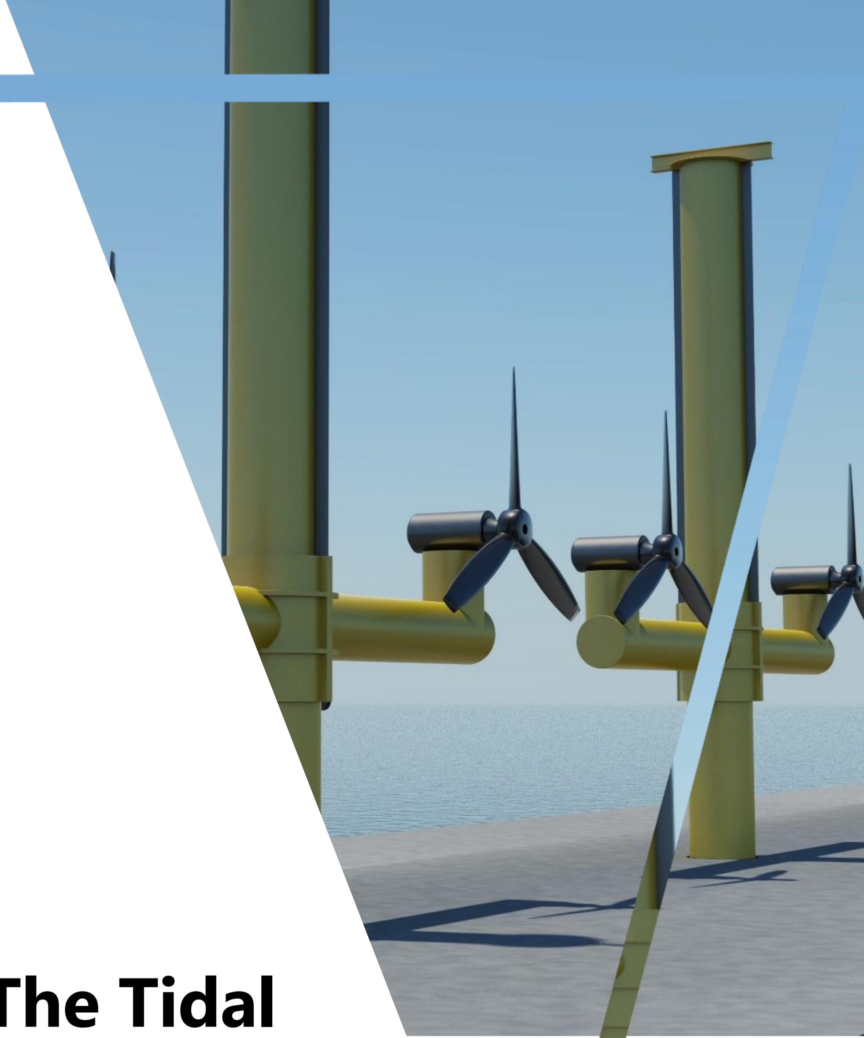

2016/ARP002 - The Tidal Turbine Reef (TTR) Feasibility Study

ARENA Tidal Turbine Design Report

Level 4, 600 Murray St
West Perth WA 6005
Australia

301320-14359-MA-REP-0003

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Project No: 301320-14359-MA-REP-0003 – 2016/ARP002 - The Tidal Turbine Reef (TTR) Feasibility Study

Rev	Description	Author	Review	Approval	Date
0	Issued for Use	Lee O'Neill	Bill Barker	Lee O'Neill	18-May-18

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1 Summary

ARENA has granted $280,000 under its Advancing Renewables Program to WorleyParsons, who has formed a partnership with EcoFin Solutions, SCHOTTEL and Civmec, to study and develop a front-end engineering design for a tidal turbine reef (TTR) device concept. The premise of this scope was to create a fixed (in location) tidal turbine energy device that has a reduced installation and maintenance cost when compared to conventional designs.

The study created an initial design for a generic tidal site so its viability could be assessed in terms of technical feasibility, project risk and key financial drivers, with the findings incorporated into a second design cycle. The second design cycle tailored the concept for a candidate site in Australia.

The resulting TTR device comprises a reinforced concrete foundation base with four steel columns that support a single row of eight turbines on a tractable support structure, as illustrated in Figure 1-1. The TTR is proposed to be installed about 200 m off the coast in Pearl Pass in water 13 m deep (relative to lowest astronomical tide, or 'LAT'), eliminating the need for subsea cabling and minimising the complexity and requirements of aerial cabling.

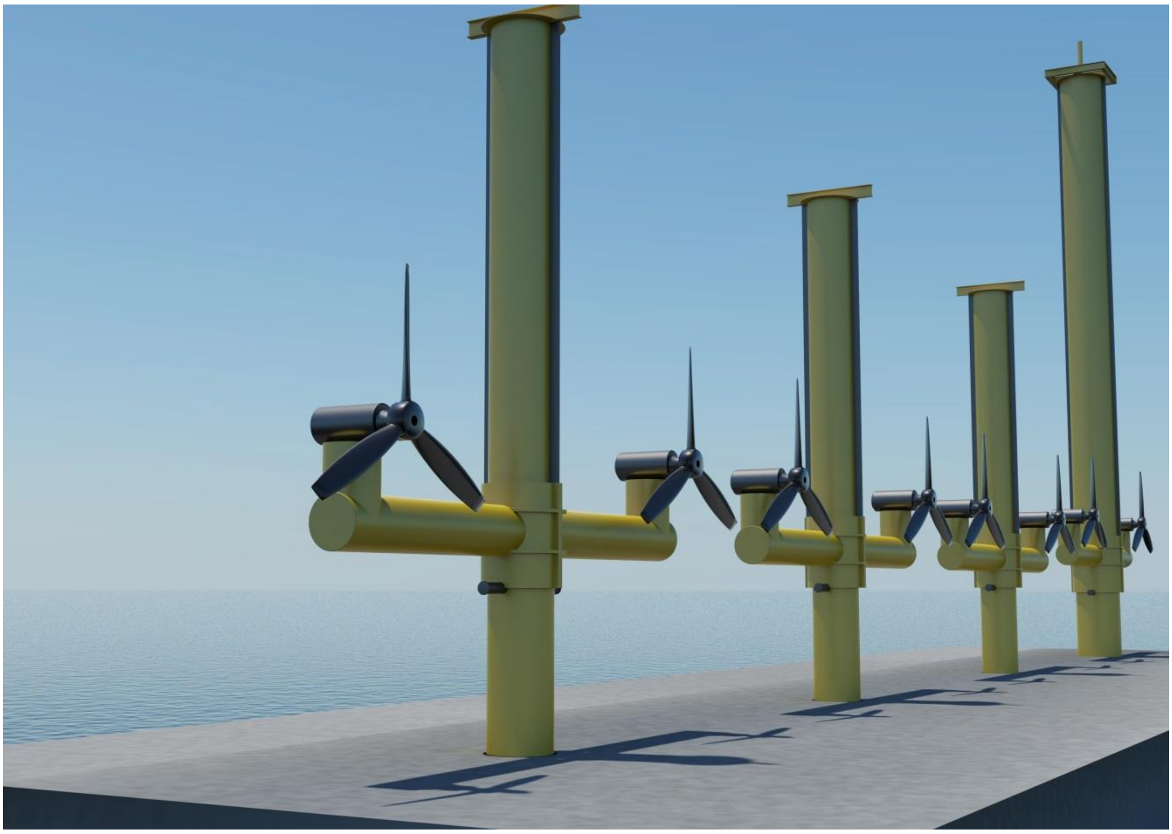

Figure 1-1: TTR device structure concept

The preliminary work in this phase has led to a foundation base approximately 15 m wide by 54 m long by 4 m high, which is divided into 16 internal compartments. The foundation base is to be grouted to the seabed after installation to adequately resist the tidal current velocities. The turbines are supported off four columns that protrude past the low tide levels. One column is taller, which allows a power pole to be located on top which will connect to a power wire that will be fed back onshore. A lifting mechanism will be installed to allow the turbine support structure to be lifted above the low tide cycle to access the turbines for maintenance.

To minimise capital expenditure (CAPEX) costs, the TTR was designed to be self-floating and self-installing to reduce the requirements of installation spreads and support vessels. The concrete foundation base was designed to contain enough reserve buoyancy to be able to be wet-towed to site using a single tug, and have compartments flooded to allow a controlled descent 'sea-chesting' installation procedure.

This concept was developed based on certain assumptions which would need to be confirmed in the next phase of development. This TTR device concept relies on a flat surface of bedrock and relatively shallow water depths to allow the structure to be sea-chested onto the seabed. Selecting a site with deeper water will increase the length of the foundation base significantly, which can potentially make this type of structure unfeasible. In addition, if the TTR requires being installed further from the coast, it would need to use expensive subsea cabling to run power back onshore, and may only then be feasible if developed in an array of multiple devices.

The TTR is proposed to be fabricated at Civmec in Henderson, where it will be launched into the quay using a floating dry dock. The TTR will be towed to Broome where it will be temporarily moored until the installation contractor tows the TTR the short distance to One Arm Point for installation. The tow from Broome to site will be weather-dependent; the journey will only go ahead if the tide is in a neap cycle and the three-day installation window forecast is calm. The advantage of breaking the entire transport into two separate tows is that the initial tow to Broome is less reliant on weather, and will not incur vessel day rate charges if the forecasted installation environment is not suitable upon arrival at Broome.

Due to limitations on the water depth of this site, the TTR concept was restricted to a single row of turbines. If a nearby location reveals slightly deeper water (required water depth is about 16-18 m relative to LAT), an additional row of turbines can be added to the TTR structure with minimal impact to the current design and therefore minimal impact to the CAPEX cost. The arrangement would need to stagger the turbine rows with a set lower than the other, to allow the current to pass without interference from the row in front. Preliminary investigations suggest there would be an optimum number of turbines installed using this technique of multiple rows that can reduce the CAPEX cost per turbine by one third.

The economic modelling of the eight-turbine device at One Arm Point shows a levelised cost of energy (LCOE) to be $825/MWhr for an estimated annual peak current speed of 10 knots. The total CAPEX for the device is estimated to be $8,795,000 with an annual operating expenditure (OPEX) of $354,868.

The TTR concept is very site-specific. For locations that have the required water depth, current speed and proximity to land, the energy production costs are still roughly an order of magnitude higher than conventionally generated electricity, but still in the same order of magnitude of remote diesel generated electricity.

2 Introduction

A partnership has been formed by WorleyParsons (engineering, procurement and construction management), EcoFin Solutions (renewable energy consultancy and financial modelling), SCHOTTEL Hydro (turbine designer and manufacturer) and Civmec (fabricator) to develop a front-end engineering design (FEED) for a tidal turbine concept. The concept is called the Tidal Turbine Reef (TTR), and the premise is to create a fixed location tidal turbine energy device that has a reduced installation and maintenance cost when compared to conventional designs. Key features include dry electrical connections, a self-installing offshore structure component, minimal equipment required for turbine inspections, and live unit turbine access.

The project involves two phases, with the aim of ultimately producing a technically and commercially optimal design.

2.1 Phase 1A

Phase 1A was completed in May 2017. In this phase of the design cycle, the initial proposed TTR design was developed to a basic stage where preliminary financial assessment could be performed against international benchmarks. Fundamental design documentation was started to capture content to be fed into this Phase 1B design development. The Phase 1A concept depicted in Figure 2-1 was shown to be economically unviable at today's electricity prices and in moderate tidal conditions, as shown in Figure 2-1. Ref [1]. Particular financial issues were around the transmission costs and the size of the supporting structure.

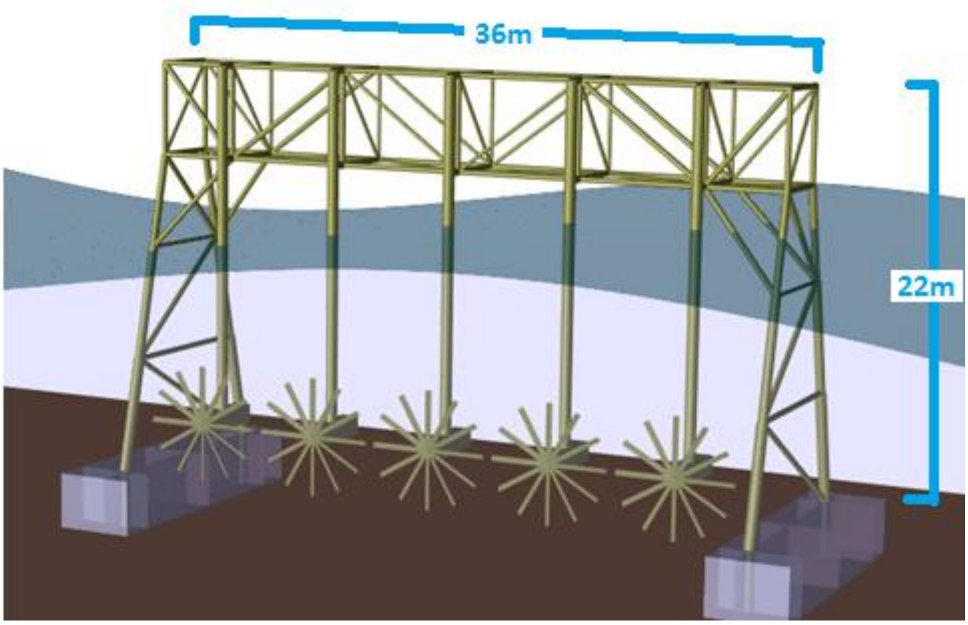

Figure 2-1: Phase 1A TTR concept

Table 2-1: Phase 1A financial modelling results

Five Turbines / Six Devices			
	2 m/s max	3 m/s max	4 m/s max
Farm Size [MW]	2.1	2.1	2.1
Max Flow [m/s]	2 (0.84 avg)	3 (1.2 avg)	4 (1.6 avg)
Annual Energy Capture [MWh]	1691	5142	8392
Capacity Factor (average)	9%	28%	45%
CAPEX [$/MW]	15,779,049	19,018,485	23,553,697
OPEX [$/MW]	675,763	805,340	986,749
Feed in Tariff [$/MWh]	140	140	140
Grant [$]	N/A	N/A	N/A
LCOE [$/MWh]	2337	939	710
Net Present Value [$]	-40,404,347	-43,852,007	-51,043,467

Key conclusions drawn from the financial modelling were:

- Cost is double industry standard
- Annual revenue projections would be unable to cover annual OPEX
- Based on assumed feed in tariffs, the current design and associated costs mean the project is a long way from being commercially viable
- Using a resource with a higher current than max 3 m/s does not make a substantial difference to the LCOE, nor does adding more turbines. That being said, any resource used with lower max current speed than 3 m/s significantly hinders the viability of the project.

2.2 Phase 1B Objectives

Phase 1B initially widened the focus of the TTR design to respond to findings from Phase 1A. The design was modified to best fit within the CAPEX and OPEX thresholds defined in Phase 1A as well as being tailored for a candidate site in Australia. Phase 1B ultimately narrowed the design down to a single concept to be built and installed off One Arm Point in Western Australia, supplying electricity to the Ardyaloon community which currently relies on diesel for power.

Key deliverables from Phase 1B are:

1. Design Report:
    a. Structural Analyses
    b. Material Take-Off and Equipment List
    c. Transportation and Installation Plan

   d. Drawings
   e. Maintenance Plan
   f. Fabrication Proposal Report
   g. Calculation Dossier.
2. Project Cost Estimate
3. Economic Feasibility Modelling:
   a. Environment Sensitivity Modelling
   b. Cost Driver Analyses
   c. Concept Comparison
   d. CAPEX and OPEX Benchmarking.

They key objective of Phase 1B was to do sufficient design, engineering and costing to state whether the concept is commercially viable, and provide enough detail so the concept can move to the next phase of development.

2.3 Acronyms

Table 2-2: Acronyms

Acronym	Meaning
CAPEX	Capital Expenditure
CD	Chart Datum
CFD	Computational Fluid Dynamics
EL	Elevation
FEED	Front-End Engineering Design
HAT	Highest Astronomical Tide
IRR	Internal Rate of Return
kW	Kilo Watt
kWh	Kilo Watt Hour
LAT	Lowest Astronomical Tide
LCOE	Levelised Cost of Energy
MW	Mega Watt
MWh	Mega Watt Hour
NPV	Net Present Value
OPEX	Operating Expenditure
SIT	SCHOTTEL Instream Turbine
SPMT	Self-Propelled Modular Transporters
TCP	Total CAPEX
TTR	Tidal Turbine Reef
VIV	Vortex Induced Vibrations

3 Basis of Design

3.1 Location Selection

The site selected for the proposed TTR device concept is at One Arm Point, located about 200 km north-east of Broome (Latitude -16.437894° and Longitude 123.079682°), as shown in Figure 3-1. One Arm Point is a remote community with 1770 MWh of diesel power consumed annually. Ref [2]. The community is close to Pearl Pass which has a semidiurnal tide range of roughly 9 m with nearby currents up to 10-12 knots, which makes this location ideal for tidal energy power.

The community has 100 houses with some shops and a fish farm, and is set about 1.5 km from Pearl Pass. About 100 m from the water's edge, a water depth of 13 m in respect to LAT can be achieved. Ref [3]. Refer to Figure 3-2 to Figure 3-4 for supporting information.

