-scale physical and numerical testing demonstrated water-tightness of critical precast connection with T-headed bars.
- Demonstration of 12% reduction in LCOE.

Stage 3 Aims

CREATE Stage 3 aimed to:

- Address remaining technical risks and reduce uncertainty in the commercial case for concrete WECs.
- Identify gaps and prime the supply chain to enable serial production of concrete WECs over the next 3-5 years.
- Develop a pathway for the WEC sector to exploit the material following completion of the CREATE project.

CREATE Stage 3 project partners

2. Project Technology

2. Project Technology

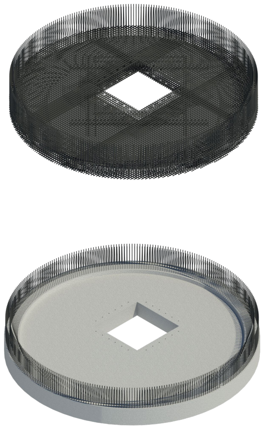
The project is technology agnostic, both in terms of the concrete material technology and WEC type. The primary advantages of reinforced concrete over steel include a low unit cost, access to an extensive supply chain and increased durability. Unlike steel structures, the design of offshore concrete structures is typically driven by strength and serviceability (e.g. corrosion protection and watertightness) requirements, rather than fatigue.

Concrete's primary constituents are **aggregate, cement and water.** The aggregate comprises crushed rock, which is bound by cement to form concrete.

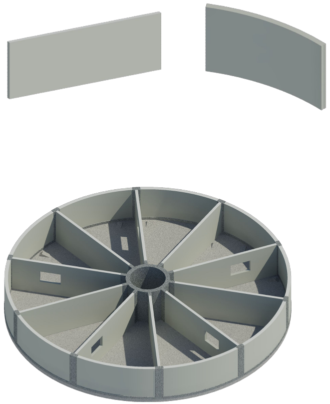
Concrete is combined with **carbon steel bars** which provide tensile strength to complement the materials' high **compressive strength**.

The three main concrete technologies are in-situ construction, precast construction and post-tensioning. **All are applicable** to WECs, but the sweet spot of technologies is highly **device-specific**.

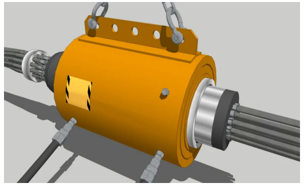
In-situ construction



Precast construction



Post-tensioning



https://3dwarehouse.sketchup.com/model/446035bb-000c-4ebd-9317-8e66a8d4a574/Post-Tensioning-jack

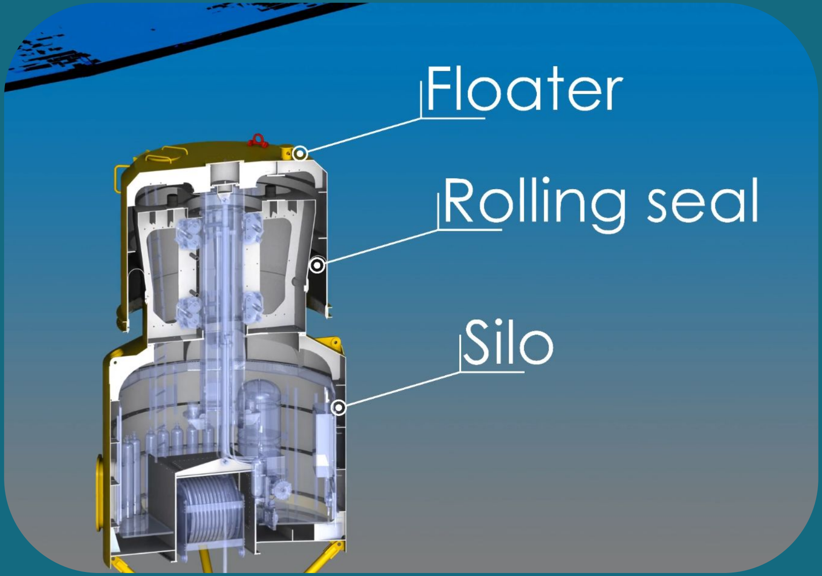
3. WEC Design Development

AWS: Archimedes Waveswing

The Archimedes Waveswing (AWS) is a submerged point absorber WEC with rated power of 250kW.

The silo is tethered to the seabed at a constant depth and the floater is free to move vertically.

The floater moves upwards under the reduced hydrostatic pressure of a wave trough, and downward under the increased hydrostatic pressure of a wave crest.



AWS: Archimedes Waveswing

There is potential benefit to constructing the silo component from concrete rather than steel.

The large target mass of the silo implies that concrete could present a more efficient structural solution by using the weight of the structure directly rather than requiring additional ballast.

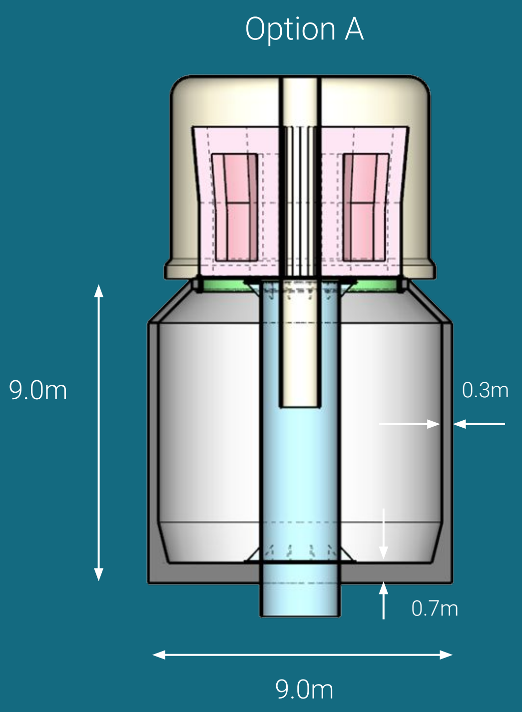
Design Philosophy

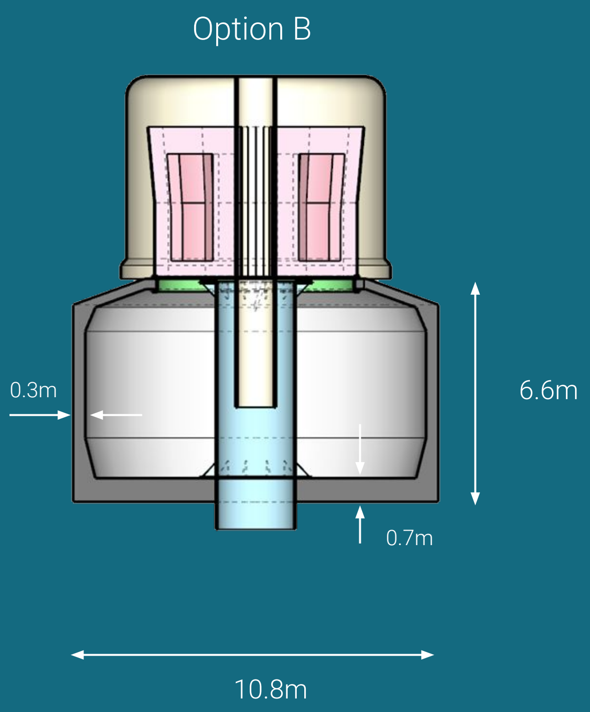
Option A

- ✔ Matches external geometry of reference design.
- ✘ Does not achieve vertical floating stability.

Option B

- ✔ Achieves vertical floating stability.
- ✘ Implications on hydrodynamic behaviour.



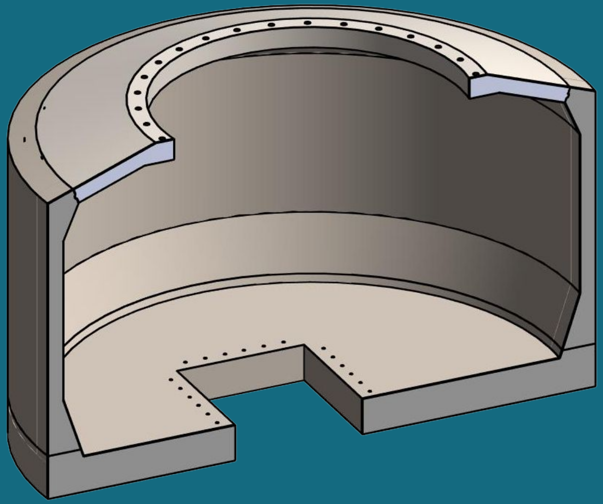


Design Philosophy

Conservative assumptions that enveloped future design iterations were considered to ensure compatibility with future designs.

The concrete silo was designed without reliance on the central steel structure, instead assuming all loads will be transferred through the concrete.

The base of the silo was designed to include a square opening to accommodate a winch.

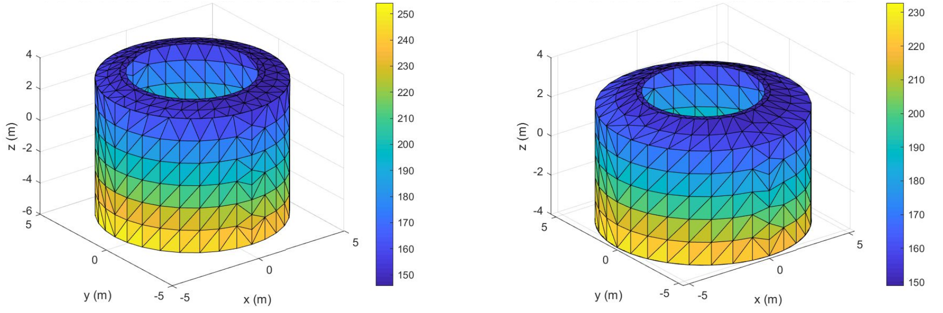


Loads & Performance

Loads and performance analyses carried out by project partner K2M indicated that it was acceptable to proceed with the design of Option B.

Case	Option A	Option B
Crushing pressure	424 kPa	412 kPa
Differential force	0.9 MN	1.3 MN
Bending moment	9.7 MN	9.1 MN
Horizontal tether force	2.6 MN	2.6 MN
Vertical tether force	9.3 MN	12.1 MN
Relative performance	100%	96%

Silo interface bending moment panel pressure (kPa)



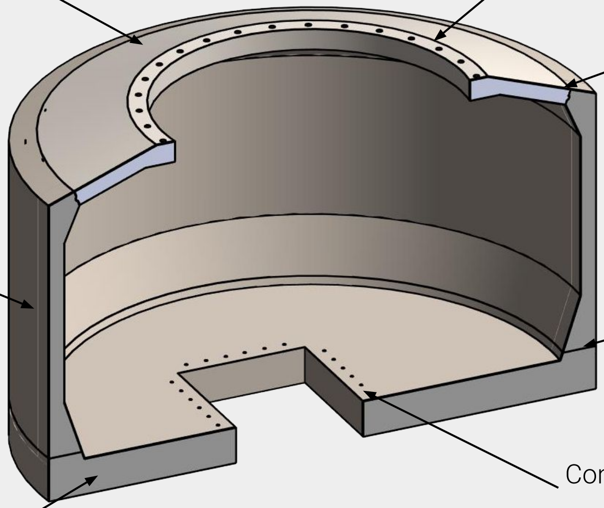
Option A Option B

Structural Design

The concrete silo is 6.6m in height with an outer diameter of 10.8m. The total weight is 355 tonnes and displaced volume 584m^3.

The design comprises the following components:

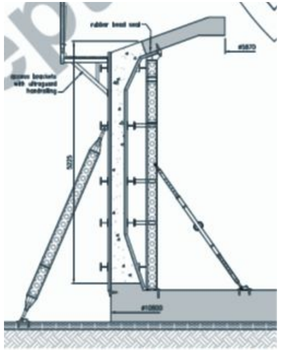
- Base slab (700mm thick, with one square 2500mm opening to accommodate the tether connection),
- Outer wall (300mm thick),
- Roof slab (300mm thick).

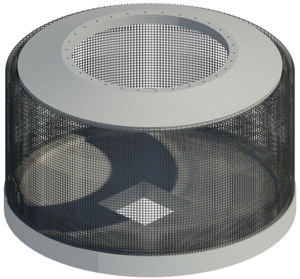


Manufacturing Assessment

Innovative construction method

Using formwork for outer wall to prop precast roof panel, eliminating need for an in-situ stitch.





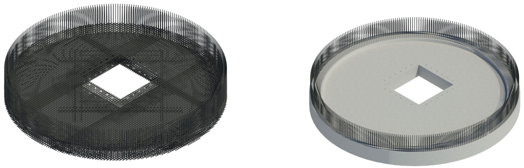
A manufacturing assessment was carried out by BAM.

Concrete silo construction	Demonstrator (1 unit)*	Mass production (100 units)
Indicative cost estimate for construction of silo (per unit)	£1,447,328	£270,924
Overall project duration from contract award	27 weeks	139 weeks
Duration to manufacture units (excluding fit-out)	12 weeks	121 weeks

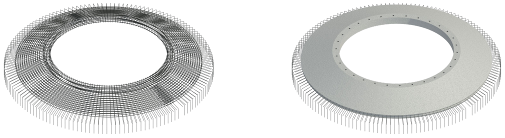
* Same production method and launch with heavy-lift crane assumed for both demonstrator and mass production.