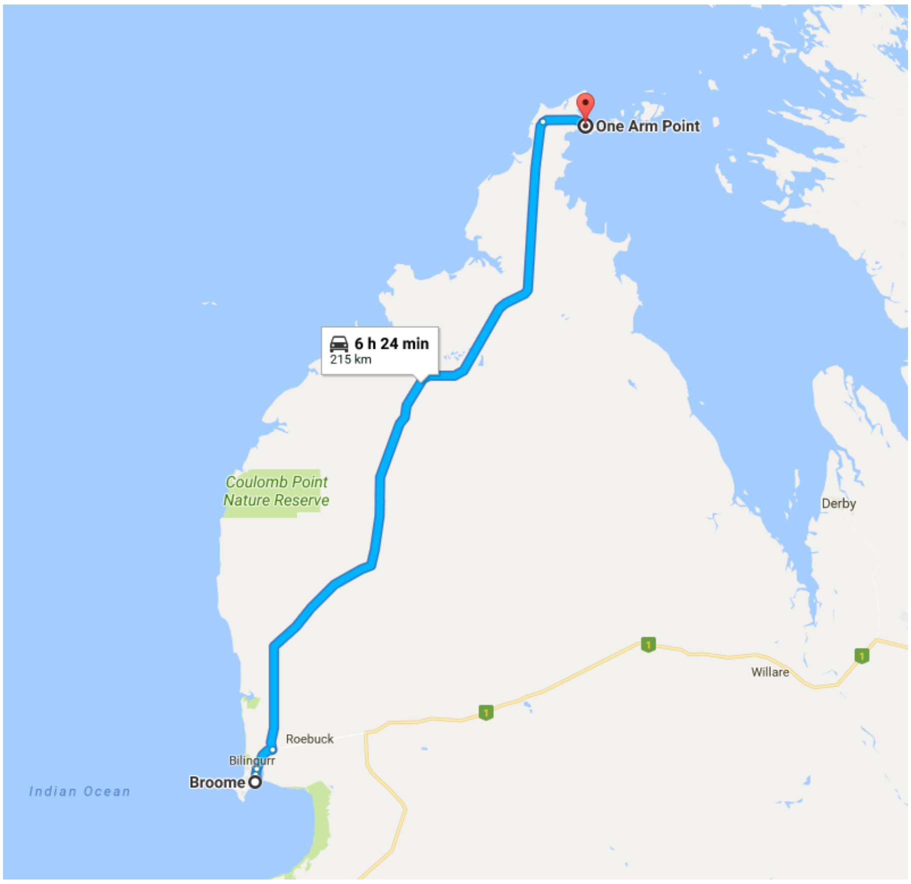

Figure 3-1: Location of One Arm Point

Figure 3-2: Map of One Arm Point and community

Figure 3-3: Proposed location of TTR device

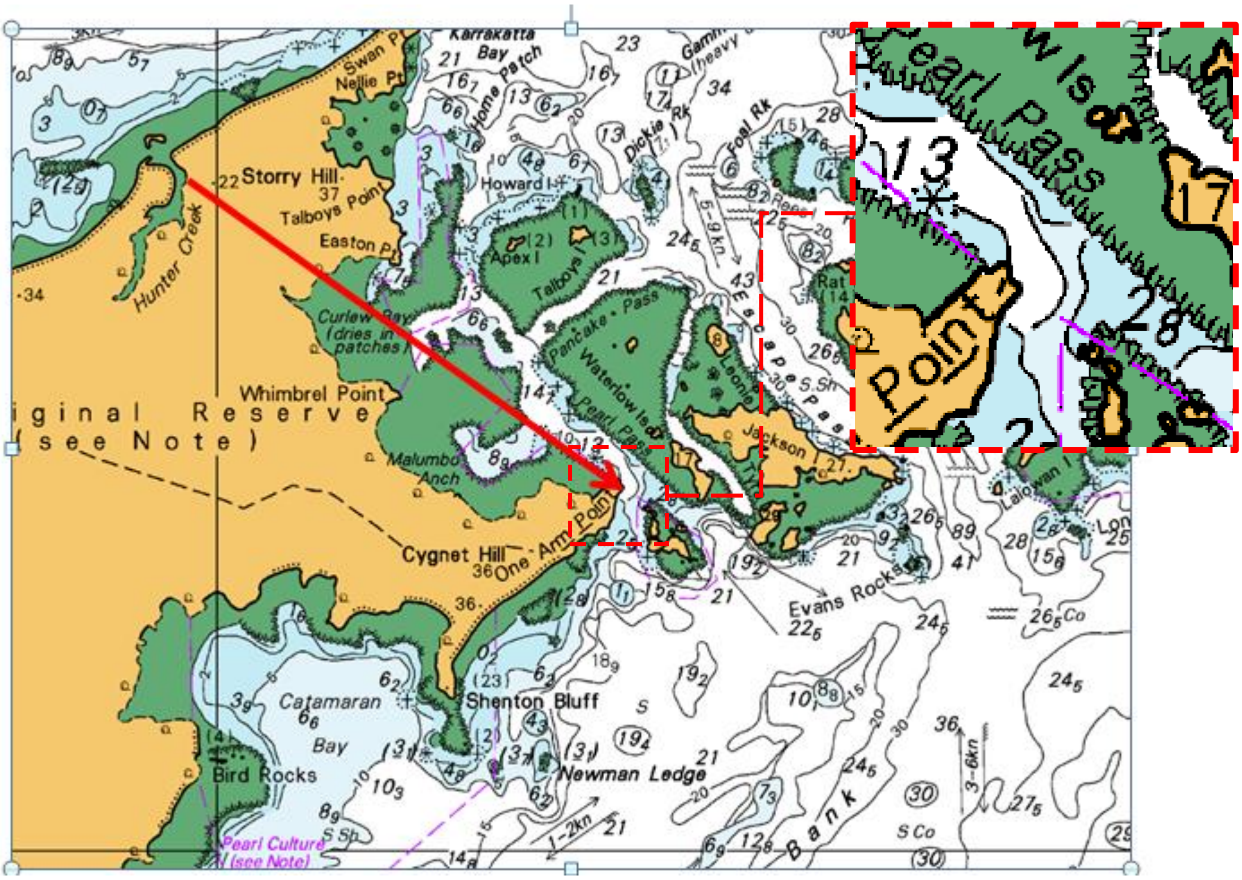

Figure 3-4: Nautical chart of One Arm Point. Ref [3]

3.2 Location Environment

3.2.1 Tidal Elevation

Tidal constituents are available for Karrakatta Bay, which is just north of One Arm Point. Based on these constituents, the following tidal predictions can be made:

- There is a significant variation of tidal range throughout a typical tidal cycle. Typical tides at spring are in the range of 8-9 m, whereas typical tides at neaps are in the range of 1-3 m.
- The magnitude of neaps and springs varies through the year, with the largest springs and smallest neaps being found around the equinoxes (March and September).

Time series for one month (March 2017) and the full year (2017) are shown in Figure 3-5 and Figure 3-6 respectively.

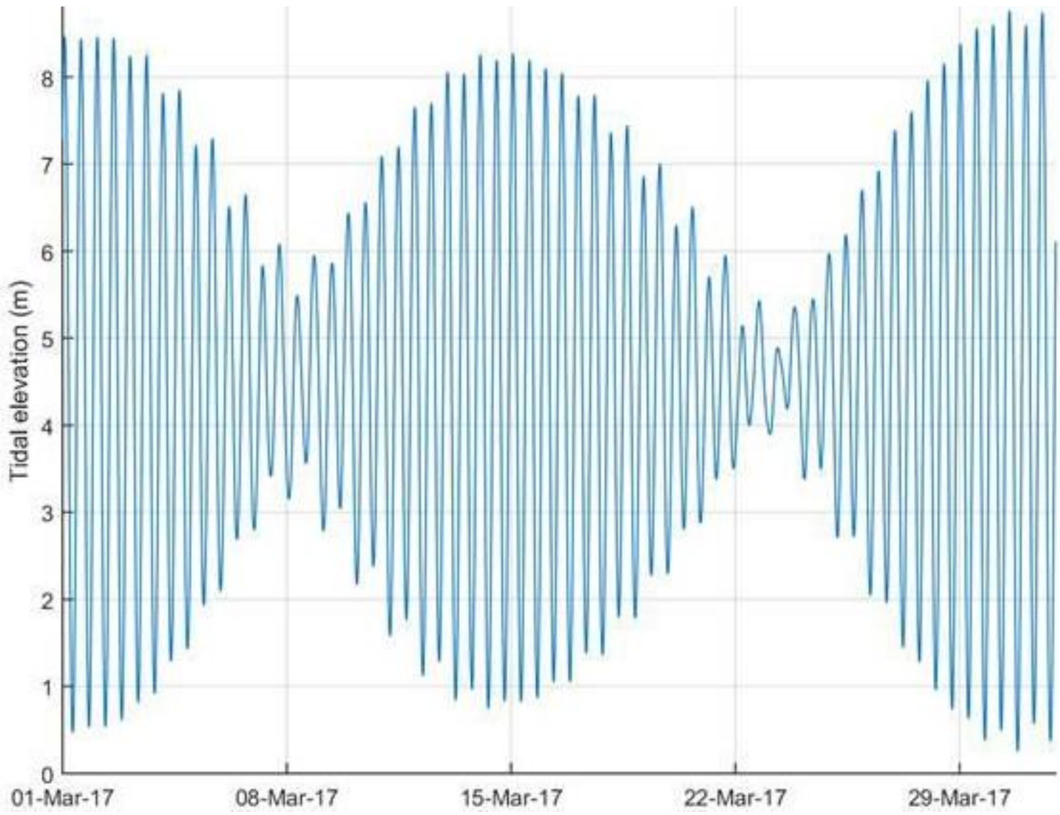

Figure 3-5: Predicted tides for March at Karrakatta Bay (One Arm Point)

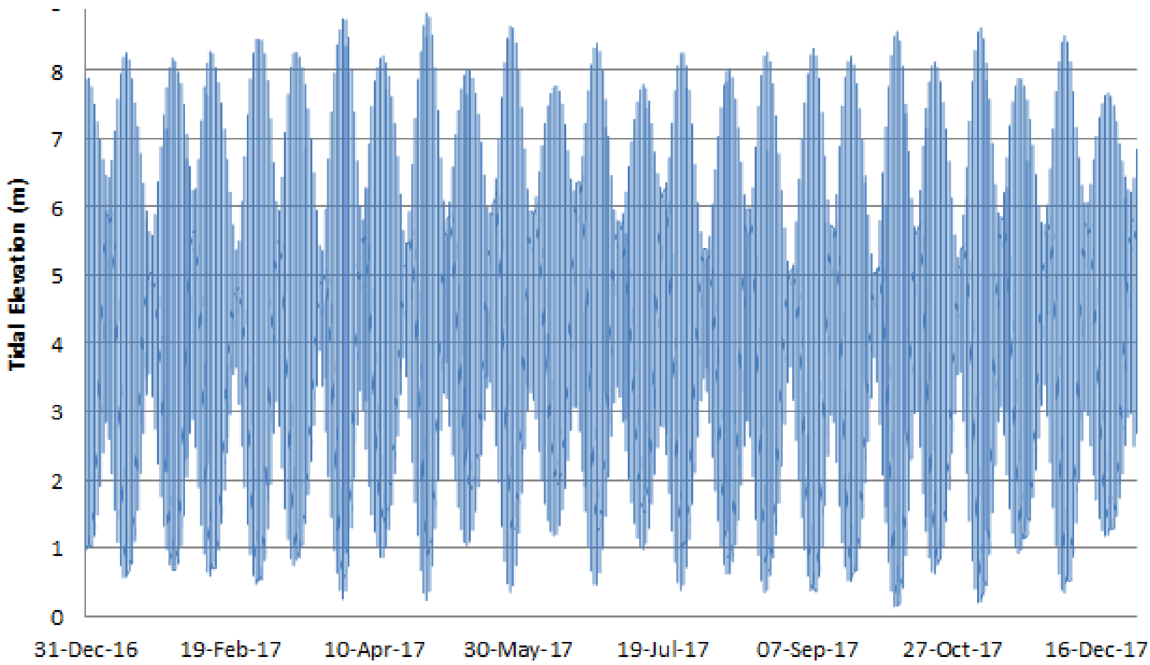

Figure 3-6: Predicted annual tides at Karrakatta Bay (One Arm Point)

3.2.2 Estimates of Current Speed

Measurements of current speed near Irvine Island (north-west of Cockatoo Island) were available as plots, along with tidal stream harmonic analysis of the current data at several locations around Irvine Island.

The profile and magnitude of current speeds are highly dependent on bathymetry. Bathymetry in the area is very complex, with many bays, outcrops and inlets. This means no current data from other locations can be applied directly to One Arm Point. However, tidal ranges and tidal cycles at both locations will be similar due to their proximity. This means the current speed is likely to vary in a similar way during a tidal cycle, and current speeds at neap tides will be significantly lower than current speeds at high tides.

Based on the harmonic analysis of the current data near Irvine Island, a generic current speed time series is generated and a scaling factor applied so the maximum current speed matches 8, 10 and 12 knots. Based on nautical charts, this is the expected maximum current in the area. No actual current speeds indicated in charts or plots exist in Pearl Pass. Arrows on the chart south of the pass indicate there is a jet current coming out and going into Pearl Pass, indicating strong currents. Currents in nearby passes are strong at 10 knots, so there is a good chance it will be the same in Pearl Pass. Ref [4,5].

The Ardyaloon website mentions that at spring tide the currents range from 12-18 knots. Ref [6]. This is very high and could be due to the pass being narrower or possibly a units mistake and should be km/hr, making it more consistent with nearby passes.

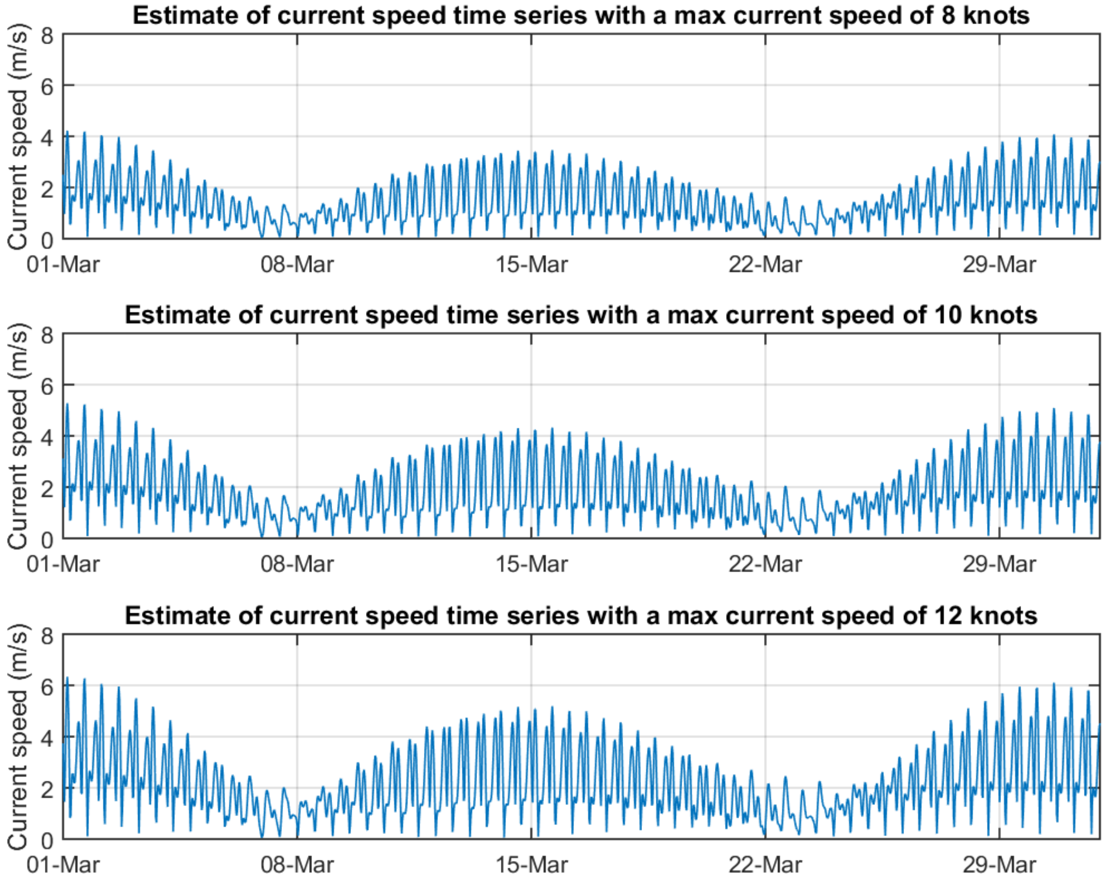

Figure 3-7: Time series of one generic tidal cycle, scaled to three maximum current speeds (8, 10, 12 knots)

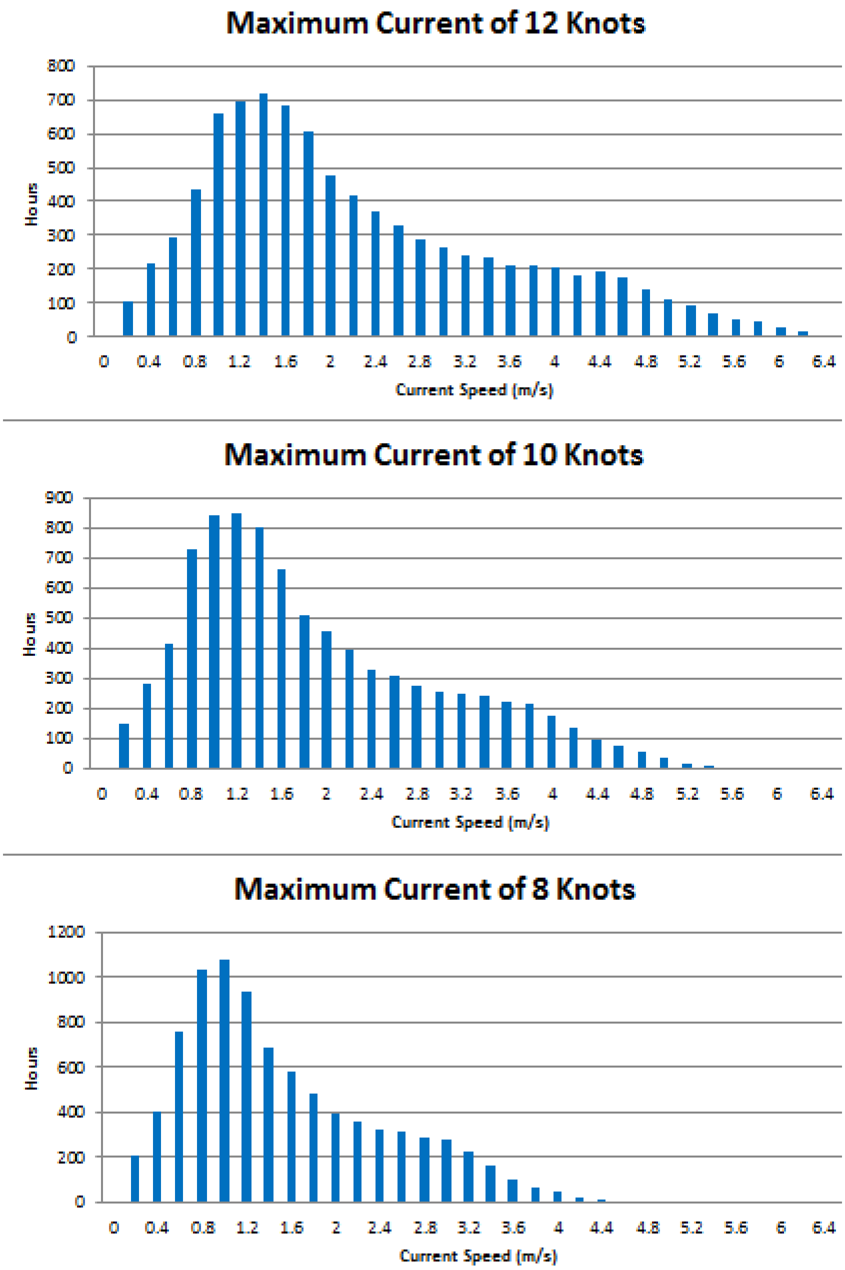

Figure 3-8: Histogram for annual current speeds based on maximum current

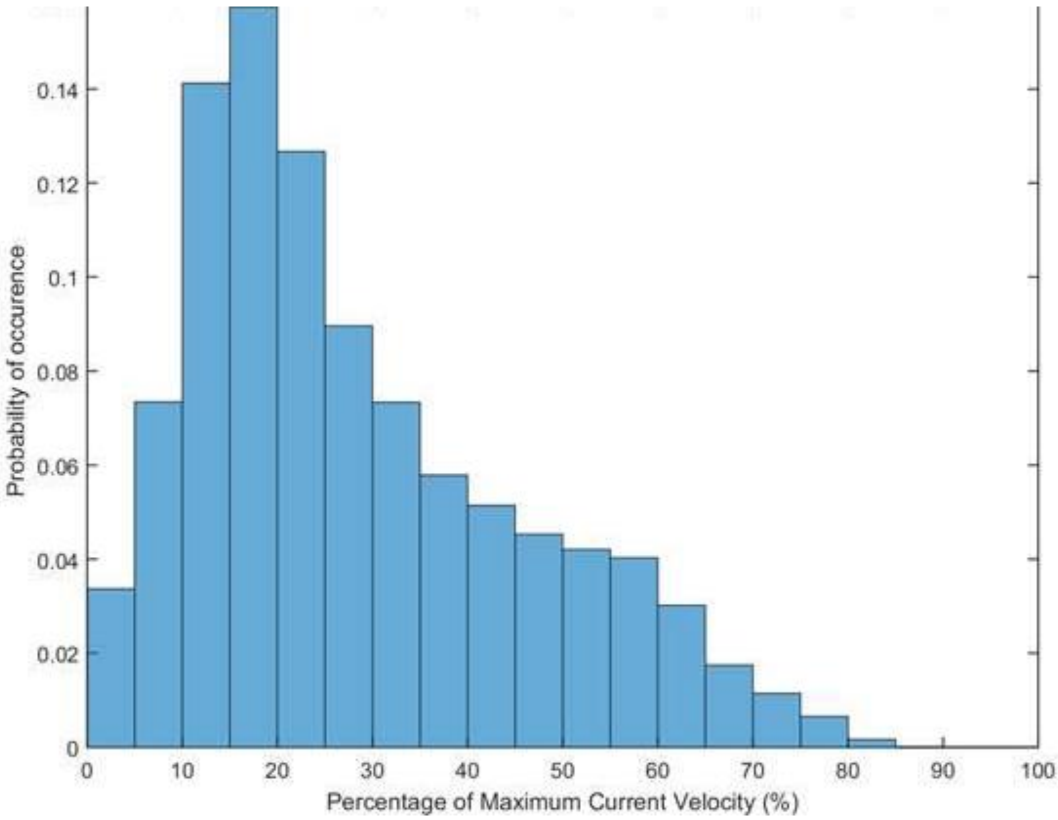

Figure 3-9: Predicted histogram of current speeds at One Arm Point

The following observations are noted on the current velocities:

- Variation in current speed along a tidal cycle follows the same pattern as the tidal elevation: large at spring tide, small at neap tide
- While the maximum peak current speeds are expected to be strong, the current speed is less than a third of the maximum current speed around 60% of the time
- At neap tide there are periods where expected peak current speed is relatively low (<1-2 m/s). This could give a window for installation if this coincides with low wind speeds.