Manufacturing Sequence

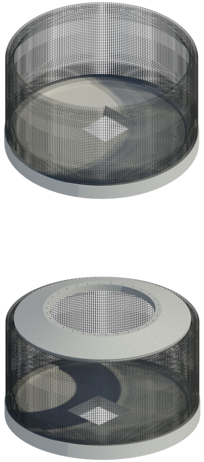
Stage 1a: Cast base slab



Stage 1b: Cast roof panels

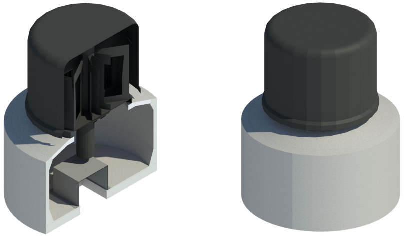


Stage 2: Construct silo



Stage 3: Move completed silo to storage area

Stage 4: MEICA fit-out and testing



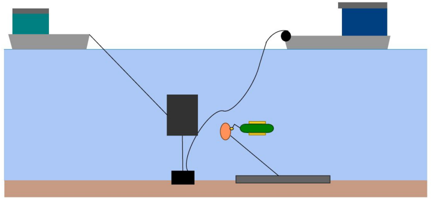
Installation Analysis

Three installation methods were assessed for the AWS device.

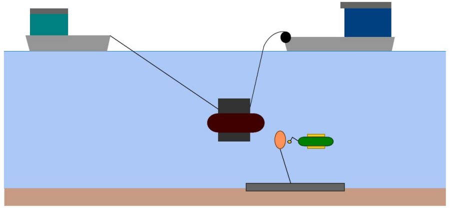
The installation method addresses the challenge of **submerging a positively buoyant** structure, and is applicable to both steel and concrete WEC devices.

Option	1	2	3
Complexity			
Stability			
Cost			

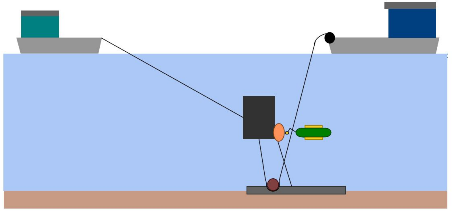
Option 1:
Gravity based ballasting block



Option 2:
Buoyancy / ballasting collars



Option 3:
Winch system



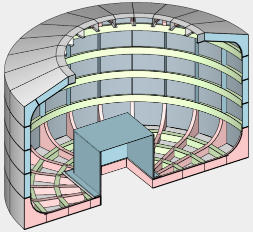
Levelised Cost of Energy

An LCOE assessment was completed following a **CAPEX assessment by BAM** of Arup’s FEED stage **concrete silo**, and" costing of an **equivalent steel silo by Arup**.

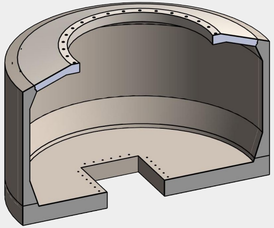
The operational mass and outer geometry of the device variants are identical, with solid ballast added to the steel device to match the concrete mass targets.

Other CAPEX components were from a previous **cost assessment by AWS** undertaken as part of their WES NWEC"Uwci g"2 project.

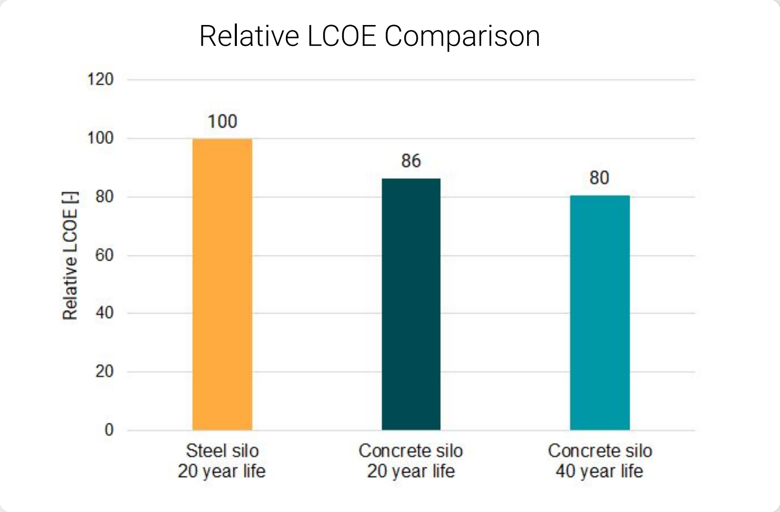
The reduction in LCOE is driven by the lower structural CAPEX cost of the concrete silo.



Steel silo



Concrete silo

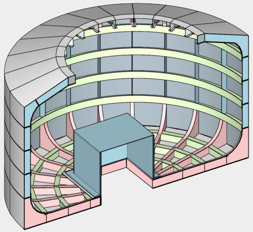


*Assuming mass production of 100 units.

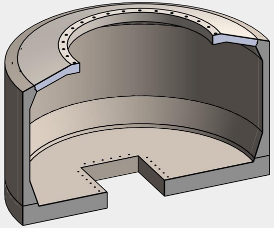
Lifecycle Assessment

A lifecycle assessment was undertaken in accordance with BS EN 15978 to quantify lifetime **environmental impacts** of the device with a concrete silo. Two scenarios were considered for steel components: virgin steel and steel with 90% recycled content.

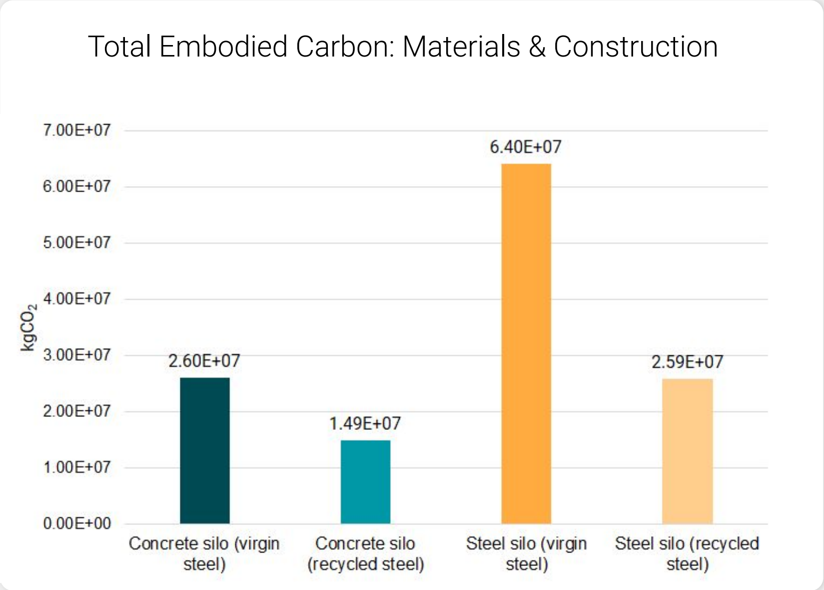
The results showed the concrete silo performs **favourably** compared to the steel silo across almost all environmental categories.



Steel silo



Concrete silo

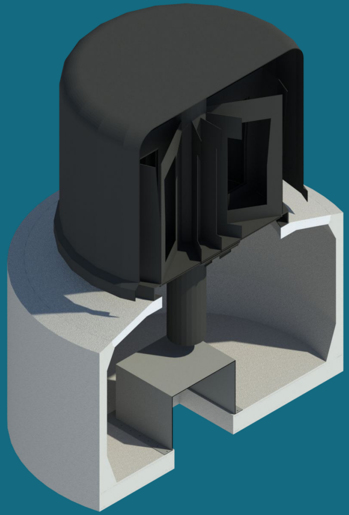


4. Findings for the WEC Sector

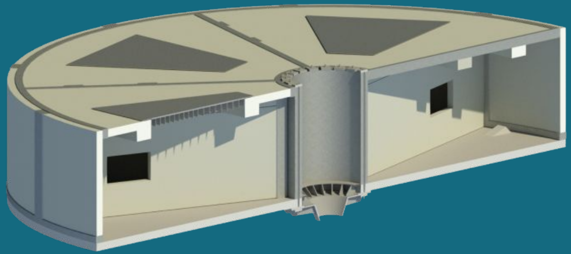
Case Studies

Two FEED-level concrete WEC designs have been developed over the course of the CREATE project: CETO 6 and AWS.

The development of these designs has resulted in several widely applicable findings for the design and manufacture of floating concrete WECs.



AWS: 250 kW



CETO 6: 1 MW

Performance

A concrete WEC may be **heavier** than the steel equivalent.

If the increased mass **is not** located in the prime mover, this is unlikely to significantly affect power performance.

If the increased mass **is** located in the prime mover, this may affect power performance. The external geometry of the structure may need modification to tune the WEC's resonant frequencies.

Device	Modelled mass increase	Change in AEP	Observations
CETO 6	+30%	-33%	Improvement may be seen if PTO settings are modified. Gain likely limited to smaller waves.
AWS	+30%	-2%	The increased mass variant showed a more severe power production in low period sea states, however the frequency of occurrence at the site of interest was relatively low.

Manufacturing Requirements

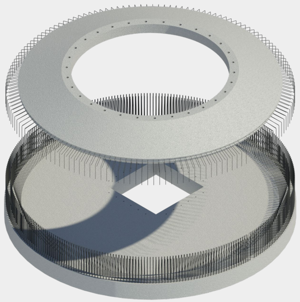
Geometry simplification
Concrete construction lends itself to straight or single curvature sections and simple extruded shapes.

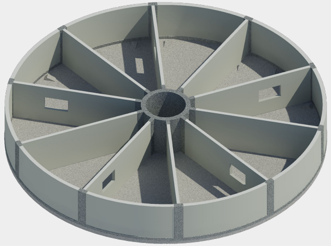
Weight assessment
A concrete device is likely to be heavier than a steel device. Methods for lifting and launch should be assessed to understand cost implications.

Design for manufacture
Early input from a contractor is important to inform the design and reduce cost of construction. Choice of construction method is highly device-specific.

Cost assessment
Concrete has a low unit cost, but a significant portion of CAPEX comes from indirect construction site costs. These depend on the selected site and available equipment.

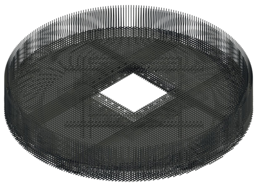
Technique selection
The most suitable manufacturing technique will vary depending on device design and scale of production. Early input from a contractor is necessary to identify the most suitable technique, which will inform the design.

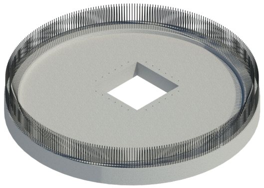




Manufacturing Techniques

In-situ construction





✔ Simple and mature technology.

✔ Achieves full strength at connections.

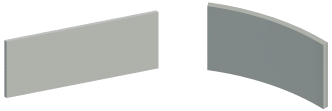
✘ Limited reuse potential for formwork.

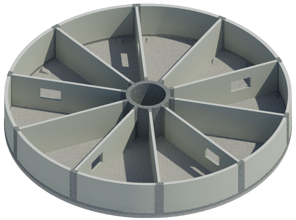
Use cases

Demonstrator devices.

Complex geometries which cannot easily be panelised.

Precast construction





✔ Efficient production of several similar components.

✔ Improved tolerance and weight control.

✘ Complex assembly and connection design.

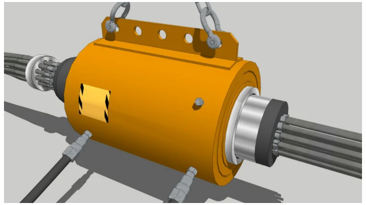
Use cases

Mass production for certain devices.

Geometries which can be panelised without a large number of stitched joints.

Manufacturing Techniques

Post-tensioning



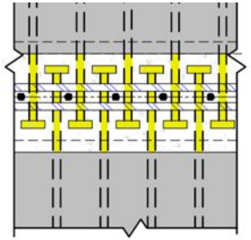
https://3dwarehouse.sketchup.com/model/446035bb-000c-4ebd-9317-8e66a8d4a574/Post-Tensioning-jack

✔ Ensures sections are under permanent compression.

Use cases

Sections that are not permanently under compression and are required to be water-tight.

T-headed bars



✔ Enables shorter stitched joints with full load-bearing capacity.

✔ Water-tightness demonstrated through full-scale testing.

✖ May place limitations on supply chain.

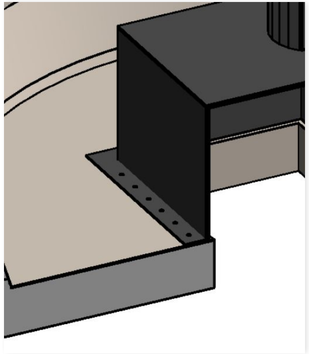
✖ Higher cost than traditional precast connection types.

Use cases

Precast construction requiring load-bearing joints and/or three-way joints

Steel-concrete Connections

Bolted flange

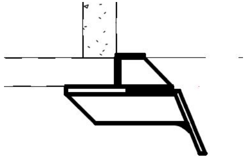


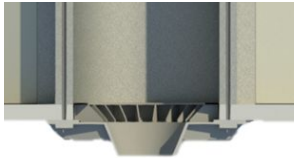
✔ Ensures efficient load transfer between steel and concrete for low shear stresses.
✔ Simple construction.

✖ May not be sufficient for high tensile loads.

Use cases
Connections where the applied shear stress is below ~5MPa.