The current predictions are based on coarse assumptions. It is highly unlikely that current speed time series at One Arm Point will look exactly like Figure 3-7. The magnitude could be different as well as the profile. Ebb-flood tides could be of the same order of magnitude, but could just as well be asymmetric (for example, flood current could be significantly stronger than ebb current). However, two items are likely to be realistic: the pattern of spring-neap variation in the ebb and flow, as well as the semidiurnal tides (two flood and ebb cycles per day) most of the time.

3.2.2.1 Installation Current Speeds

Currents for TTR installation should be based on neap tides. Operations that may take up to 24 hours should be designed for current speeds of 2 m/s, while temporary operations of 1-2 hours could target current speeds as low as 0.5 m/s. See Figure 3-10 for current speeds over a neap tide.

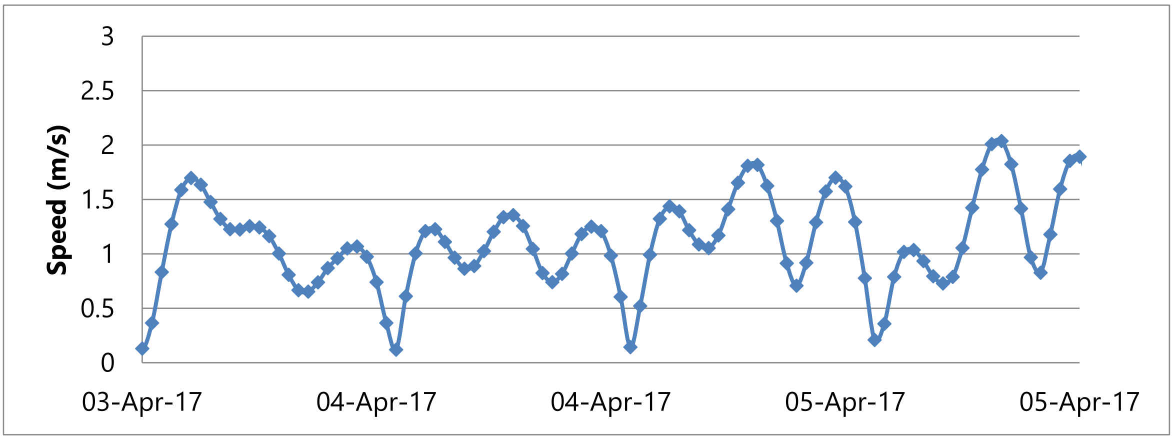

Figure 3-10: Current speeds during a neap tide based on a maximum current of 10 knots

3.2.3 Waves

The bathymetry in the area is complex. To properly assess wave conditions on site, there would need to be modelling combined with a measurement campaign to calibrate the model. Below are some observations using high level assumptions:

- The Kimberley coastline is usually exposed to relatively low wave energy, except during cyclones.
- The area around One Arm Point is very well protected against waves at low tide, with shoals giving protection from all directions except south-west and south-east. From these two directions, waves can only get in through a fairly narrow channel.
- With the large tidal range, the shelter shoals provide from northerly waves decreases significantly at high tide. Higher waves are expected to occur at high tides, for relatively short durations (in the order of hours). There is good protection from westerly and easterly waves at all tides.
- One Arm Point is very protected from ocean swell, and no significant waves are usually expected to penetrate from the ocean side.
- High current velocities will have a significant impact on the wave climate. Generally waves going against currents make for steeper waves (breaking faster), whereas waves going in the same direction as currents lower the wave height. These interactions are quite complex and should be studied further if wave forces are a potential issue.

Expected wave heights based on high level assumptions:

Northerly direction: Offshore wave heights in cyclones can exceed 10 m. The many shoals north of One Arm Point provide protection. Exact bathymetry of the shoals is not marked on the nautical charts. If we assume the shoals are 3 m above chart datum (CD), the wave heights will be limited by depth. At a certain depth, waves will break and the wave height will decrease as energy is dissipated.

- Low tide: no waves will penetrate
- High tide: following rules of thumb (breaking wave height ≈ 0.8 x depth), at high tide (8 m CD) water depth would be 5 m, resulting in waves of approximately 4 m.

Southerly directions:

- Fetch from south-west: 30 km. 30 m/s wind could generate waves with Hs=4.5 m and Tp=5.5 s
- Fetch from south-east: 100 km. 30 m/s wind could generate waves with Hs=7 m and Tp=8 s. This seems unrealistic and will need further investigation.
- Low tide limits waves by a depth of 3 m below CD. Hs=2.3 m.
- High tide (8 m) limits waves by a depth of 9 m. This is larger than what could be generated in a 100 km fetch, so is unlikely to happen.

Installation seas: To establish wave conditions for installation, it is safe to assume there will be no swell coming in from the ocean and waves at One Arm Point will be locally generated.

- For all directions except southerly (120-200), fetch is limited to approximately 5 km at high tide and much less at low tide
- Using wind data from Broome and assuming it is representative of One Arm Point, the wind speed is below 5 m/s 40% of the time
- A 5 km fetch at 5 m/s results in waves with Hs in the order of 0.2 m-0.3 m in open water and a peak period of <2 s.

Based on the above, we can say it is likely to find waves of 0.2-0.3 m or less for 40% of the time.

For the rest of the time, waves could still be within that range, because fetches are much smaller than 5 km for easterly and westerly directions (1 km). For this, fetch wind speeds of 10 m/s are needed to generate 0.3 m waves.

3.2.4 Sea Level

Besides tidal elevation, the location sea level will be affected by:

- Storm surge: as a general rule, a Category 5 tropical cyclone can generate a barometric surge of 0.5-1 m
- Sea Level Rise: guidelines indicate an expected 50-year sea level rise (2070) of around 0.4 m. Ref [6].

3.3 Concept Description

3.3.1 Power Output Required

To power the community, the TTR device is designed to accommodate eight turbines. Each turbine has a maximum power output of 70 kW. In the first phase of the project, it was found that for currents with a maximum greater than 4 m/s, the turbines can be expected to have a capacity factor of 0.5. Ref [1]. Eight turbines will produce an average monthly energy output of 280 kW and an annual energy output of 2452 MW. Currently Horizon Power produces 1770 kWh of power for the Ardyaloon community from diesel generators. Ref [2]. The eight turbines will produce approximately 40% more energy annually than the community would need, allowing for downtime of the turbines and inefficiency in storage systems and transmission.

3.3.2 TTR Offshore Structural Concept

The TTR device structure consists of a reinforced concrete foundation base that will support steel columns, and a retractable structure that will support the turbines. A preliminary analysis shows the size of the foundation to be about 15 m wide by 54 m long and 4 m high, which will be divided into 16 internal compartments as illustrated in Figure 3-11. The foundation base will be grouted against the seabed in its in-place condition to provide the required lateral resistance.

The turbines are supported off four columns that protrude past the low tide levels, to allow the turbines to be lifted above the water for maintenance. One column is taller, which allows a power pole to be located on top which will connect to a power wire that will be fed back onshore, as illustrated in Figure 3-12. The tall column can be used to provide a working platform to house a switch and transformer, depending on the electrical cabling requirements back to shore.

A lifting mechanism will be installed to allow the turbine support structure to be lifted above the low tide cycle to access the turbines for maintenance. Figure 3-13 illustrates the turbine support structure moved along the column and above the waterline.

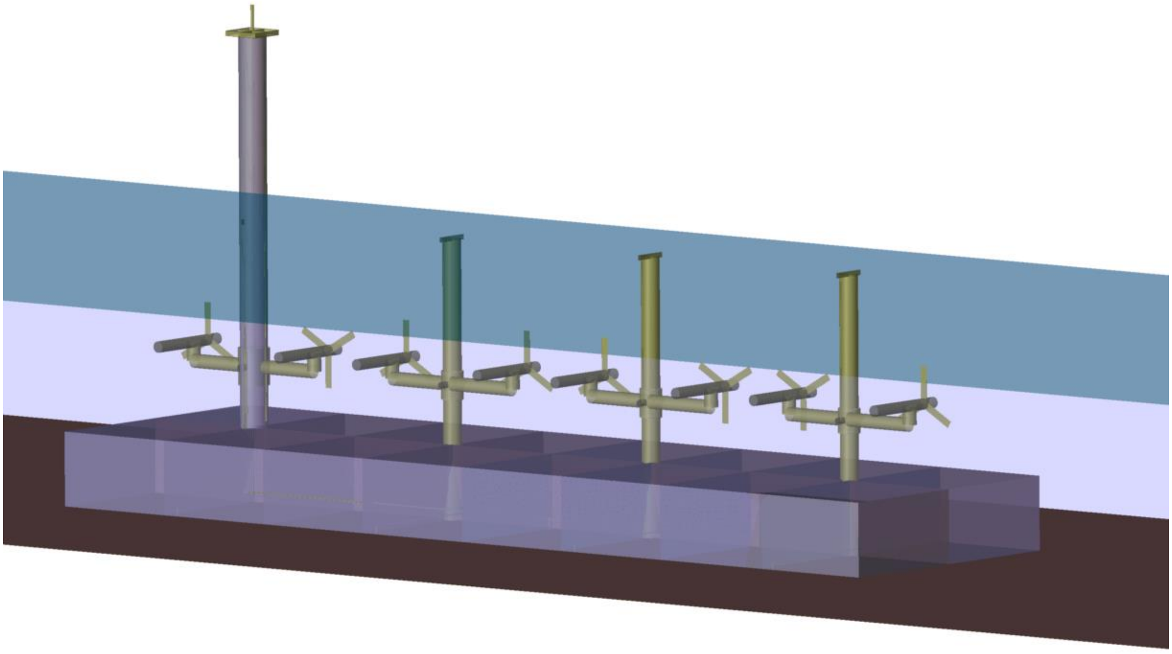

Figure 3-11: TTR device concept – general arrangement

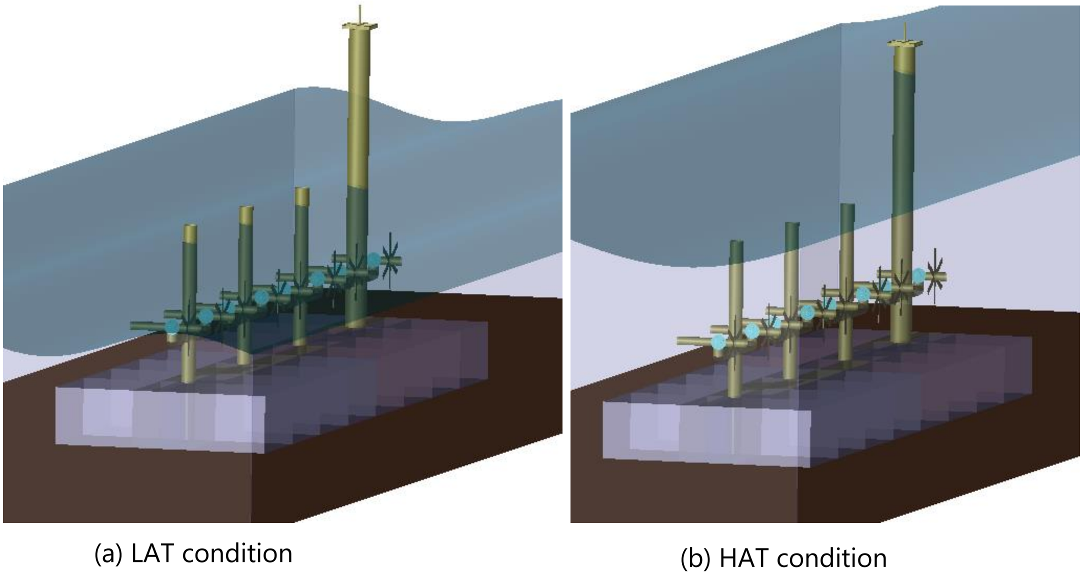

Figure 3-12: TTR device in its in-place condition during low and high tide

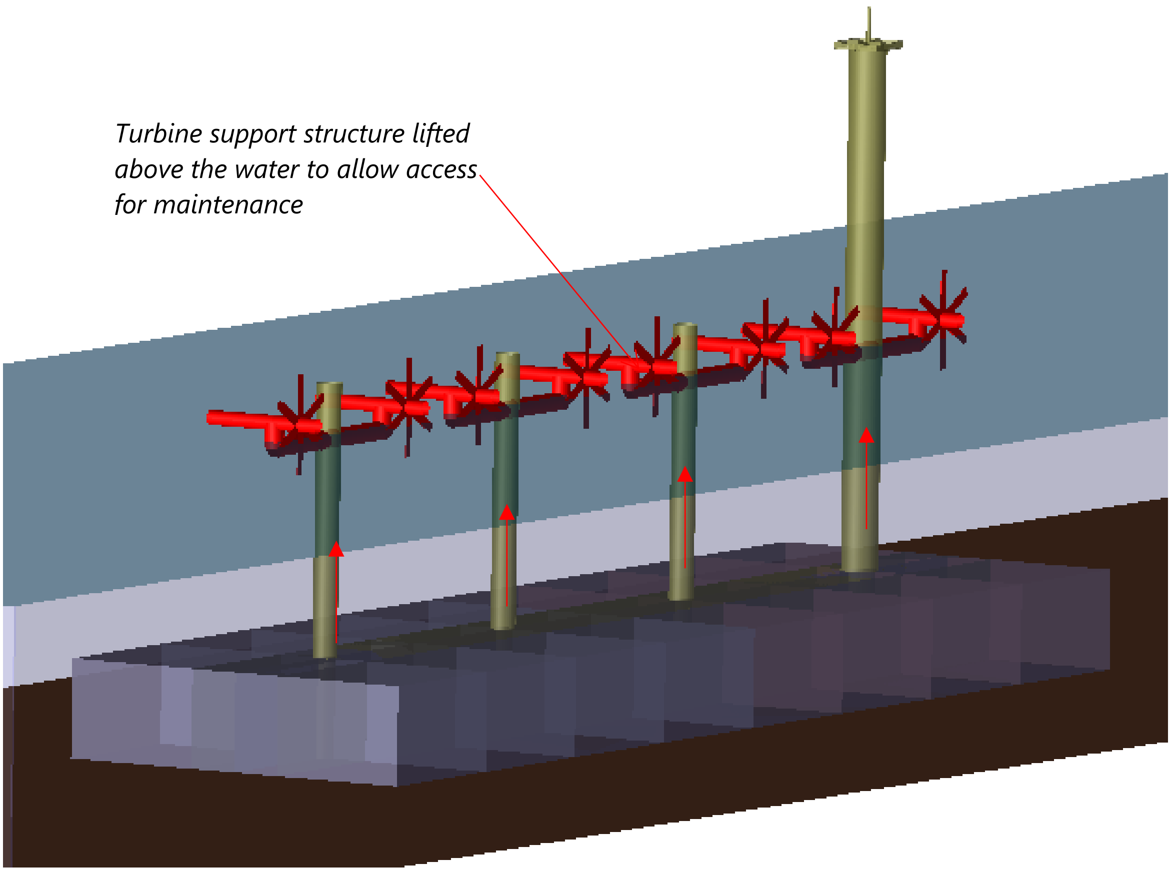

Figure 3-13: Turbines lifted above the water for maintenance

3.3.3 Power Transmission

The TTR is designed to use aerial cabling ashore, avoiding the need for expensive subsea cabling. For One Arm Point, the design considered a 100 m and 200 m distance to shore. A graphic of the 200 m cable run is shown in Figure 3-14. The power can be transmitted in direct current from the turbines, or as alternating current through a transformer located on the TTR switchboard platform.

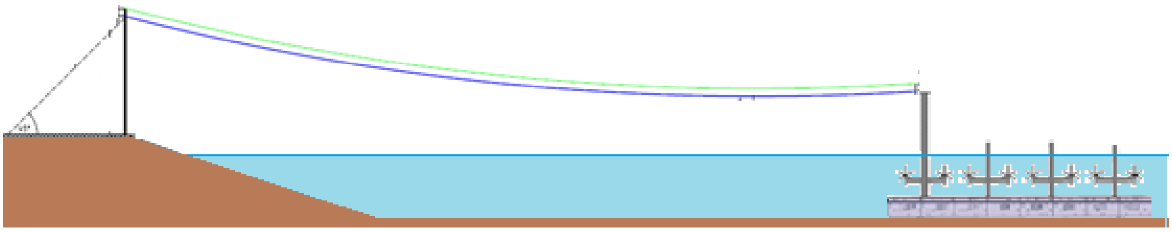

Figure 3-14: TTR aerial cable to shore

3.4 Design Parameters

3.4.1 Environmental Criteria and Parameters

The environmental loads shall be calculated using a return period of 50 years, with the combined current, wave and wind load effect calculated as the maximum load effect during a 10-minute period, in accordance with DNVGL-ST-0164.

Table 3-1 presents the design parameters used for the structural and naval analysis of the TTR.

Table 3-1: Design parameters

Description	Value
Design Life	25
Water Depth (to LAT)	13.0 m
Tidal Range	8.6 m
Max Current Velocity (Ultimate Limit State)[1]	5 m/s
Current Profile Power Function	N = 12
Max Design Wave Height at highest astronomical tide (HAT)	4.0 m
Wind Data Region[2]	C
Wind Site Category	2
Transportation Wave Height	8 m
Transportation Speed	8 Knots

1) The power law current profile is used for the assessment, assuming an exponent equal to 12

2) Wind loads shall be calculated in accordance with AS 1170.2.

3.4.2 Marine Growth

The structural analysis shall include the effects of marine growth that can impact the cross-sectional dimension and alter the hydrodynamic coefficients of structures that are submerged or in the splash zone. It is assumed the columns used to support the turbines will be periodically cleaned of all soft marine growth during maintenance. Therefore, in lieu of site-specific marine growth data, it is assumed that a one-year marine growth profile of 50 mm with a submerged density of 250 kg/m^3 from the mudline to mean seal level shall be used for the structural assessment.

3.4.3 Corrosion Allowance

A corrosion allowance shall be applied to structural steel members in the splash zone. In lieu of more accurate data, a corrosion allowance of 5 mm shall be used.

The splash zone is defined between elevations EL(+) 9.0 m and EL(-) 1.0 m as estimated using the rules in DNV-OS-C101.

More accurate corrosion allowances may be calculated in accordance with AS 4997, section 6.4.4.7, once a design life is confirmed.

Corrosion protection would be required to meet the necessary design life. Protection can be obtained by using anodes to provide cathodic protection in the submerged zone, and specialised coating systems to provide protection in the splash zone. A painting system in the submerged zone may be used and should be considered in the next phase.

3.5 Seabed Properties

For the concept development and analysis work completed in this phase, it is assumed the seabed will mainly comprise fairly smooth rock, as the high tidal current velocity will most likely wash all loose and light particles away. It is assumed a location will be available that will be reasonably flat to lay the TTR device. For the stability and foundation analysis, the following properties shall be assumed:

- Friction coefficient between concrete and seabed μ = 0.35
- Seabed bearing pressure = 250 kPa
- Grout shear transfer strength = 100 kPa
- Geotechnical reduction factor on grouted connection = 0.5.

3.6 Structural Design Parameters

The concept will be based on a structure that is fixed to the seabed as a gravity based solution, or using a grout connection between the underside of the base and seabed rock. The structural concept will assume the material properties as described in Table 3-2.

Table 3-2: Material parameters

Description	Symbol	Value
Concrete Density	ρ_c	2400 kg/m^3
Concrete Elastic Modulus	E_c	25 GPa
Concrete Poisson Ratio	v_c	0.2
Concrete Characteristic Compression Strength	f_{cr}	40 MPa
Steel Density	ρ_c	7850 kg/m^3
Steel Elastic Modulus	E_s	200 GPa
Steel Poisson Ratio	v_s	0.3
Steel Yield Strength	F_y	350 MPa
Grout Density	ρ_c	1900 kg/m^3

4 Fabrication and Installation Methodology

4.1 Fabrication Methodology

During this concept development phase, WorleyParsons and Civmec have discussed the methods of fabricating the proposed TTR device concept. Civmec has developed a fabrication plan of the proposed TTR device structure and explored various forms of fabrication methods for the proposed TTR and for alternative materials. The following sections summarise Civmec's fabrication plan.

Appendix A contains concept drawings of the proposed TTR device structure, along with fabrication details to illustrate the construction philosophy.

4.1.1 Comparison of Concrete Construction Methods

Each of the alternative concrete construction methods would require the base slab to be cast in-situ. Permanent roof soffit panels with an in-situ topping would obviate the need for roof soffit falsework.