Steel transfer structure



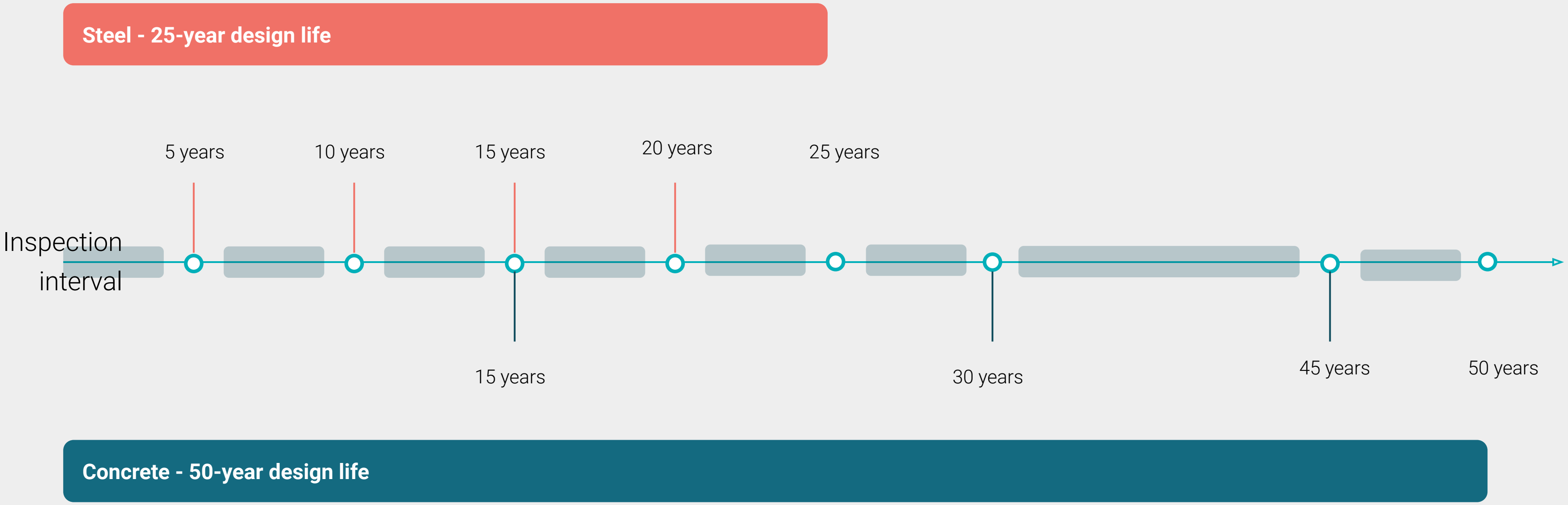


✔ Ensures efficient load transfer between steel and concrete for higher shear stresses.

✖ Depending on the design, may be expensive and complex to construct.

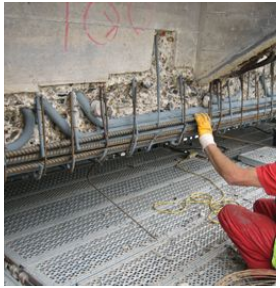
Use cases
Connections where high tensile forces must be transferred through concrete.

Maintenance & Planned Inspection



Concrete Repair

Concrete defect	Severity	Repair technique
Broken cover resulting from quayside or ship impact.	Low	Surface coatings and additional sacrificial layers. Surface removal and recasting. Injection grouting into cracks.
Spalling, where the concrete cracks and delaminates, for example as a result of reinforcement corrosion and expansion.		
Construction defects; including damage to waterproofing strips or water bars, and honeycombing (hollow cavities in the concrete due to inadequate vibration and workability).	Medium/ High	Traditional mechanical full-section removal. Hydro-demolition [use of high-pressure water jet to remove concrete]
Major quayside or ship impact.		

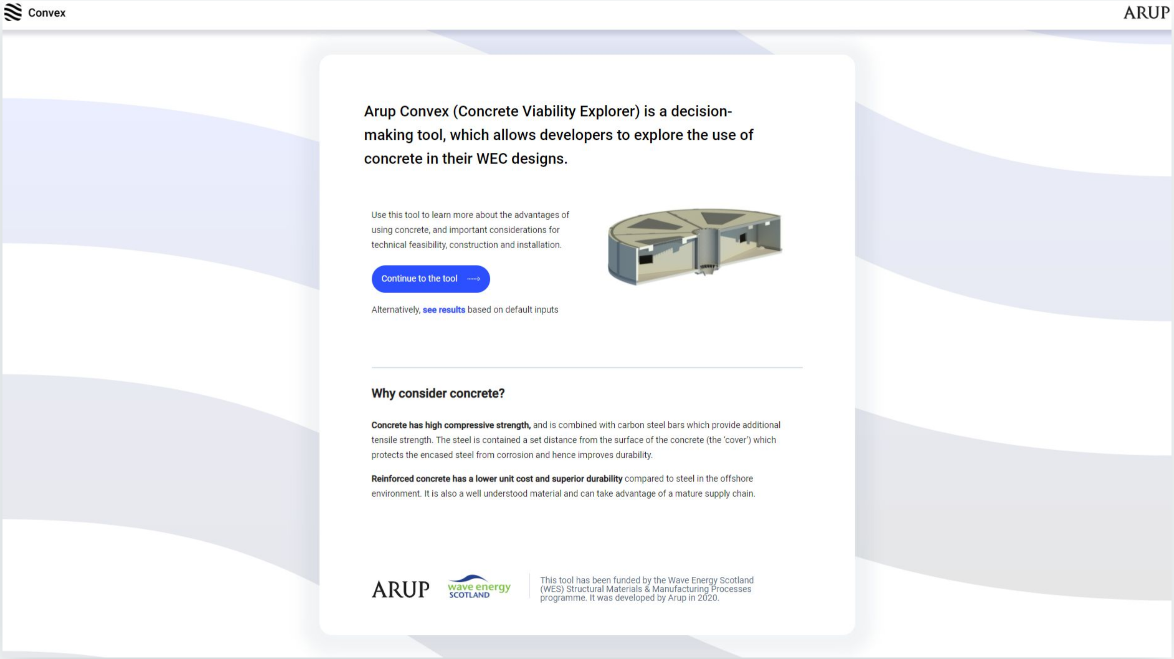


Convex

Concrete Viability Explorer

The key findings of the CREATE project are captured in **Convex**, a decision-making tool which allows developers to explore the use of concrete in their WEC designs.

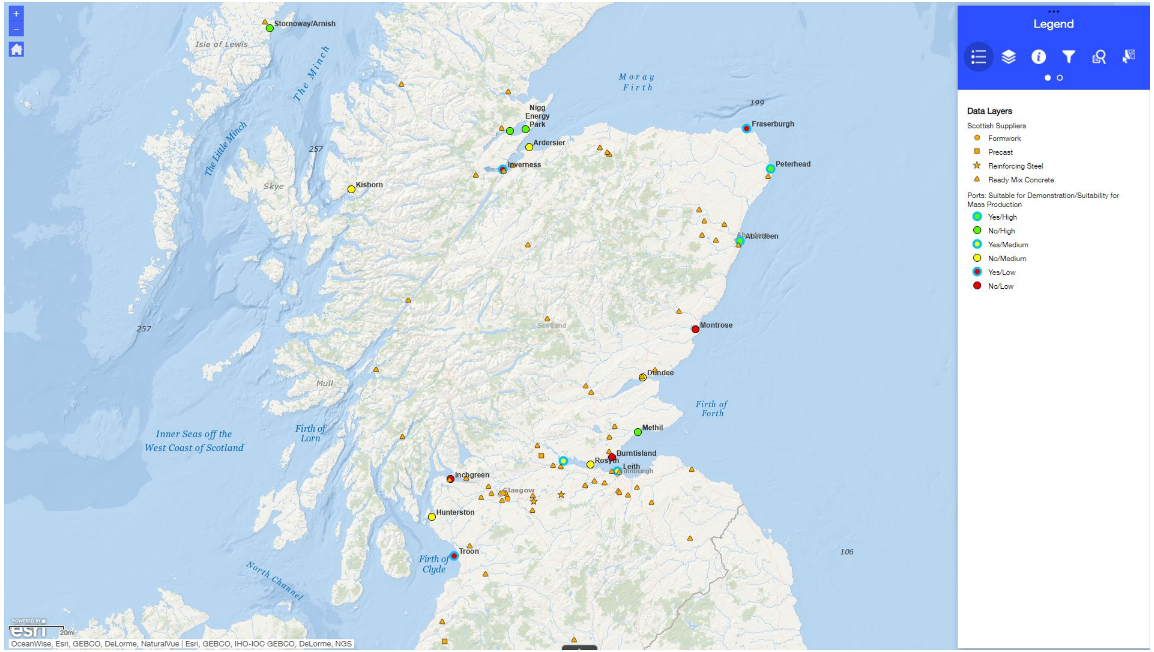
http://convex.ade.arup.com/



Supply Chain Map

An interactive supply chain map has been developed to assist the investigation of potential Scottish construction sites.

The map can be accessed through Convex.

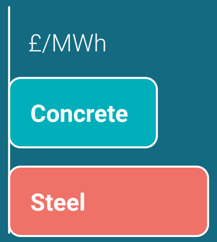


https://atlas-gb.arup.com/portal/apps/webappviewer/index.html?id=a608d8a2d60347cdaea8fd02f7449efa

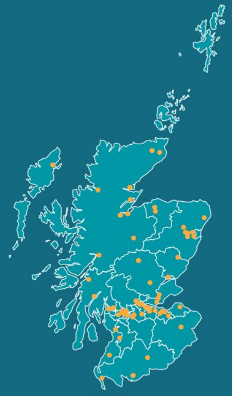
5. Route to Commercialisation

Concrete for Floating WECs

LCOE reduction
of up to 20%
compared to steel

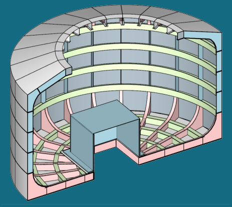


Lower unit production cost:
30%+ CAPEX savings

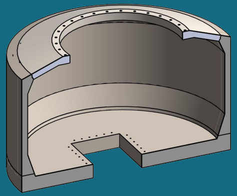


Mature local supply chain

More efficient use of materials

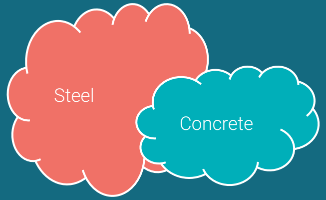


Steel



Concrete

Longer design life



CO_2 reduction

Key Findings

Concrete is a **feasible and cost-effective** material for **floating** wave energy devices.

Concrete can offer a **more efficient** solution by using the **weight** of the structure directly, rather than requiring additional **ballast**.

Concrete enables access to a **mature, local supply chain**.

Concrete has **lower** unit production **cost** and improved **durability** characteristics.

There is a compelling case for **wider commercial adoption** of this **versatile** material, including applications in **floating offshore wind** foundations.

Key Audiences

WEC Developers

Understanding the **trade-offs** between cost, performance and manufacturing considerations.

High level information to build the **business** case.

Understanding the concrete **supply chain** available locally.

Knowledge of **state-of-the-art concrete design and construction** methods.

Concrete Supply Chain

Technical viability of concrete for floating wave energy devices.

Financial viability of concrete for floating wave energy devices.

The case for wider **commercial adoption** of concrete.

Investors

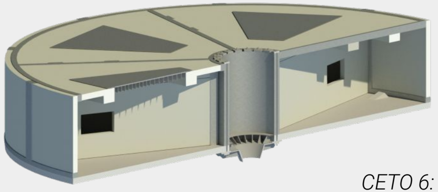
Implications of concrete on **cost-competitiveness** of WECs, and potential for reducing **risks**.

Projected route to **commercialisation** and availability of the **supply chain**.

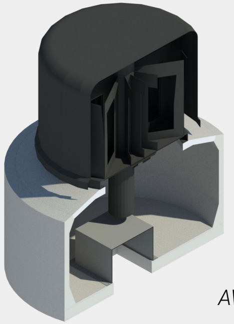
The **target market and customers** for concrete WECs.

Sustainability and carbon implications of concrete WECs.

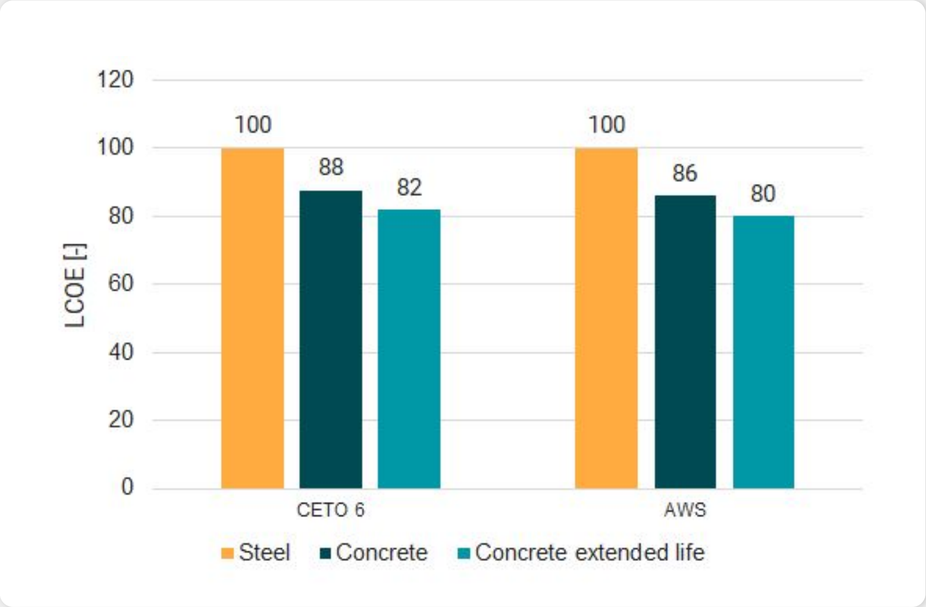
Value Case for Floating Concrete WECs



CETO 6: 1 MW



AWS: 250 kW



Based on 100 devices.