The walls could either be precast or cast in-situ. In either case, making the compartments square in plan would allow the formwork to be used more efficiently.

The project duration will be inversely proportional to the number of formwork panels used. However, for this proposed scheme, the construction schedule was not considered to be a factor.

Each of these relationships is assessed further below.

The actual construction method is described in Section 4.1.2.

4.1.1.1 In-Situ Formwork Panel Cost/Reuse

For both in-situ and precast methods, there is an inverse relationship between the material costs and the number of re-uses of formwork. The cost of the formwork material and fabrication are inversely proportional to the number of re-uses achieved.

The labour cost of fixing and stripping the formwork will be the same, irrespective of the number of wall forms that are used. The number of re-uses of formwork is usually determined by the quality of finish required. In the case of the TTR support structure, neither face of the walls is visible so this is not a relevant factor.

Amending the design to make the internal dimensions of the chambers square in plan would maximise the potential for formwork re-use, thereby slightly reducing the construction costs.

4.1.1.2 In-Situ versus Precast Formwork

These relationships will vary considerably depending on the relative heights and thicknesses of the walls being assessed.

Calculating from 1st principles for these particular walls, the in-situ formwork accounts for around 50% of the total cost, and the reinforcement and concrete each account for approximately 25%.

Pre-casting the walls face-down would not alter the quantities of either concrete or reinforcement as, whichever construction technique is used, they need to resist the hydrostatic loads from floating and flooding of the TTR support structure.

The area and complexity of formwork required to precast the panels face-down will minimise the formwork cost, as there are minimal hydrostatic loads or access to be considered. The precast wall option is approximately 75% of the cost of constructing walls in-situ.

There are additional costs in tilting-up the precast panels, propping and grouting them into the vertical position. That cost is around 20% of the precast total.

4.1.1.3 In-Situ Formwork Panel versus Duration

For either in-situ or precast construction, the project duration will be inversely proportional to the number of formwork panels used and directly proportional to the number of formwork re-uses.

However, for this proposed scheme, the construction schedule was not considered to be a factor.

4.1.2 Proposed Construction Method

4.1.2.1 Base Slab

The base slab will be cast in-situ on an elevated casting bed. This is to allow self-propelled modular transporters (SPMTs) to drive under the base, raise it off the casting bed, and transport it to the floating dock for launching/towing to site, as illustrated in Figure 4-1.

Traditional plywood formwork panels will be used around the perimeter and strutted externally. The internal wall kicker (~150 mm high) will be hung (cantilevered) from the edge formwork.

Reinforcement steel will be supplied cut and bent, and prefabricated in sections to expedite the construction.

Figure 4-1: Self-propelled modular transporters

The complete TTR support structure weighs about 2,500 tonnes (Te). Multiple SPMTs, each able to carry ~200 Te, are hydraulically interlinked so the load is raised simultaneously.

The elevated casting bed will comprise three longitudinal upstand beams running lengthwise, with removable soffit formwork between them. Once the TTR is ready for launching, the SPMTs will travel underneath it – between the beams – and raise the floor hydraulically.

The SPMTs will then carry the TTR support structure to the floating dock for launching.

4.1.2.2 Wall Construction

Considering the factors discussed in Section 4.1.1 above, Civmec proposes to employ a combination of in-situ and precast wall construction methods as shown in Figure 4-2.

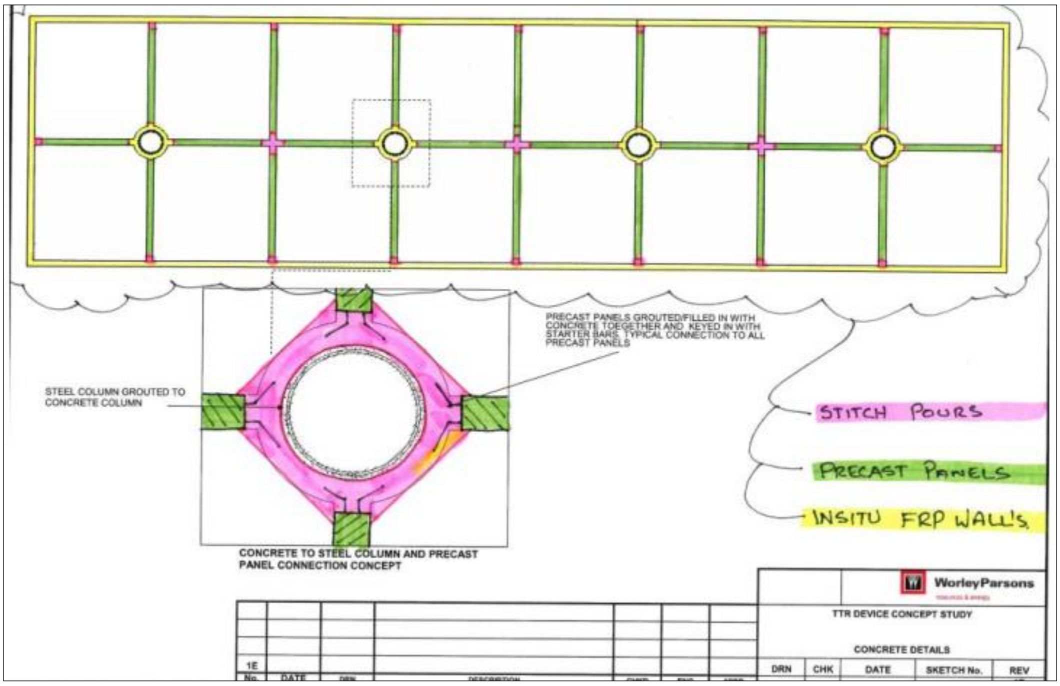

Figure 4-2: Wall construction

The water-tightness of the joint between the in-situ cast base slab and perimeter walls will be ensured by casting a proprietary water-bar in the middle of the wall, spanning across the construction joint.

We have retained the even number of internal chambers to simplify the internal walls and infill/stitch panels required.

Precast walls will be used internally. These will be propped and grouted into rebates in the slab floor, and locked in place with the mast infill/stitch pours.

A proprietary formwork system will be used for the in-situ walls, incorporating work platforms to place concrete. The inner form would be erected first to support the wall reinforcement, and the outer form fixed once the reinforcement has been completed and inspected.

A 75 Te mobile crane will be used to install prefabricated reinforcement cages, formwork and precast wall panels.

Due to the relatively small quantity of concrete per wall, either multiple walls would be cast simultaneously to maximise pump utilisation, or the crane and kibble would be used to maintain turnover of formwork.

4.1.2.3 Roof Slab

The roof slab will be constructed using composite precast soffit panels with an in-situ concrete topping. The precast panels act as permanent formwork and do not need to be removed.

4.1.2.4 Masts/Steel Columns

The masts, collar slides and turbine support arms would be fabricated from stockist-supplied tubular steel.

After fabrication and painting, the mast would be inserted into the concrete sockets in the centre of the TTR support structure, then grouted into place.

The turbines would be fixed onto their cross-arms before the assembly is lifted onto the mast.

4.1.2.5 Commissioning

It would be better to perform these activities before launching to eliminate any issues with working 'over water'.

Civmec would facilitate others in commissioning and testing the turbines.

4.1.2.6 Launching

Once commissioning is completed, the TTD will be transported by multiple SPMTs to the floating dock adjacent to the prefabrication area. The main characteristics of the floating dock are:

- Max width 41.8 m
- Max length 102.3 m
- Max vessel draught 9.2 m
- Lifting capacity 12,000 t.

4.1.2.7 Equipment/Resources

Both the concrete and steel options would use standard techniques for the respective materials – welding, or formwork and reinforcement.

Using an elevated bed and the SPMTs enables the prefabricated TTR support structure (steel or concrete) to be moved to the floating dock for launching.

This eliminates the construction of temporary dry docks or having to construct in-situ.

4.1.3 Steel versus Concrete Foundation Base

In Phase 1A, the project based its design on a steel foundation. Upon review, it was shown to be cheaper to change to concrete for fabrication, and the increased weight would benefit the in-place load restraint condition. Through further development of the concept design, the concrete base doubled in size from the initial estimate, and its final in-place condition relies on the bond of grout to seabed instead of weight.

It appears that a steel base may be in the same price range as the concrete base, but there are still engineering questions that would need to be answered and costed, such as:

- How after installation the steel base remains in place before the grout sets
- How the overturning is resisted given the lack of weight
- What the long-term price is for corrosion resistance.

4.1.4 Power Cables to Shore

An onshore construction campaign will be required out of Broome to run standard power poles and conductor wire 1.5 km to the town site from the shore of the turbine farm. At the shore end of the traditional power cable run, a large foundation, two guidewires and large steel pole will need to be constructed to receive the offshore conductors.

4.1.5 Mooring

Before the TTR arrives onsite, four onshore anchor points for the moorings will need to set by the offshore contractor. Assuming the area is rock, the basis is that a hand-held pneumatic rock drill will be used to drill 600 mm deep holes to receive M36 chemical bolts. The bolts will be used to hold down a plate with a suitably sized bollard. If the rock is not level enough, a concrete foundation may need to be poured. The bolts can be used to resist the bollard load through shear or by tension and friction connection of the plate.

4.2 Transportation Methodology

The TTR device is designed to be towed by a single tug from the fabrication site in Perth to Broome, where it will be temporarily moored until the installation contractor tows the TTR the short distance to One Arm Point for installation. Refer to Figure 4-3. The tow from Perth to Broome is expected to take ten days and requires a single tug with 2200 brake horsepower.

The tow from Broome to site will be weather-dependent, with the journey only going ahead if the tide is in a neap cycle and the three-day forecast is calm.

The advantage of breaking the entire transport into two separate tows is that the initial tow to Broome is less reliant on weather, and will not incur vessel day rate charges if the forecasted installation environment is not suitable upon arrival at Broome. The project schedule is also de-risked by having float between the two activities.

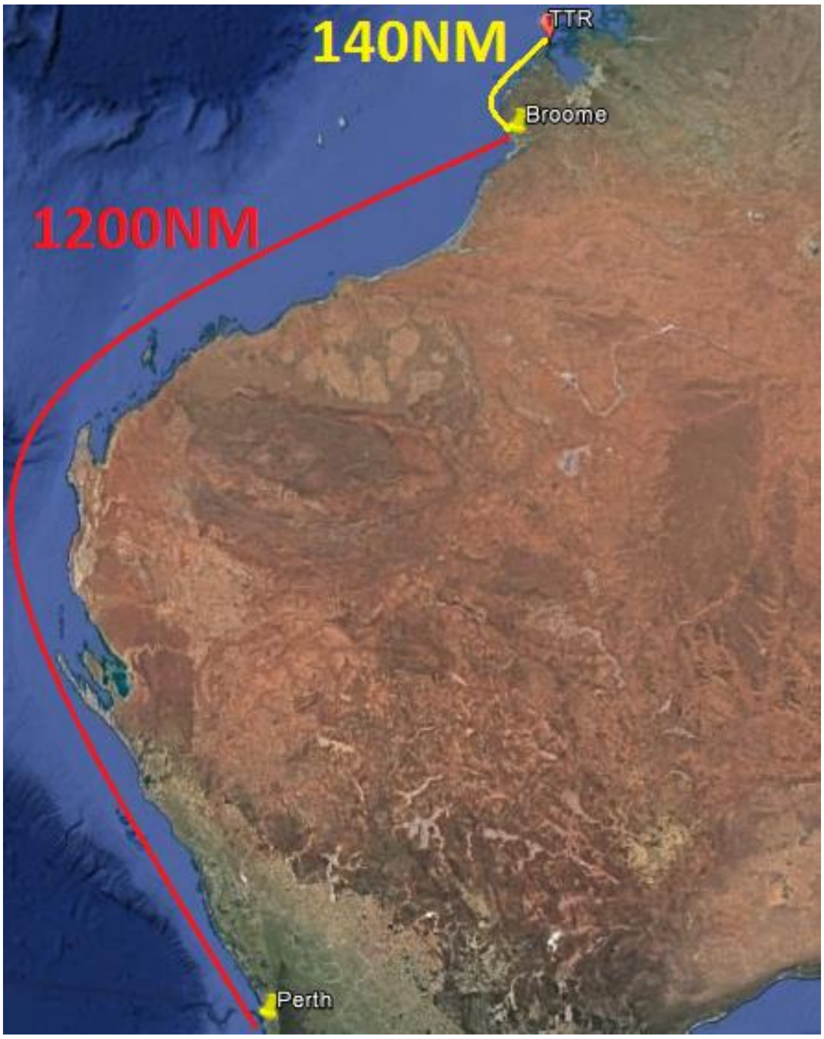

Figure 4-3: TTR transportation route

4.3 Installation Methodology

The installation methodology starts when the TTR arrives on site and is connected to the mooring system, as illustrated in Figure 4-4. The TTR installation is dependent on weather and the tide cycle, as shown in Table 4-1. It is important to install the TTR in neap tides, to limit the current as well as the possible water depth it has to ballast down through to the seabed. It is envisioned that the tow and installation will occur out of cyclone season, November to April, for the region.

Table 4-1: TTR mooring and installation environment limitations

Parameter	Limit
Wave	Hs=0.3 m Tp<3 s
Wind	10 m/s (3 sec gust)
Tidal Range	2 m
Mean Sea Level	15 m
Maximum Current	2 m/s

Figure 4-4: TTR installation mooring configuration

The installation mooring system is designed so the TTR can keep station while ballasting setup is occurring and awaiting the correct tide conditions. The mooring system allows to accurately locate the TTR using an onshore winch and the winch on the installation vessel, shown in Figure 4-4.

The TTR is installed by flooding the rear two stern tanks until initial seabed touch down occurs. Two more tanks are then flooded in the bow until it is fully on the seabed (refer Figure 4-5). All tanks are then flooded to ensure the TTR has enough self-weight to remain in place in a moderate environment.

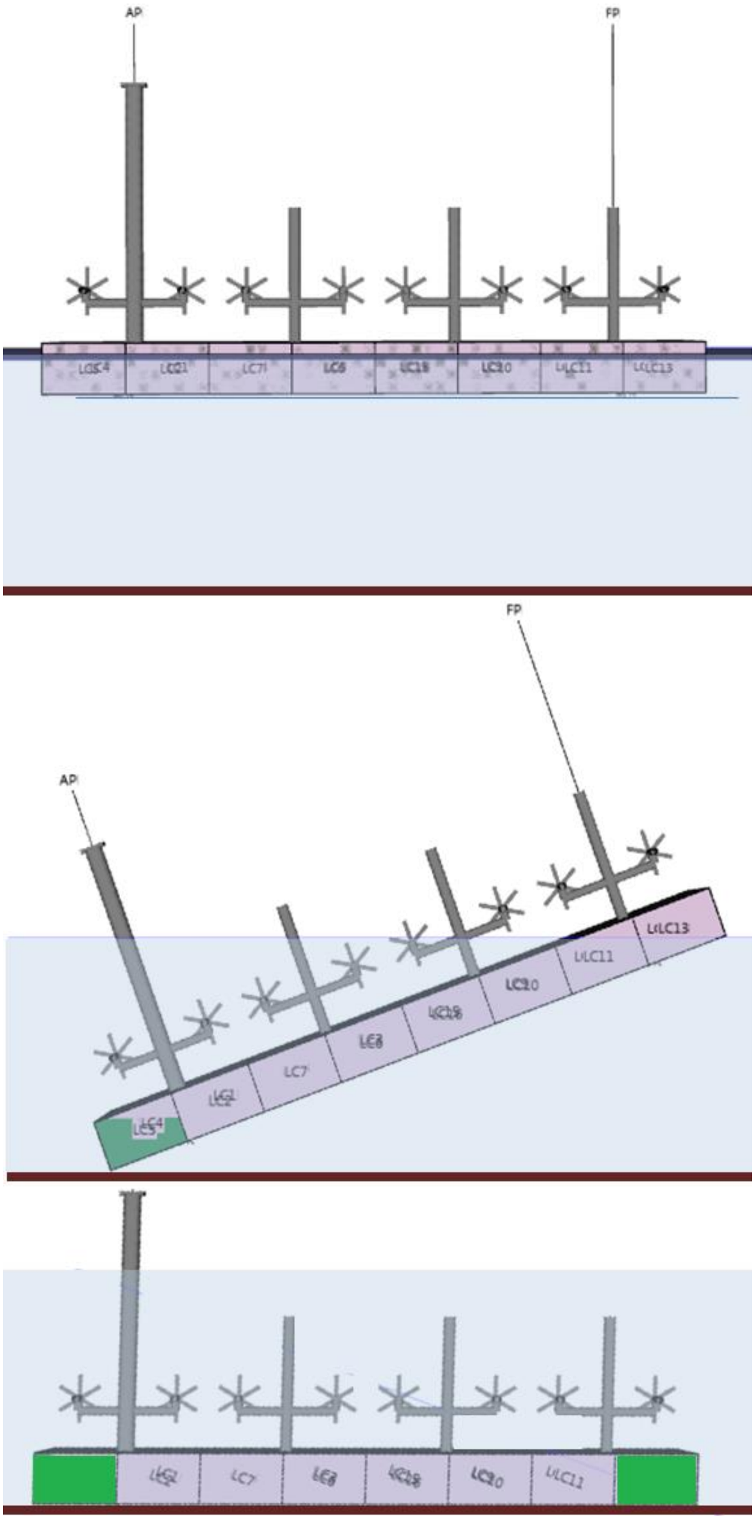

Figure 4-5: TTR ballast sequence

The flooding of the TTR is controlled using pneumatic valves with lines running back to the installation vessel. The entire ballast procedure will have redundant control through multiple valves, lines and alternative flood tank options. The installation has considered the required stability, strength and contact energy to ensure the approach is robust.

4.3.1.1 Foundation Installation

The TTR will be installed with timber cribbing on the base of the structure that lines up with longitudinal and transverse bulkheads, as illustrated in Figure 4-6. The timber cribbing will help settle the structure on an uneven seabed. The cribbing will be de-formed and take the shape of the seabed imperfections.

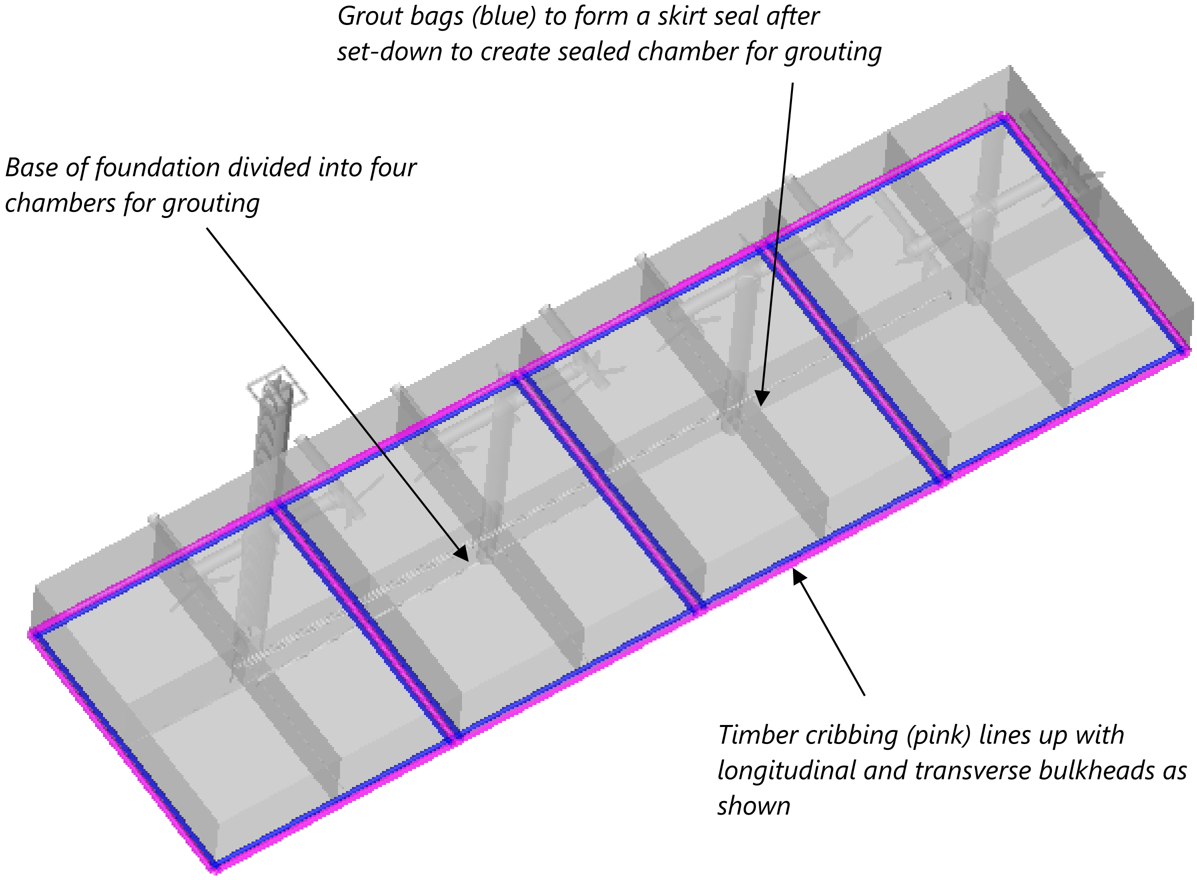

Figure 4-6: Timber cribbing and grout bags under base of TTR structure

Once the TTR is positioned on the seabed and grout lines from shore to the TTR control tower are run, grout is initially injected into skirting bags along the parameter of the base of the TTR to create a seal with the uneven rocky seabed. Once the grout bags are filled, the internal cavity created is then filled with grout, creating a bond between the rocky seabed and the cement base of the TTR. After grouting, the final electrical cables are run and the turbines engaged.