Ocean Energy Applications

Applications where concrete WECs may provide a unique advantage over steel equivalents have been identified.

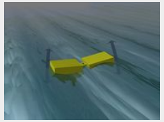
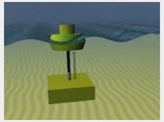
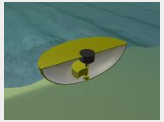
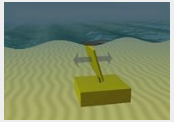
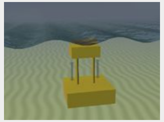
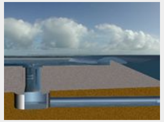
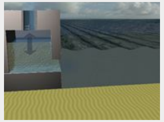
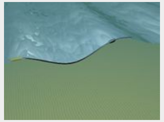
Smaller scale, niche applications present the best opportunity for wave energy devices.

- Offshore oil and gas extraction, processing, and decommissioning.
- Isolated power systems, e.g. islands and microgrids.
- Ocean observation and navigation.
- Unmanned underwater vehicle charging.
- Marine aquaculture and algae.
- Seawater mining.
- Desalination.

Concrete Specific Advantages

- Potential uses for structure at end of life
- Onboard integrated storage
- Longer device life
- Tolerance to boat impact
- Reduced fatigue and inspection
- Integration with coastal resilience strategies

Market Analysis: Sector Wide

Device Type	Attenuator	Point Absorber	Rotating Mass	Oscillating Wave Surge	Submerged Pressure Differential	Overtopping	Oscillating Water Column	Bulge Wave
Technical Feasibility	~	✓	~	~	✓	✓	✓	✗
Construction & Installation	✓	✓	✓	✓	✓	✓	✓	✗
Cost Reduction Potential	~	✓	~	~	✓	✓	✓	✗

Market Analysis: Floating WECs

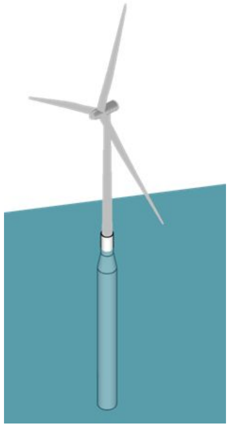
Scale	Technical Feasibility	Construction & Installation	Cost Reduction Potential	Case Studies
25kw (dia~5m)	~	✓	✓	AWS 250kw
250kW (dia~10m)	~	✓	✓	CETO 6 1MW
1MW (dia~20m)	✓	✓	✓	Wello 1MW RM3 1MW
5MW (dia~30m)	✓	~	✓	Arup WES Very Large-Scale Wave Energy Generation

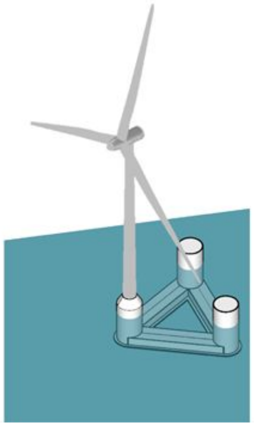
Market Analysis: Offshore Floating Wind

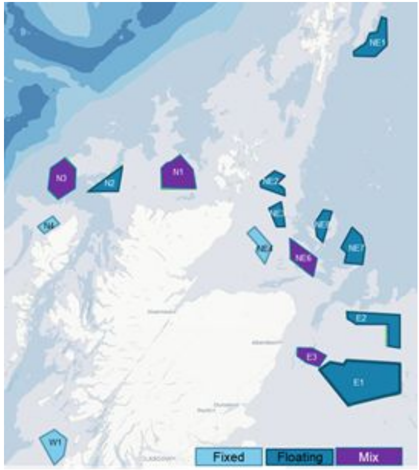
Floating wind substructures are well suited to construction from **concrete** due to their significant **ballast requirements**.

Steel floating substructures typically require **stiffening** to **sustain hydrostatic forces**. Concrete cylinders do not require stiffening and can present a more **cost effective** solution.

Traditional concrete **construction techniques** including in-situ, slip-forming and precast construction are suitable for both WECs and floating wind substructures.







Market Analysis: Offshore Floating Wind

WECs and floating wind substructures are of significantly **different scale**. This remains the case for WECs at the largest expected scale (circa 5MW).

This has implications for the **capacity of the concrete supply chain** to deliver both structures.

Construction sites developed for WEC structures are unlikely to have capacity for floating wind. It may be **uneconomic** to use sites developed for floating wind for WEC structures.

Device or foundation	Weight	Size
AWS concrete silo	495te	Diameter 10.8m Height 12.6m
CETO 6 concrete buoyant actuator	900te	Diameter 20m Height 3.5m
Concrete spar foundation	11,000te excluding ballast	Diameter 15.5m Length 180m
Concrete semi-submersible foundation	18,500te excluding ballast	Outer diameter 80m Height 40m

Concrete WEC Exploitation Activities

Short Term (<1 Year)

WEC Developers

Assess **technical feasibility** and **potential commercial benefits** of concrete using the outputs of CREATE.

Where concrete is a viable choice, seek **early contractor input** to identify the best construction port and manufacturing process for a given device. This is important to inform the design and **reduce the cost** of construction in the long term.

WES & Scottish Government

Disseminate **Convex** to ensure access by developers across the sector.

Use website data captured by Convex to **assess market interest** in concrete WECs.

Update the **GIS supply chain map** through parallel studies being undertaken by Arup into the capacity of the concrete supply chain for **floating wind substructures**.

Concrete WEC Exploitation Activities

Medium Term (2-5 Years)

WEC Developers

Contact Gael Force Group to assess the feasibility and implications of concrete construction using their **barge infrastructure**.

Assess the potential for **transitioning to concrete** devices once **commercial arrays** are ready to be constructed. A lighter material with established fabrication facilities, such as steel, could be used for **demonstrator production** in this case.

WES & Scottish Government

Identify **priority dry docks** for demonstrator construction. Will depend on proximity to demonstrator sites and operational status.

Support developers to **secure facilities** required for demonstrator production through influencing or incentivising these facilities to undertake this work. Investment to refurbish an unused dock dedicated to **low-volume WEC production** may present an opportunity depending on construction demand levels.