5 Operating and Maintenance Methodology

5.1 Turbine Maintenance

The SCHOTTEL instream turbine (SIT) requires a six-monthly inspection and fluid top-up. The design life of components varies between five and twenty years. Components subjected to wear are designed for five years, whereas components like the housing are designed for 20 years. A maintenance plan is shown in Table 5-1.

Table 5-1: Maintenance plan

Period	Type of Maintenance	Effort
Six months	Regular inspection at site	Dry components: ▪ Inspection of electrical components (removing dirt and contamination) ▪ Inspection of any critical installations of electronics (are all screws tightened?). Submerged components: ▪ Cleaning with steam cleaner, removal of marine growth ▪ Inspection of corrosion protection system ▪ Optical inspection of all turbines, blades, etcetera ▪ Checking of lube oil level and magnetic plugs, taking of samples.
Five years	Overhaul	▪ Workshop inspection and exchange of worn parts such as brake disks, bearings, dynamic and static sealings, liner and gear box ▪ New lube oil filling ▪ Test run after assembly ▪ Refurbishment of corrosion protection system.

5.2 Turbine Retrieval

The TTR was designed with the turbine support structure (as illustrated in Figure 5-1) attached onto a sleeve that fits around the steel columns (masts), which allows the support structure to be lifted.

The turbine support structure is lifted using chains/wire that is pre-attached to a lifting beam atop the steel columns. Figure 5-2 shows the lifting beam and chains, and illustrates the turbine at the operating and maintenance positions. The chains can be accessed with a small working boat that would attach a chain block or winch system that could connect to the pre-slung chain. The concept allows for two lifting points to control the movement of the structure without rotating and jamming up onto the column.

The dry weight of the turbine support structure (includes turbines, and dry weight of the structure and marine growth) is estimated at about 14 tonnes, with a submerged weight of about 8 tonnes (accounts for the submerged weight of steel, and buoyancy in the tubular members and marine growth). The lifting process is envisaged to be slow and would therefore generate minimal added mass, due to displaced volume of water surrounding it and low velocities for increased weight due to drag. Suitable equipment would be needed to lift the dry weight of the structure.

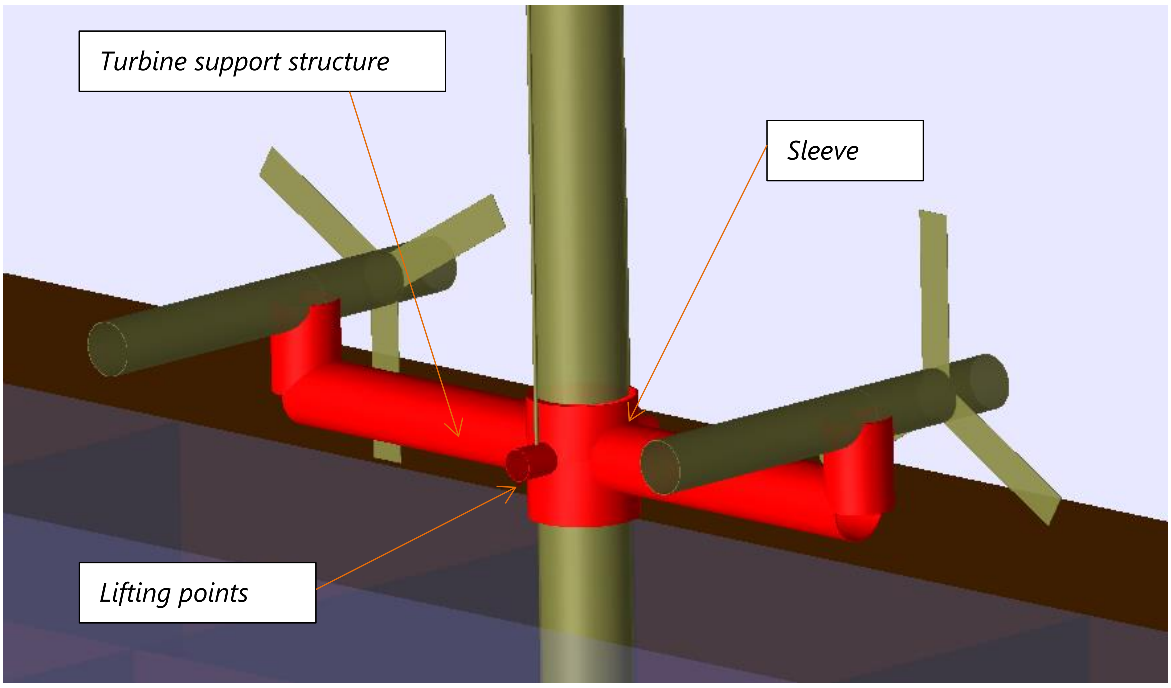

Figure 5-1: Turbine support structure and sleeve

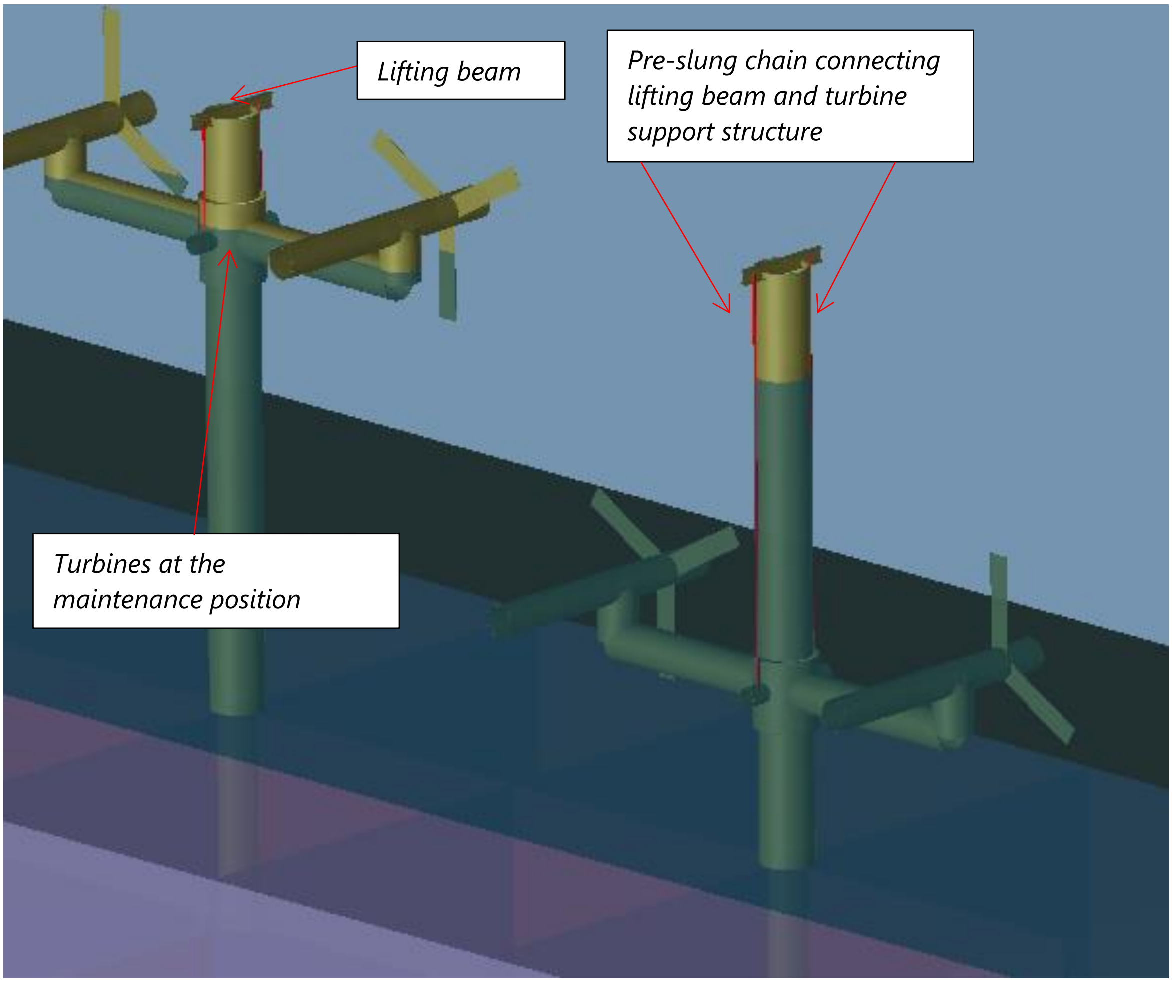

Figure 5-2: Lifting system details

6 Electrical and Turbine Interface Design

The TTR design is based on the benefits of multiple turbines in parallel, not a single large turbine. The use of smaller turbines has been found to be more economical; as turbines increase in size, their weight increases with the cube of the scale, while the benefit (energy capture) only increases with the square of scale. Small turbines will therefore have a larger power/weight ratio and corresponding power/cost ratio than large ones. Hence, smaller turbines weigh less and are more cost-effective than large ones, as shown in Figure 6-1. Of course, turbine size cannot continue to be decreased toward zero, as the cost of the complexity of the installation then becomes prohibitive.

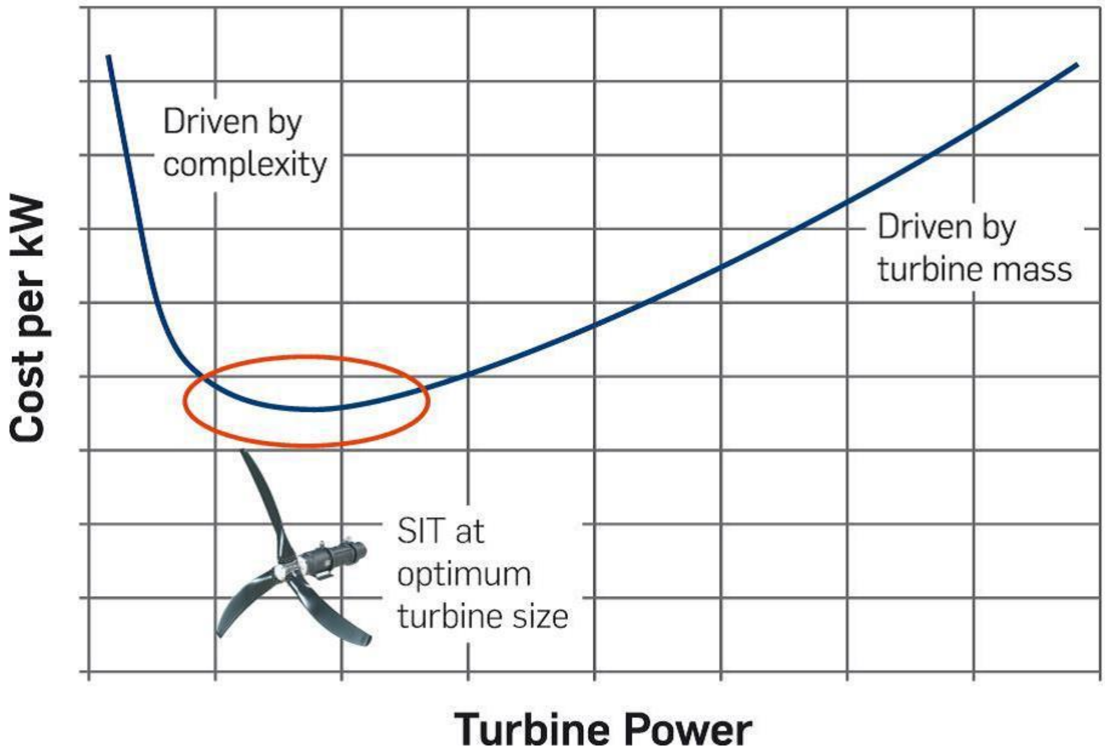

Figure 6-1: Effect on cost per unit of power

It was found that, in between the two extremes of excessive complexity and excessive turbine mass, lies an optimum turbine size with respect to the cost per unit of generated power, as indicated by the red ellipse in Figure 6-1. This optimum lies between 50 kW and 300 kW. On this basis, the SIT 250 has been selected to be integrated into the TTR structure.

6.1 SIT Characteristics

For the TTR, an SIT 250 turbine with a 4 m diameter is proposed. The SIT is simple and robust, without complex subsystems. It consists of a three-bladed rotor, planetary gearbox and asynchronous generator, both cooled by the flow of ambient water (Figure 6-2).

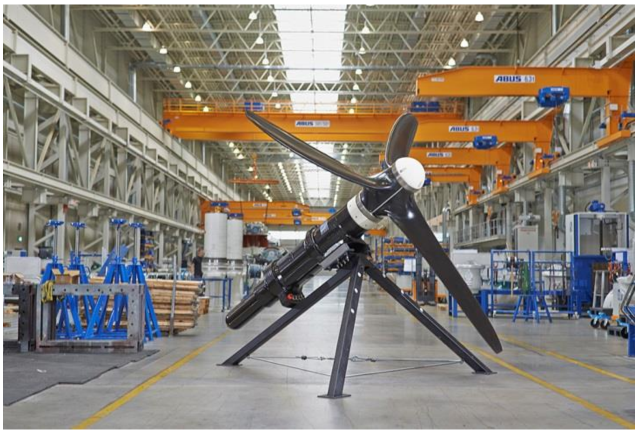

Figure 6-2: SIT 250 4 m diameter

An SIT 250 shown in Figure 6-3 has a rated electrical power of 70 kW. The power train consists of:

- Three blades mounted to the hub (passive-adaptive)
- Slow running shaft including bearing and sealing system
- Two-stage planetary gearbox
- Induction generator
- Multidisc brake (hydraulically released).

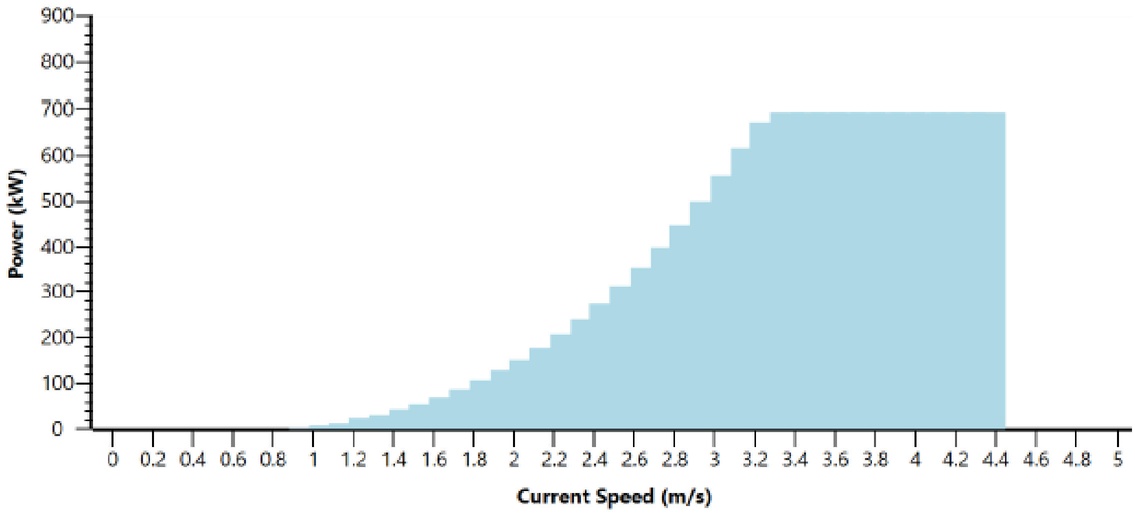

Figure 6-3: STI 250 power to velocity curve

Table 6-1: SIT 250 datasheet

Rotor diameter	[m]	4
Gearbox ratio	[-]	≈ 1:36
Nominal flow velocity	[m/s]	2.3
Nominal power (electrical)	[kW]	70
Nominal turbine speed	[rpm]	64
Nominal generator speed	[rpm]	2300
Max. operational torque	[Nm]	12500
Max. generator torque	[Nm]	343
Thrust at nominal power	[kN]	60.6
Cut out flow velocity (with brake)	[m/s]	3.0
Max. continuous turbine speed for braking	[m/s]	2.7
Max. turbine speed (without brake)	[rpm]	98.2
Max. generator speed	[rpm]	3553
Max. operational thrust	[kN]	69.7
Breaking torque (high speed side)	[Nm]	1250
Max. thrust during braking (@ $c_{t\ max}$)	[kN]	80

6.2 Integration of Turbine into TTR Platform

The SIT 250 is mounted on a passive swivel which allows the turbine to operate in a downstream arrangement to passively yaw around its vertical axis. The turbine will be pulled passively by the current, and will thereby be aligned into the direction of flow. This until now is still a concept and needs to be further assessed.

6.3 Turbine System

The TTR platform can host multiple turbines. The overall scope of supply for a TTR project comprises a complete SIT 250 system, including the turbines and the associated electrical power conversion system, to be mounted into containerised substations.

An overview of the proposed turbine is shown in Figure 6-4.

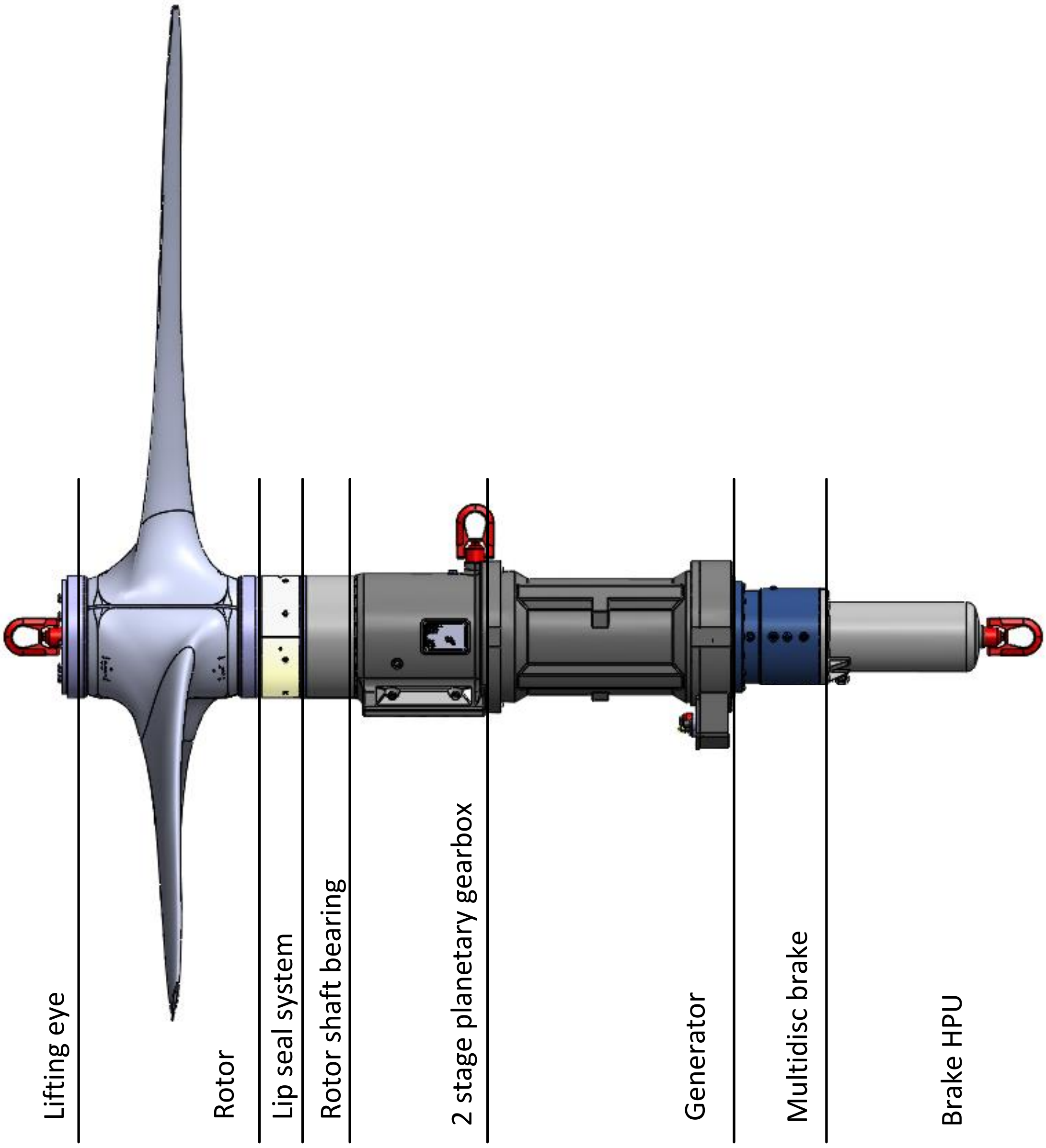

Figure 6-4: Overview of the SIT 250

In reality, the thrust distribution over the rotor area is expected to be uneven. Hence, the thrust force is considered to attack with an eccentricity regarding the rotational axis. The radius of the thrust eccentricity circle is assumed to be one eighth of the rotor radius.

Figure 6-5 shows a single line diagram of the proposed electrical power conversion setup. As a first estimation, the weight per SIT 250 for the entire power conversion equipment would be 232 kg (including the transformer). Further, up to 20 turbines can be packaged into a single 20-foot container.

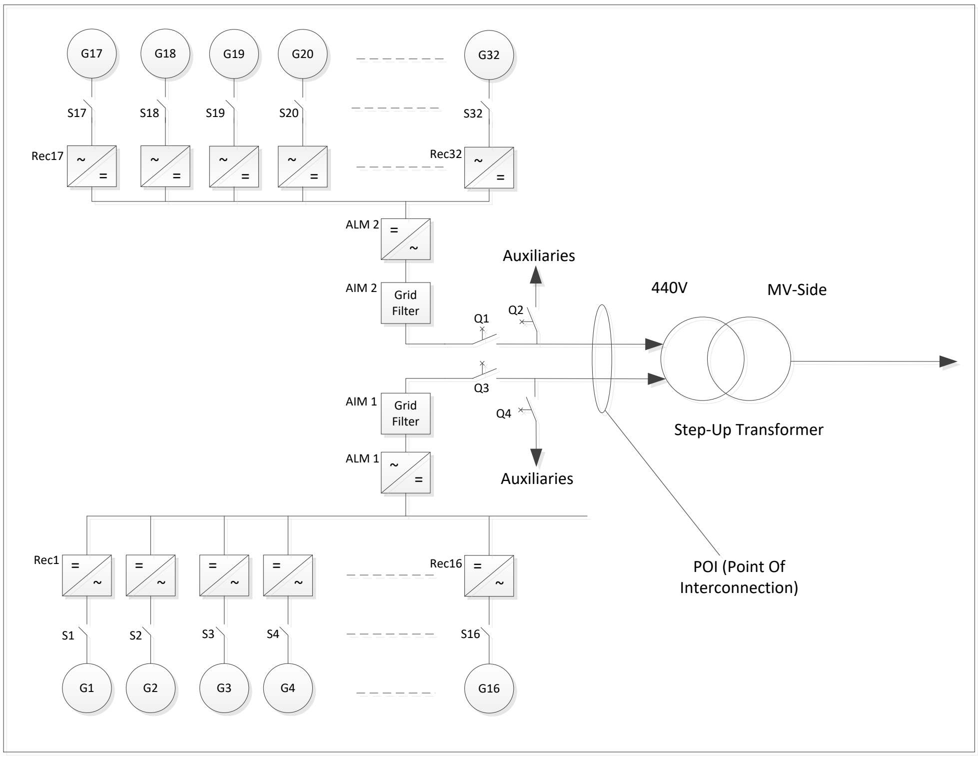

Figure 6-5: Single line diagram of power conversion system

7 Economic Modelling

An initial viability assessment was completed in Phase 1A, estimating cash flows and LCOE and identifying key financial drivers. The LCOE analysis was based on an initial design concept and a generic tidal site. Phase 1B has significantly advanced from Phase 1A, using a more detailed and dynamic financial model, a revised tidal device solution, greater granularity of costs and a specific site.

During Phase 1B, expense assumptions have been updated for the eight-turbine TTR device, located off the coast of One Arm Point, Western Australia. An optional 16-turbine TTR device has also been modelled for comparison. Cost associated with the 16-turbine device have been scaled from the original single-row concept. Each scenario has been tested against three different modelled generic resources, with a maximum current of 12 knots, 10 knots and 8 knots.

To accurately model the two scenarios, the ExceedenceFINANCE globally recognised marine renewable energy techno-financial modelling software has been used.

This section provides a detailed overview of how the models have been developed, a comparison to the wider tidal industry market (mainly in Europe) where suitable, and recommendations for next steps.

7.1 Model Overview

ExceedenceFINANCE has been used to model the feasibility of the TTR. It is important to note that the software has been reviewed and calibrated with Ernst & Young and Wave Energy Scotland.

The model has an intuitive workflow, illustrated by the flowchart in Figure 7-1. The technical aspects of the model consist of location, resource and device selection. The financial aspects of the model consist of CAPEX, OPEX and other financial inputs. The software then calculates the LCOE, Internal Rate of Return (IRR) and NPV. Once outputs have been calculated, the Analysis Module can be used to ask the all-important ‘what if’ questions by conducting a ‘goal seek’ or examining parametric sensitivities.

The model contains a database of renewable locations together with technical information on leading devices. The user can add to these databases by uploading their own location or device information. The model then uses this information to calculate the amount of energy a particular device will produce at a particular location.

The financial section allows the user to input all the costs associated with planning, installing, commissioning, operating and decommissioning a marine renewable project.

By combining the financial information with the energy output data, the model produces a series of cash flows for the entire duration of the project. It also calculates key financial metrics such as NPV, LCOE, IRR and payback period. Other metrics are also available such as total power (MW), annual energy delivered (MWh), CAPEX, OPEX, discounted payback period, equivalent annual charge and NPV/MW.

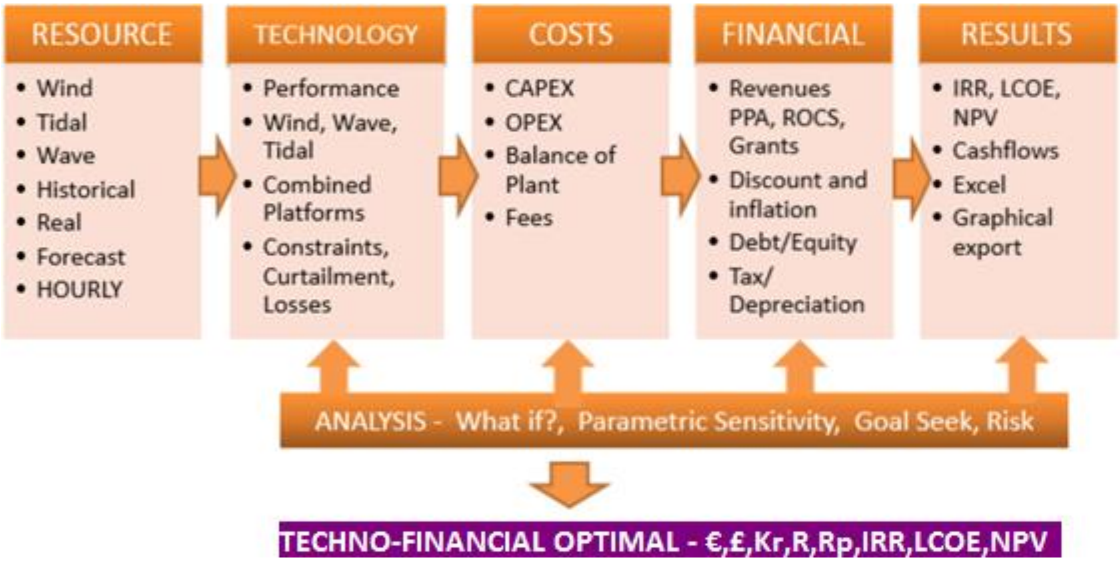

Figure 7-1: Flow schematic techno-financial modelling methodology

7.2 Cost Summary

Costs have been summarised in detail and presented in Table 7-1. The total cost for the eight-turbine TTR concept is AUD 8.8 million, which gives a cost of AUD 15.7 million per MW. In contrast, the 16-turbine concept costs AUD 11.8 million, giving a cost of AUD 10.5 million per MW.

Table 7-1: Summary of tidal turbine estimates (rounded) in Australian Dollars Q4 2017 ±30%

Cost Type	8 Turbines	16 Turbines
Procurement	1,678,000	3,335,000
Fabrication	2,473,000	3,044,000
Transportation	309,000	309,000
Supply & Installation	730,000	730,000
Installation Onshore	229,000	229,000
Installation Offshore	173,000	173,000
Allowance	372,000	506,000
Indirect Costs	1,366,000	1,484,000
Contingency	1,466,000	1,962,000
TOTAL	**8,795,000**	**11,771,000**
Per Turbine	**1,099,000**	**736,000**
CAPEX per MW	**15,682,550**	**10,494,396**
OPEX per MW	**632,790**	**436,625**

With an exchange rate of 1.73 AUD = 1 GBP (17.01.2018), this means the eight- and 16-turbine concepts cost about GBP 9.1 million and GBP 6.1 million per MW respectively. To put this in perspective, the Meygen Phase 1A project costs about GBP 8.5 million per MW (CAPEX of GBP 51 million and 4*1.5 MW turbines). Ref [7].

7.3 Annual Delivered Energy

Once the location and power curve are selected, the annual energy production can be calculated, including any losses in yield (e.g. availability). It is normal to include a loss of 3% in transmission via the electrical cables, and an availability of 95%. Ref [8]. The model provides the total yield with no losses, as well as the annual delivered energy which includes the losses. The latter is the more important result, as it is key in determining the financial outcomes of the project. The resulting yield and capacity factors are shown in Table 7-2.

Table 7-2: Annual delivered energy and capacity factor for the 8 and 16 TTR concepts

	8 Turbines			16 Turbines		
Maximum current speed	12 kn	10 kn	8 kn	12 kn	10 kn	8 kn
Transmission loss	3%			3%		
Availability	95%			95%		
Annual energy production (MWh)	1,397	1,326	960	2,794	2,651	1,921
Annual delivered energy (MWh)	1,287	1,222	885	2,575	2,443	1,770
Capacity factor	27.0%	25.6%	18.6%	27.0%	25.6%	18.6%

The capacity factors outlined in Table 7-2 are in line with current industry standards. The learning rates across the sector indicate improvements as a result of operational time in ocean current environments.

The resulting energy yields show that the best eight-turbine scenario will only cover 73% of the required energy demand at One Arm Point. The 16-turbine scenario shows that all three resources will cover the required energy demand, with the best resource producing 58% more than required. The number of turbines should be chosen based on what level of energy demand is to be covered or required. This will need to be balanced with the resulting LCOE, discussed in Section 7.7.

7.4 Capital Expenditure

The model calculates expense on a 'cost per turbine' basis, not per TTR device. The detailed costs outlined in Section 7.2 have been manipulated to be per turbine. The costs for the eight and 16 turbines are shown in Table 7-3.

The cost per MW compares favourably with similar international projects such as the Meygen project Phase 1A (AUD 14.7 per MW). To put this in the context of offshore wind, the median CAPEX in 2015 was AUD 6.7 million per MW (GBP ~3.5 million per MW). Ref [9].

Table 7-3: Summary CAPEX per MW

	8 Turbines	16 Turbines
Device cost per MW ($)	3,135,342	3,115,728
Foundation cost per MW ($/MW)	4,817,684	2,966,437
Balance of Plant cost per MW ($/MW)	5,049,166	3,072,052
Farm cost per MW ($/MW)	2,680,358	1,340,179
TOTAL CAPEX per MW ($/MW)	**15,682,550**	**10,494,396**

7.5 Operational Expenditure

During Phase 1A, OPEX was estimated to be 18% of total project costs. Ref [10]. In Phase 1B, the design costs also include an estimated maintenance cost based on a combination of six-monthly inspections and five-yearly shop repairs. These costs have been summed for five years, then averaged per year. A 25% contingency for failure has also been added to the maintenance cost.

The estimated maintenance cost is for the eight turbines, which is doubled for the 16 turbines. Ref [11]. The UK Renewable Advisory Board provides a generic OPEX cost breakdown. Ref [12]. The cost items and associated percentages are:

- Operation (15%)
- Maintenance (38%)
- Port activities (31%)
- Licence fee (4%)
- Other costs (12%).

Effective and efficient operations at the port location are vital for operation and maintenance activities. It is standard practice to co-locate the office, parts storage and quayside facility. Ref [13]. This particular cost may not be vital for this project, but has been included to cover all eventual costs. Using the estimated maintenance cost, the other costs including total OPEX can be calculated for the eight-turbine scenario, as shown in Table 7-4. To estimate the 16-turbine OPEX, the maintenance cost is doubled, and the other costs are kept the same as in the eight-turbine scenario. These costs should not increase between the two scenarios, as they are not directly associated with maintenance. Also shown in Table 7-4 is the total OPEX per MW, per MWh, and as a percentage of total CAPEX (TCP).

Table 7-4: Summary of OPEX costs

	8 Turbines	16 Turbines
Maintenance	134,850	269,700
Operation	53,940	53,940
Port activities	110,009	110,009
Licence fee	13,485	13,485
Other costs	42,584	42,584
TOTAL OPEX	354,868	489,718
TOTAL OPEX per MW	632,790	436,625
TOTAL OPEX per MWh*	276; 290; 401	190; 200; 277
TOTAL OPEX as a % of TCP	4.0%	4.2%

** The three numbers refer to the resource at 12 knots, 10 knots and 8 knots respectively*

The total OPEX per MW for both scenarios is in the lower half of the expected cost for an early tidal array or first project as reported in IEA-OES, which estimates OPEX to between AUD 215,200 and 1,560,200 per MW when using the conversion rate 1 USD = 1.345 AUD (2015). Ref [14]. Wave Energy Scotland currently suggests an OPEX between 2% and 6% of TCP, depending on the site. Ref [15]. Both scenarios provide a good starting point at about 4% of TCP. Another way to view OPEX is as a percentage of the lifecycle costs, which in this case puts OPEX for both scenarios at about 30% of total project costs. This again is in line with current industry standards, which expect OPEX for offshore wind projects to contribute between 20% and 30% of total lifecycle costs. Ref [16].

However, the OPEX per MWh indicates there is room for some cost reduction. New offshore wind farms to be commissioned in 2020 are estimated to have an OPEX cost of AUD 47 per MWh. Ref [17]. The best case OPEX for the eight- and 16-turbine scenarios are six and four times more than this. The wind energy industry however has the benefit of being more mature; the installed capacity worldwide for offshore wind is more than 14 GW, and the industry has consistently reduced costs through economies of scale and larger turbines. Ref [18,19].

7.6 Other Assumptions

The final inputs to the models are the discount rate, debt/equity ratio and the expected revenue. The discount rate is set to 8%, as it would be expected to have a lower risk than wave energy, which currently calculates LCOE using a 10% discount rate. Ref [15]. Both models also assume a 75/25 debt/equity ratio with a borrowing term of 20 years at a borrowing rate of 4%. The models have not considered tax in the calculations, however this can be added into the model if required. The revenue needed to achieve a positive NPV and credible IRR of 12% is found through the ‘goal seek’ function, once the results of LCOE, NPV and IRR have been calculated.

7.7 Resulting LCOE, NPV and IRR

The resulting LCOE for the eight-turbine scenario ranges between AUD 782 and 1,138 per MWh, depending on the resource. In the same way, LCOE for the 16-turbine scenario ranges between AUD 527 and 766 per MWh, with the lowest LCOE being achieved in the highest flows. The caveat is that the generated flow data is generic; only detailed modelling or real measured data can provide robust flow data. A summary of the LCOE results, as well as the required revenue to achieve a positive NPV and IRR of 12%, are found in Table 7-5.

When combining the LCOE results with the associated energy yield, the 16-turbine device seems to deliver the best results. For all three resources it can produce at a minimum the required energy demand. The 16-turbine device scenarios also show lower LCOE than the best resource eight-turbine device scenarios.

Table 7-5: Resulting LCOE, NPV, IRR and required revenue

	8 Turbines			16 Turbines		
	12 kn	10 kn	8 kn	12 kn	10 kn	8 kn
LCOE ($/MWh)	782	825	1,138	527	555	766
IRR (%)	12	12%	12%	12%	12%	12%
Required Revenue ($/MWh)	853	899	1,240	573	604	834
Resulting NPV per MW ($/MW)	1,731,902	1,731,722	1,717,841	1,138,795	1,140,991	1,146,769

The target LCOE, as per the Strategic Energy Technology Plan for tidal devices, is to reach AUD 230 per MWh by 2025, and AUD 153 per MWh by 2030. Ref [8]. The conversion rate is 1.53 AUD = 1 EUR (as at 17-Jan-2018). These cost reduction goals are driven by the intended large scale tidal energy delivering electricity to the electricity market. Current technology will need to reduce costs by 75% to reach these targets. If the 16-turbine and 12 knot resource LCOE of 527 is realistic, costs need to be reduced by about 56% to reach the 2025 target. This could be done via a combination of reducing CAPEX and OPEX costs by 56% each, or alternatively focussing on OPEX to target current offshore wind costs of 47 AUD per MWh, thus limiting the CAPEX cost reduction to 46% instead (5.7 m/MW).

An initial estimate of diesel cost is up to AUD 678.94 per MWh. The calculated LCOEs in Table 7-5 for the TTR compare favourably to this estimated diesel cost. It is also worth remembering that the costs associated with a first project like the TTR are often relatively high, and subsequent projects will likely reduce cost further. Early adopters, such as rural communities or island communities, tend to have a higher price point acceptance where the advantage of energy security outweigh the higher cost. Energy security can be both in terms of a reliable resource, but also a potential decrease in dependency on fossil fuel.

7.8 Sensitivity Analysis

CAPEX and OPEX project estimates are in line with current industry norms for first projects; the target LCOE for tidal is AUD 230 per MWh by 2025 and AUD 153 per MWh by 2030. To achieve these targets, the current tidal technology will need to reduce costs by an average of 75%. Ref [8]. The best-case scenario (16-turbine and 12-knots) will need to reduce costs by about 55% and 70% to reach the 2025 and 2030 targets respectively. Sensitivity has been analysed in two ways:

1. Cost projections using learning rates to a 1 GW cumulative installed capacity
2. A tornado chart detailing the key cost drivers in CAPEX and OPEX.

7.8.1 Project Curves

Learning can be expected between the first project and the nth project, where SI OCEAN uses 12% tidal learning rates to push cost reduction curves toward a 1 GW cumulative installed capacity. Ref [10]. The learning rate is applied for each doubling of capacity. Figure 7-2 shows the estimated reduced cost based on the learning rate for the poorest and the best scenario, as well as the average between the two. It also shows the 2025 and 2030 targets, as well as the current reference LCOE as per JRC. Ref [8]. The current LCOE for tidal ranges between AUD 826 and 1,086 per MWh, with the reference starting at AUD 949 per MWh. This reference is about 10% more than the average LCOE for the scenarios detailed in this report. The best-case scenario shows it has the potential to respectively reach the 2025 and 2030 targets at about 100 MW and 1 GW cumulative deployment, by reducing the learning rate cost.