Concrete WEC Exploitation Activities

Long Term (5+ Years)

WEC Developers

Develop a **long-term relationship** with a **major engineering contractor** to manage serial production.

Examples include:
BAM Nuttall, Hochtief, Balfour Beatty and Costain.

WES & Scottish Government

Understand requirements of different developers in relation to manufacturing, launch and O&M activities.

Lobby on behalf of the wave sector when **port infrastructure** is being planned.

Provide guidance and access to **funding mechanisms** for ports.

Liaise further with **major contractors** to understand the capacity and appetite for offshore concrete construction.

Concrete Supply Chain

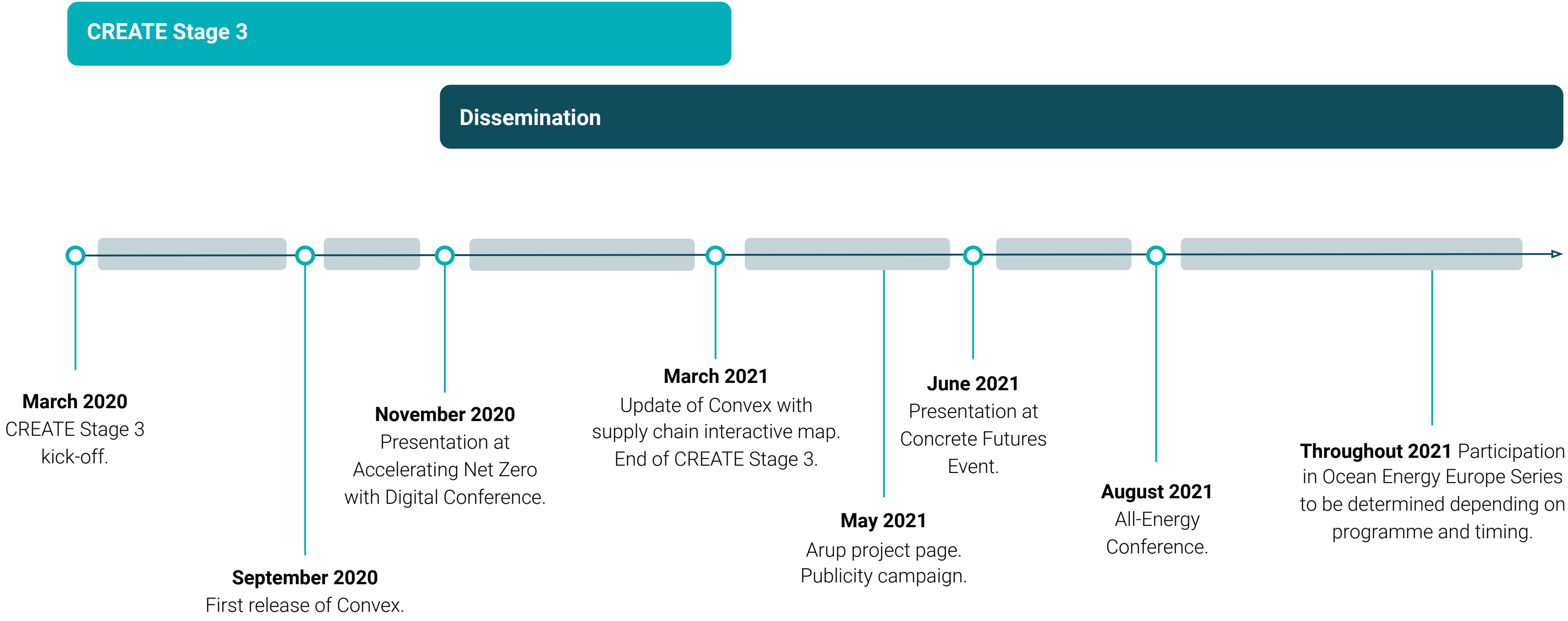
Support **skills development** in Scotland. Demand from the sector is likely to bring key supervision and operative skills to Scotland.

Assess opportunities for **upfront capital investment** in construction infrastructure to reduce costs in the long term. **Collocation** options may be effective.

Establish a relatively small site suitable for dedicated **serial WEC manufacture**.

6. Communications and Publicity Activity

Dissemination Plan



Weblinks

Convex: Concrete Viability Explorer (2021)
http://convex.ade.arup.com/

Arup conference: Accelerating net zero with digital (2020)
https://www.arup.com/perspectives/accelerating-net-zero-with-digital

Arup press release (2020)
https://www.arup.com/news-and-events/arup-consortium-secures-funding-from-wave-energy-scotland-aiming-to-bring-down-cost-of-wave-power

Arup project page
https://www.arup.com/projects/convex

WES project page
https://www.waveenergyscotland.co.uk/programmes/details/structural-materials/concrete-as-a-technology-enabler-create/

7. References

Codes and Standards

Publicly Available

Code	Title	Issue
DNVGL-ST-C502	Offshore standard: Offshore Concrete Structures	Feb 2018
BS EN 1992-1-1:2010	Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings	2010
BS 4449:2005	Steel for the reinforcement of concrete – Weldable reinforcing steel, bar, coil and decoiled product	2005
IEC TS 62600-2:2016(E)	Marine energy – Wave, tidal and other water current converters – Part 2: Design requirements for marine energy systems	2016
BS 3692:2014	ISO metric precision hexagon bolts, screws and nuts – Specification	Oct 2014
DNVGL-ST-0126	Offshore standard: Support structures for wind turbines	April 2016
DNVGL-RP-C203	Fatigue design of offshore steel structures	April 2016
BS 7608:2014	Guide to fatigue design and assessment of steel products	March 2014
DNVGL-OS-C101	Design of offshore steel structures	July 2015
BS EN 15978:2011	Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method	Nov 2011

Project Documents

Available on Request

Author	Stage	Document Ref.	Title
Arup	2	WES_ARP_MT21_D06	Structural Design Report
Arup	2	WES_ARP_MC21_D09	Manufacturing Report
Arup	2	WES_ARP_MT21_D10	LCOE Assessment
K2M	3	WES_ARP_MT31_D06	AWS Loads and Performance
Arup	3	WES_ARP_MT31_D04	Analysis Report Structural Design Report
Arup	3	WES_ARP_MT31_D02b	Manufacturing Report – AWS
Arup	3	WES_ARP_MT31_D02a	Manufacturing Report – General
Arup	3	WES_ARP_MT31_D04a	Maintenance and Marine Operations
Arup	3	WES_ARP_MT31_D04b	AWS Installation Analysis
Arup	3	WES_ARP_MT31_D07a	LCOE Assessment
Arup	3	WES_ARP_MT31_D07b	Business Plan
Arup	3	WES_ARP_MT31_D08	Exploitation Plan

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