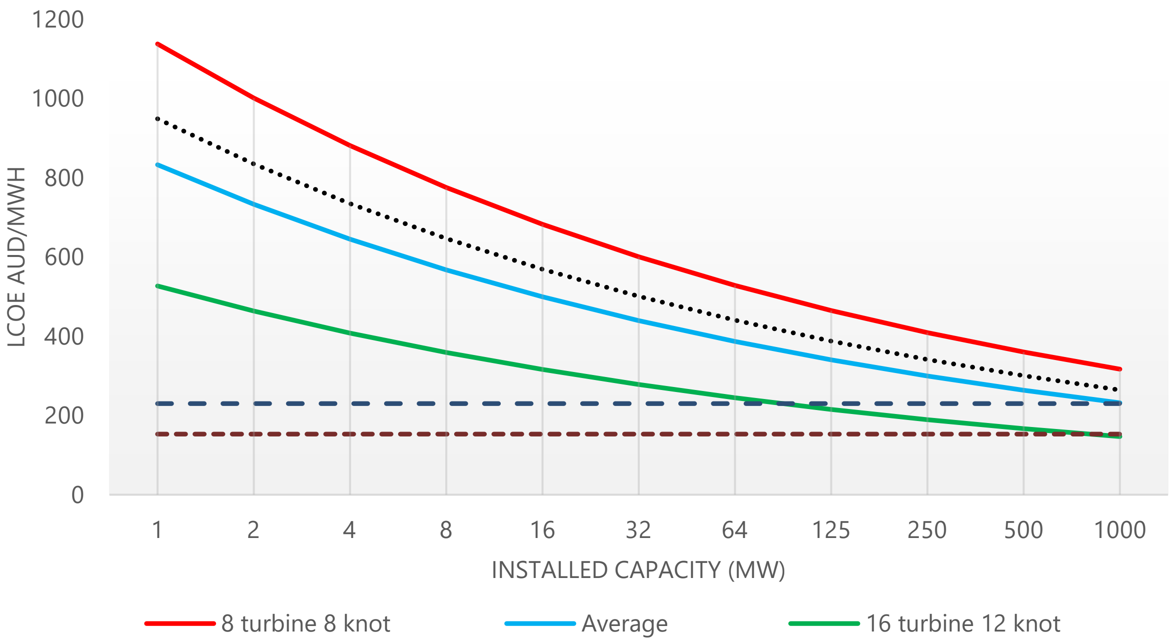

Figure 7-2: Cost project curves using learning rate 12% to a 1 GW cumulative deployment

7.8.2 Tornado Chart

A tornado chart is useful to highlight the key cost drivers in a project. By adjusting each cost by ±10%, while keeping all other costs the same, the impact on LCOE for each cost item can be seen. The LCOE reference around which the CAPEX and OPEX costs will be adjusted is the best-case scenario (16-turbine and 12 knots LCOE of AUD 527 per MWh). Figure 7-3 shows the high-level cost items and their impact on LCOE. It also shows the impact of a ±10% energy yield. As illustrated, the energy yield has the largest impact on LCOE, and strongly indicates the importance of having real resource data (modelled and measured) to truly understand the expected energy yield from the site. Total CAPEX and OPEX are the next key cost drivers. The four high-level cost categories are also shown.

In Figure 7-4, the nine CAPEX cost categories are listed. This illustrates that the key cost drivers are procurement, fabrication and contingency. A 10% decrease in each of these together accounts for approximately 75% of CAPEX reduction (of an equal 10%). The final figure, Figure 7-5, shows the key cost drivers for OPEX. The maintenance cost was estimated by the project, whereas other OPEX costs were calculated based on the cost categories currently used in offshore wind. It is therefore no surprise that maintenance cost is the key cost driver, as it is the largest cost at 38% of OPEX. This suggests that a more detailed OPEX estimate needs to be made as a next step in the project.

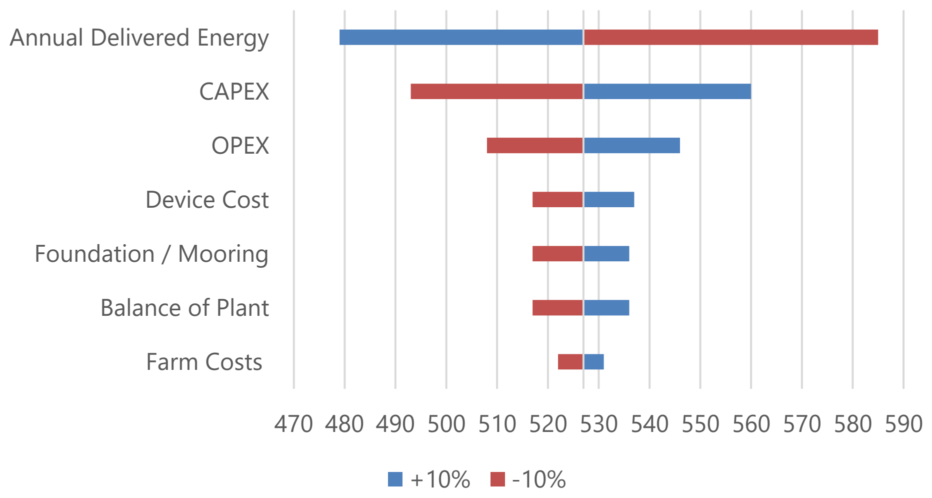

Figure 7-3: Key cost drivers for the different project costs

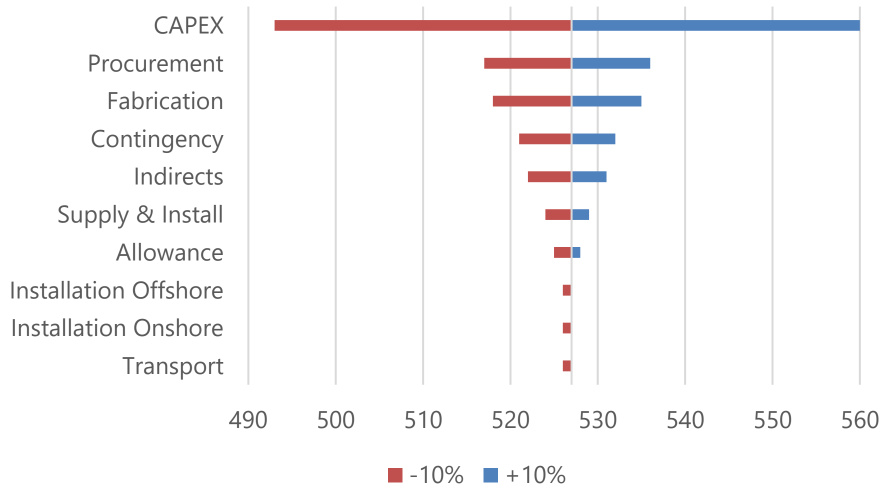

Figure 7-4: Key cost drivers for CAPEX divided into nine different cost categories

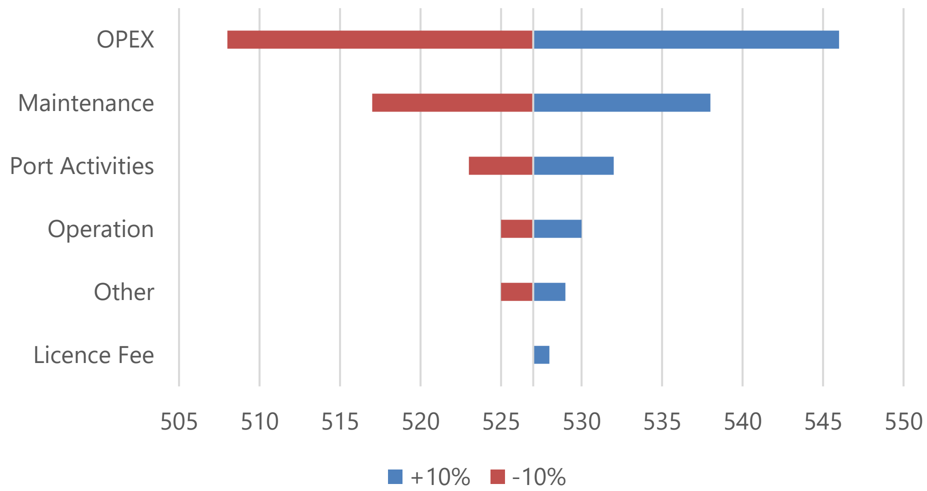

Figure 7-5: Key cost drivers for the OPEX cost categories

7.9 Key Findings

Based on the techno-financial analysis of the two TTR scenarios, the following key findings are made:

1. The eight and 16 turbines have an estimated CAPEX of AUD 15.7 million and 10.5 million per MW. This compares favourably with similar international projects such as the Meygen project Phase 1A, which had a CAPEX cost of AUD 14.7 per MW. The median CAPEX cost for offshore wind projects in 2015 was AUD 6.7 million per MW.
2. Current OPEX estimates are approximately 4% of total CAPEX, which is in line with what Wave Energy Scotland is using in its OPEX estimates (between 2% to 6% depending on site).

3. The best case OPEX per MWh for the eight and 16 turbines are estimated at AUD 276 and 190 per MWh. Compared to offshore wind, with an average OPEX of AUD 47 per MWh, these are six and four times higher. It should however also be noted that offshore wind has reached a cumulative deployment of more than 14 GW.
4. The maintenance cost has been estimated within the project, with all other costs based on OPEX breakdown (in percent) for offshore wind. Ref [11]. A next step should be to calculate a bottom-up OPEX for the entire project to gain further confidence in the results.
5. The calculated LCOE for the eight and 16 turbines range from AUD 527 to 1,138 per MWh. The current reference as quoted by the EU JRC is AUD 949 per MWh.
6. The European Strategic Energy Technology Plan has ambitious targets to achieve an LCOE of AUD 230 per MWh by 2025 and AUD 153 per MWh by 2030. To achieve these targets, cost reductions of up to 75% on current technology is required. For the best-case scenario (16-turbine in the 12-knot resource), the costs will need to be reduced by at least 56%. It is also expected that an improvement in the capacity factor combined with a confirmed tidal resource will provide a good foundation for further development. It is believed the resource is conservative. Combining this with a refined CAPEX (-30%) and a predetermined OPEX would offer a unique opportunity for One Arm Point.
7. Cost projections show that with learning rates, the best-case scenario may reach the 2025 and 2030 targets at approximately 100 MW and 1 GW cumulative deployment respectively.
8. The best LCOE was garnered with 16 turbines in the 12-knot resource. This highlights the importance of maximising power output and a good resource to achieve a strong LCOE.
9. Sensitivity analysis using tornado charts highlight the key drivers as energy yield, procurement, fabrication and contingency. The key cost driver within OPEX was maintenance.
10. Even at this relative high LCOE for the electricity market, early adopters such as One Arm Point may have a higher price point tolerance that outweighs the current cost of a tidal device. Energy security, reliability and decreased fossil fuel dependency are but a few advantages of a local tidal device.
11. Based on the generic tidal site, only the 16-turbine concept may produce enough power to support the community at One Arm Point. The lowest resource shows energy yield to match the energy demand, whereas the higher resources show energy yields of 40% to 60% more than demand. The eight-turbine concept may only produce up to about 73% of the electricity demand.
12. The availability of data is a significant limitation to the modelling. There is currently no data for the chosen location. There are options for the next stage in terms of detailed numerical modelling, but ideally physical measurement of the site would be conducted.
13. There are current plans to develop a Tidal Atlas for Australia. Once this is complete, the new data can be used to update these techno-financial models.

8 Discussion (Opportunities)

8.1 Learnings

During the concept development, several key learning points were discovered. The points noted below are based on a reinforced concrete TTR structure:

1. The foundation base length was found to be governed by the 'sea-chesting' installation procedure, to ensure the TTR remains stable and the descent is controlled.
2. The designs of the floor, wall and roof thicknesses of the concrete panels are governed by the hydrostatic pressure during the 'sea-chesting' installation procedure. As the weight of the structure is relatively heavy compared to other materials, the TTR doesn't require much ballasting to lower to the seabed. As a result, most of the compartments within the foundation base will be subject to the full head of hydrostatic pressure.
3. Although the length is required for 'sea-chesting' installation, if a shorter base is to be used then the dimensions will be governed by damaged stability. The damaged stability can be mitigated by increasing the height of the base, however, a higher base will increase in-place loads.
4. Steel columns (masts) were governed by vortex induced vibrations (VIV). This is an issue for all fixed tidal structures and becomes harder to solve as water depths increase.
5. The weight of the structure alone is not sufficient to resist the base shear caused by the large (survival) tidal current lateral loads. As a result, a grout shear interface foundation system is required to help resist the base shear that causes a sliding failure mode due to the more extreme current velocities (>2 m/s). However, the overturning moment is resisted by relying on the weight of the structure.
6. The grouting installation procedure was estimated to be effective in days, therefore the TTR structure must remain in-place during a small tidal cycle that would be subject to smaller tidal currents (assumed to be <2 m/s). The structure requires a certain amount of weight to remain stable during this time under its self-weight (behaving as a gravity based structure). Therefore, too much optimisation to reduce weight will be a disadvantage.
7. A significant portion of the lateral load was caused by the foundation base. The computational fluid dynamics (CFD) analysis shows the load can be significantly reduced by rounding the corners if required. Although this can be an advantage for reducing the load, it will impact the fabrication cost.
8. This concept was developed for a water depth of 13.0 m (in respect to LAT) with a tidal cycle of about 9 m. This concept may not be achievable in significantly deeper water, as the length of the columns would increase and therefore increase the column diameter to avoid VIV problems. This will then restart the design cycle, and could lead to another aspect governing the design (i.e. overturning moment due to the increased height of the structure and load generated from the columns, which will then demand more self-weight to keep stable in its in-place condition).
9. Formwork for concrete is a significant contributor in the cost. The fabrication methodology would need to investigate the impact on schedule to optimise the cost savings in re-using formwork.

10. Power cable span of 200 m was found to be close to the conventional limit, without introducing more complex taller structures or intermediate supporting structures across the cable span.
11. The mooring loads are based on a small wave environment, but if the mooring system is stiff or the environment is higher than assumed, loads will quickly grow to unmanageable levels.
12. The SCHOTTEL turbines considered for this project had limited customisation; they came with either a 4 m or 6.3 m diameter rotor, meaning their power curves could not be completely optimised to the site flow. For the slower end of the current speeds, the turbines did not achieve maximum output; at the higher end of the current speeds, the turbines cut out, producing no output.

8.1.1 Fabrication

The use of alternative materials to construct the foundation base was preliminarily investigated during this phase. There are several advantages and disadvantages between a reinforced concrete foundation base and a steel foundation base. The key learnings discovered during this phase were:

1. Preliminary screening showed reinforced concrete will be cheaper.
2. The use of steel would result in a lighter overall structure, so the issues surrounding the sea-chesting installation method would be reduced, potentially reducing the length of the TTR vessel. However, as pointed out above, there is a disadvantage with making the structure too light as this would bring a challenge to the installation, particularly resisting the lateral loads caused by a tide cycle during the installation period, which currently relies on a certain amount of self-weight.
3. In addition to the installation period, the overturning moment is resisted by weight in the structure, and therefore the weight in the structure would need to be built up once in place to resist the in-place loads.
4. The de-ballasting control would be easier with a steel structure, given the reserve buoyancy would be much larger. The reinforced concrete option doesn't require a lot of ballast to sink the tip of the structure to the seabed.
5. Reinforced concrete has its advantages in the marine environment compared to steel. The durability in concrete can be controlled by providing adequate cover and limiting the stresses in the reinforcement steel, where steel would require a significant increase in corrosion control. This would need to be applied through specialised coatings or cathodic protection that would significantly increase the maintenance required throughout the life of the structure.
6. Turbine integration onto a swivel is not an off-the-shelf item. Further work is required to fully understand the functionality of a swivel and wiring.
7. It has been found that using smaller turbines is more economical; as turbines increase in size, their weight increases with the cube of the scale while the benefit (energy capture) only increases with the square of scale.

8.2 Opportunities

There are several points worth noting as key opportunities that have been discovered during this phase:

1. The current concept is for a single row of turbines. If a slightly deeper location was used, a second row of turbines can be added which will have a marginal impact on costs. The installation cost will be almost negligible and the fabrication cost will be marginal, as the increase in the foundation base will most likely be insignificant. Some parameters of the design would need to change. For example, the diameter of the mast would need to be larger to combat the VIV requirements. The significant aspects of a two-row system that would be required are the additional masts and fit-out to accommodate more turbines.

   Figure 8-1 shows a two-row system in water 17 m deep.

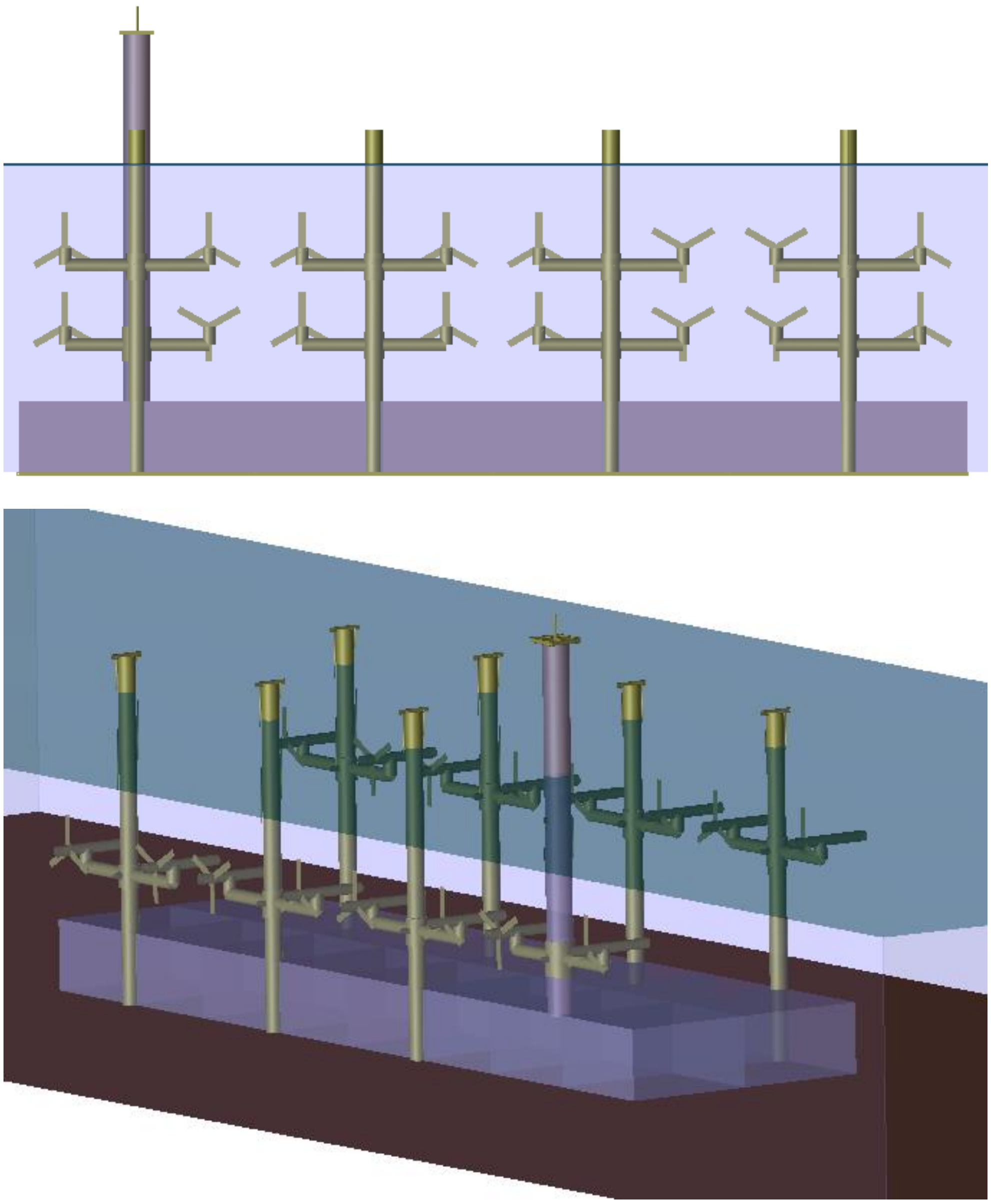

Figure 8-1: Two row system TTR device structure

2. As per Civmec's improvements, the compartments can be designed square to reuse formwork to reduce fabrication cost.
3. Further refinement of the turbine design may allow the power curve to get more out of the high speed currents.

8.3 Risks

The key risks of this concept are as follows:

1. Assumptions made in this report are conservative.
2. The concept relies on a grouted seabed system. If a detailed investigation reveals a seabed that is not suitable for this type of foundation resistant system, the current foundation system will not work and would need to be revisited.
3. The installation of the TTR device is heavily dependent on good weather. It is essential that the tidal currents during this window are minimised. The installation of this offshore structure can be delayed until these conditions are met. Although this is a risk, with more accurate site investigation, the tidal movements and current speeds can be highly predictable.
4. The current installation doesn't allow for levelling the structure. It is assumed the ground conditions would be relatively flat and the TTR device will be installed to a reasonable tolerance.
5. This phase has not considered any environmental approvals that may be required for this concept to go ahead. Tidal turbines in an open marine environment are not well understood in Australia.
6. The current environment at site is difficult to work in, and all offshore operations duration and contingency is underestimated. It is not a common task for boats and workers to be in these conditions.
7. The turbine swivel design concept and wiring configuration requires further design development and may prove too costly or maintenance-intensive. A variable pitch turbine may be the answer to this risk.
8. A possible design change for future projects would be to reduce the turbine complexity even more by taking the brake out of the system. This would however require having the ability to stop the turbine by other means, e.g. yawing it out of the flow.

8.4 Recommended Future Work

Based on the work completed in this phase, the recommend future work includes:

1. A detailed geotechnical and site investigation/modelling is required to determine:
   - Seabed soil/rock properties
   - Bathymetry of the proposed and surrounding area
   - Accurate tidal range and tidal velocities, specifically in Pearl Pass
   - Metocean data to confirm design parameters.

2. The CFD suggests the current around the base can be heavily disturbed locally. The CFD model is based on a 2D system, and future work would be needed to ensure the local disturbance of the current velocity around the structure is not an issue.
3. A simplified VIV calculation was performed using DnV. Ref [20]. As the steel columns are governed by VIV, a more detailed analysis would be required to confirm the simplified assessment is valid. This would include determining more accurately the natural period of the steel columns, the effect the flexibility of the base may have on the columns' natural period, and the local flow around the structure as pointed out above.
4. Further work is required into the design of the passive swivel, with a widening of the design to consider other options to align the turbines into the current flow.
5. Traditional Owners should be consulted to ensure they are engaged and possible issues with Native Title are foreseen and addressed.
6. An environmental impact assessment should be completed for any proposed site.

9 References

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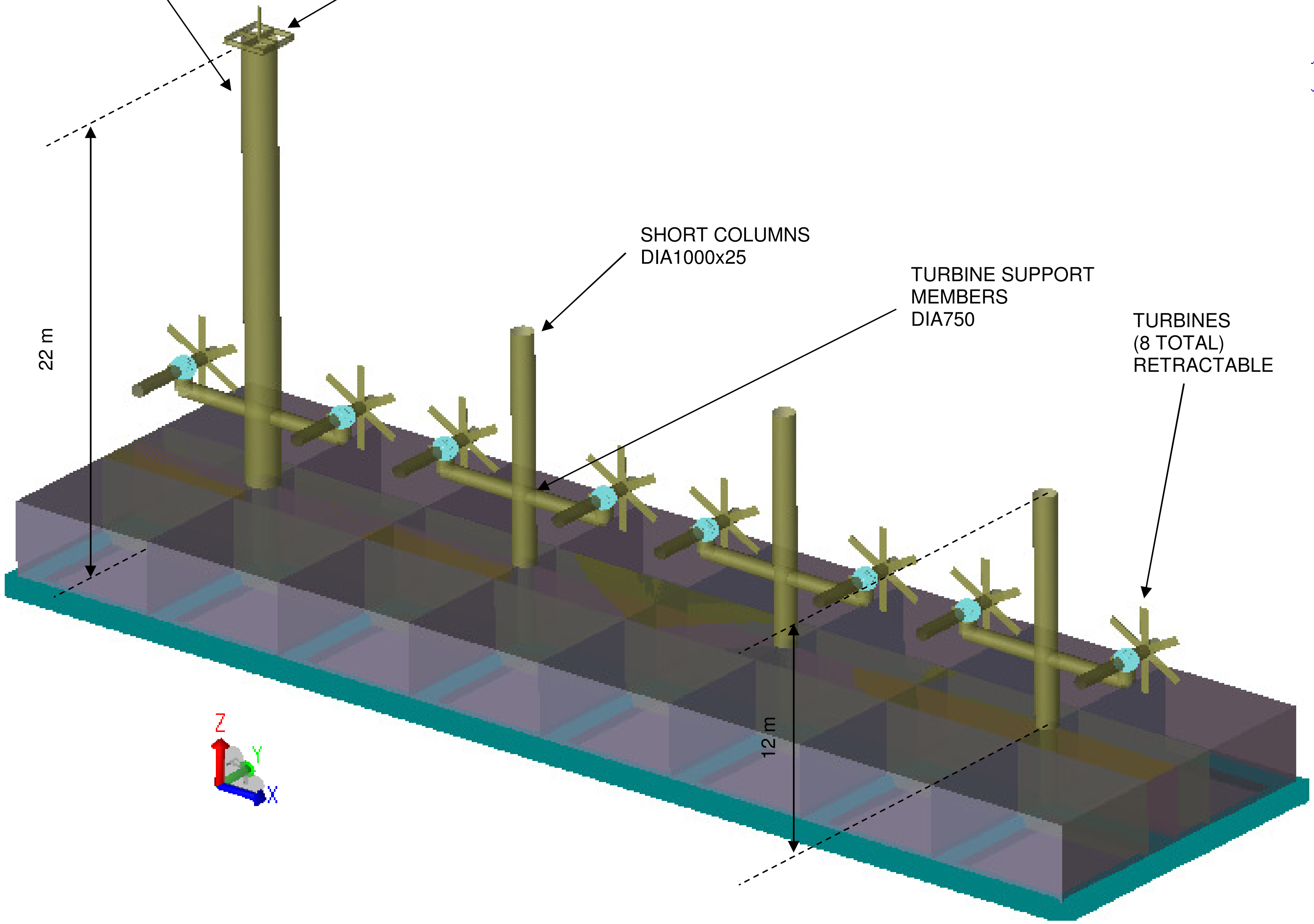
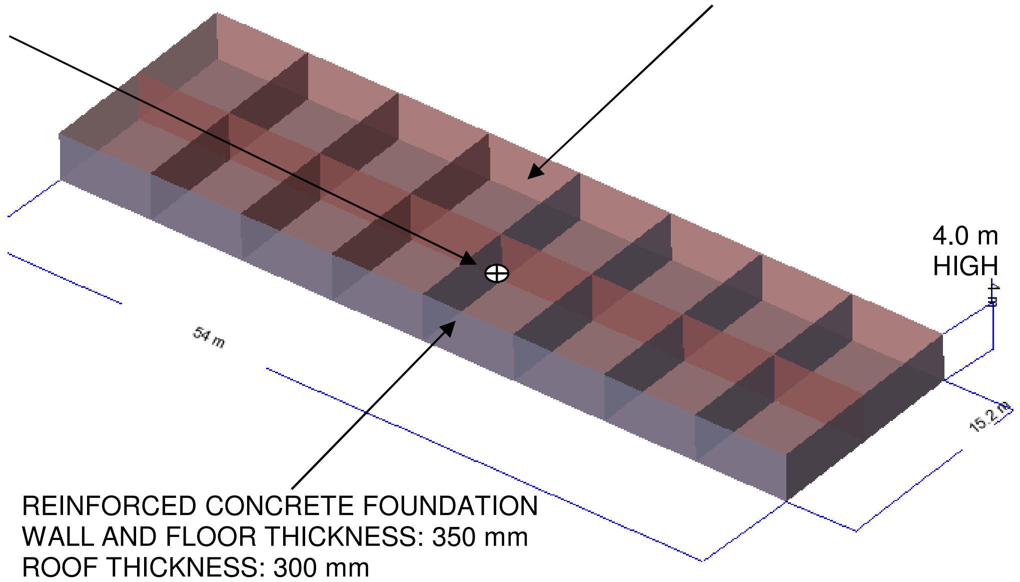
Appendix A Drawings Dossier

Drawing/Sketch Number	Drawing/Sketch Title
ST-DSK-0001	General Arrangement
ST-DSK-0002	Concrete Details
ST-DSK-0003	Steel Column Concept Details
ST-DSK-0004	Foundation Base and Grout Pipework Details
ST-DSK-0005	Onshore Power Pole Details
ST-DSK-0006	Power Pole Foundation Details
SH-DSK-0001	SIT 250



OVERALL GENERAL ARRANGEMENT



FOUNDATION ARRANGEMENT
(ROOF OMITTED FOR CLARITY)

WEIGHT ESTIMATE	WEIGHT (T)
REINFORCED CONCRETE	2360
STEEL COLUMNS	66
TURBINE SUPPORT STRUCTURE	22
POWER PLATFORM	2
TURBINES	16
TOTAL	**2470**

Total weight includes a 5% contingency on concrete weight and a 20% to 30% contingency on steel weight

COG [m]		
X	Y	Z
-0.181	0	2.98

PRELIMINARY
NOT FOR CONSTRUCTION

No.	DATE	DRN	DESCRIPTION	CHKD	ENG	APPR
1F						

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TTR DEVICE CONCEPT STUDY

GENERAL ARRANGEMENT

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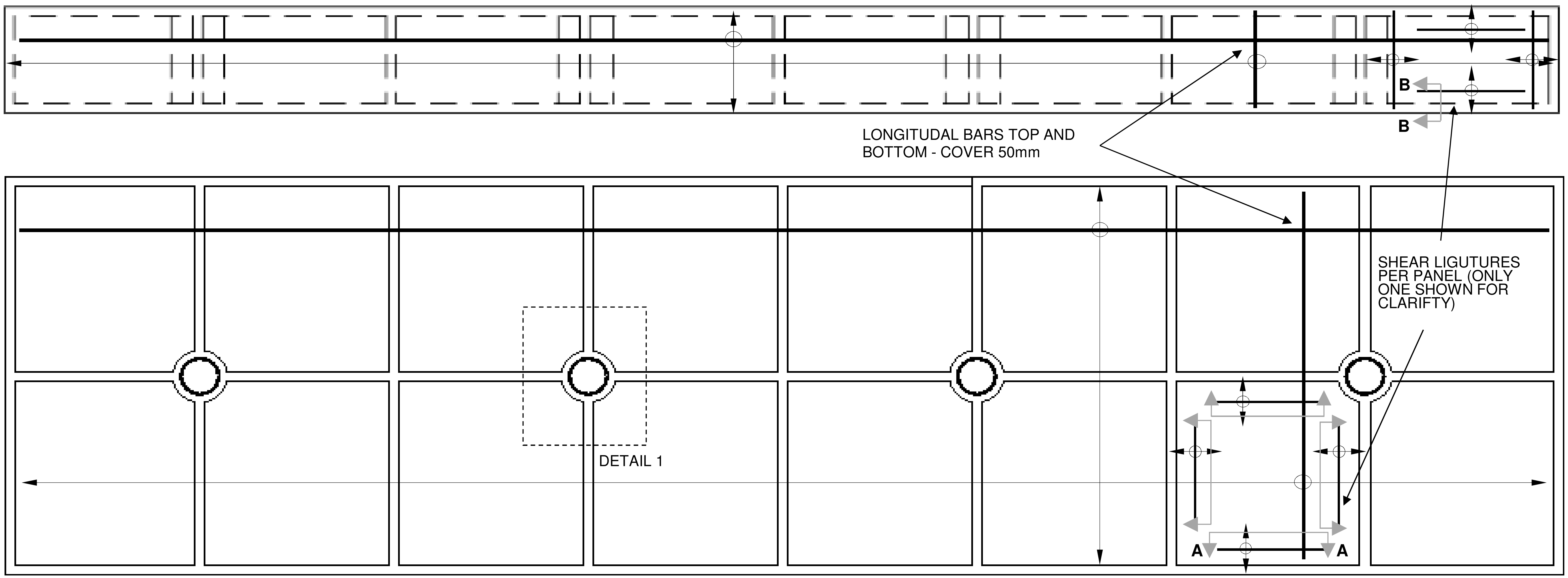
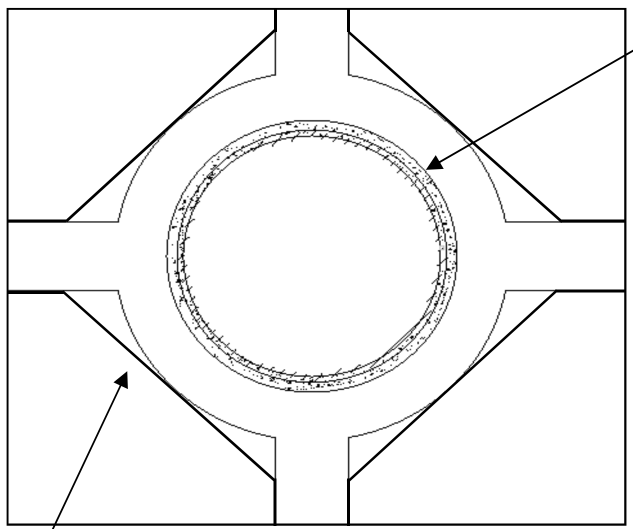
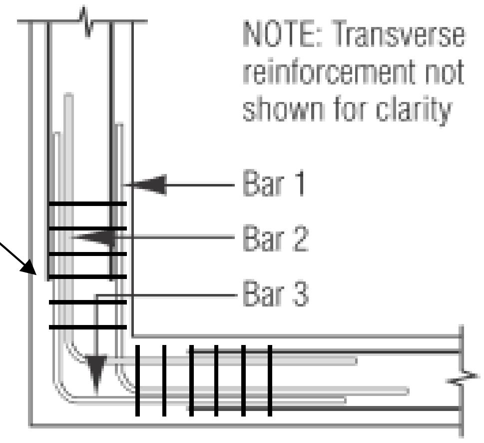


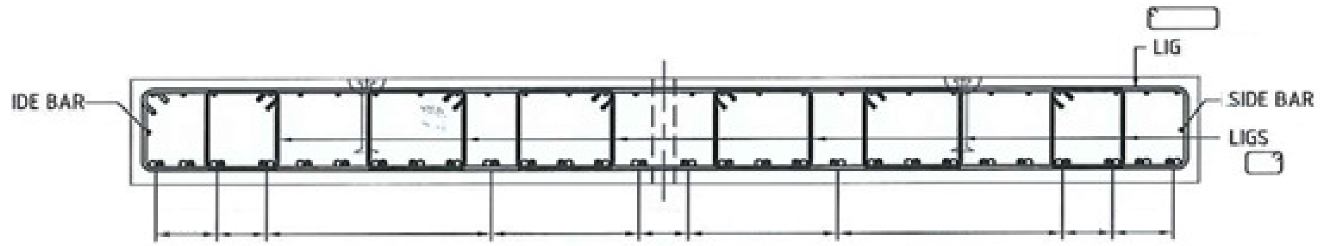


DETAIL 1
CONCRETE TO STEEL COLUMN AND
PRECAST PANEL CONNECTION CONCEPT

ALTERNATIVE CONCRETE
COLUMN DETAIL



SECTION B-B



SECTION A-A

PRELIMINARY
NOT FOR CONSTRUCTION

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No.	DATE	DRN	DESCRIPTION	CHKD	ENG	APPR
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TTR DEVICE CONCEPT STUDY

CONCRETE DETAILS

DRN	CHK	DATE	SKETCH No.	REV
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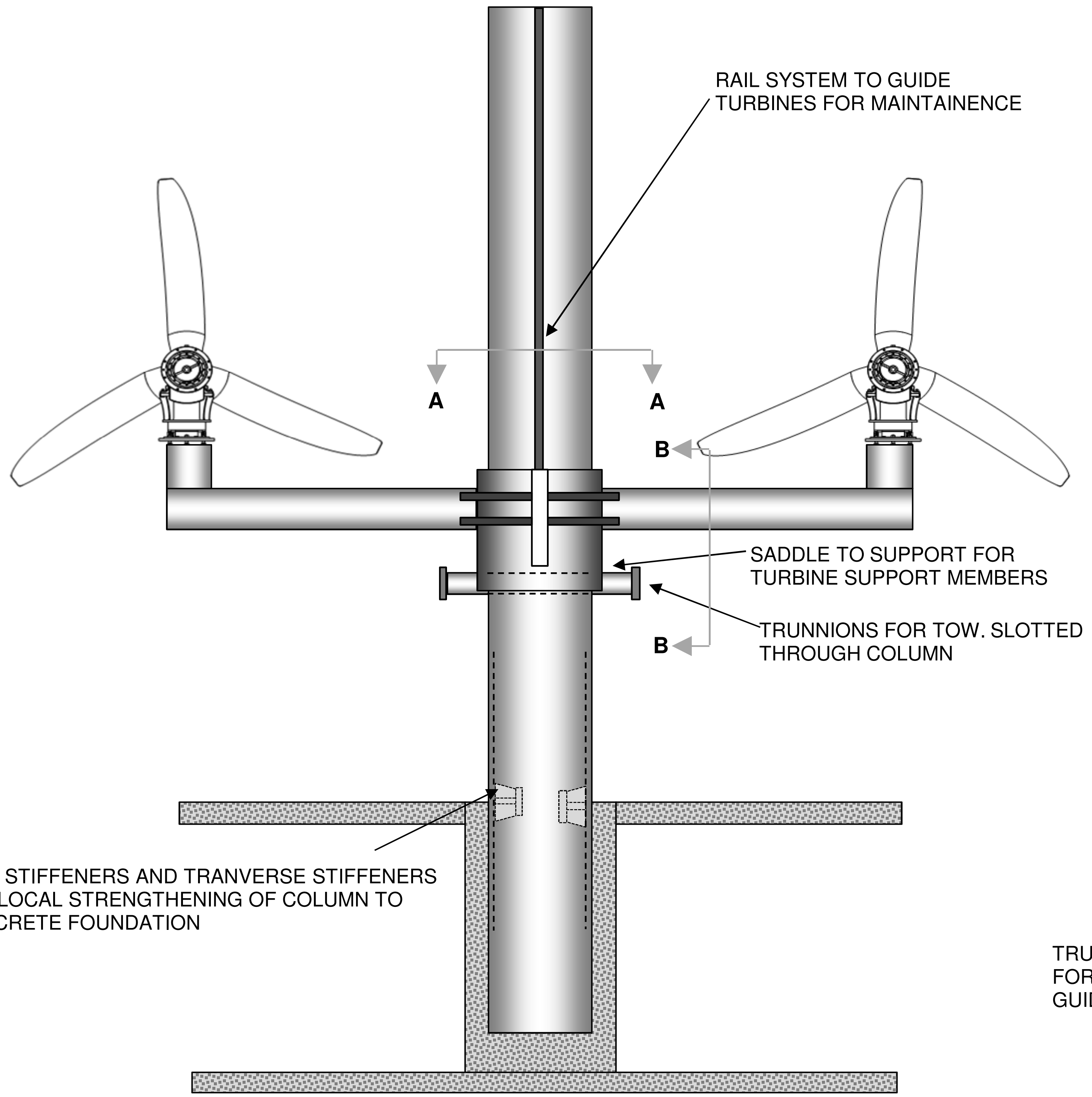
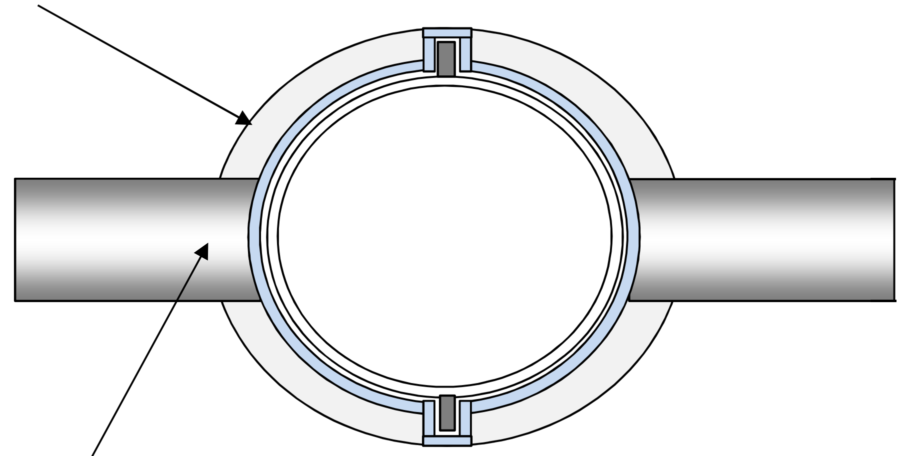
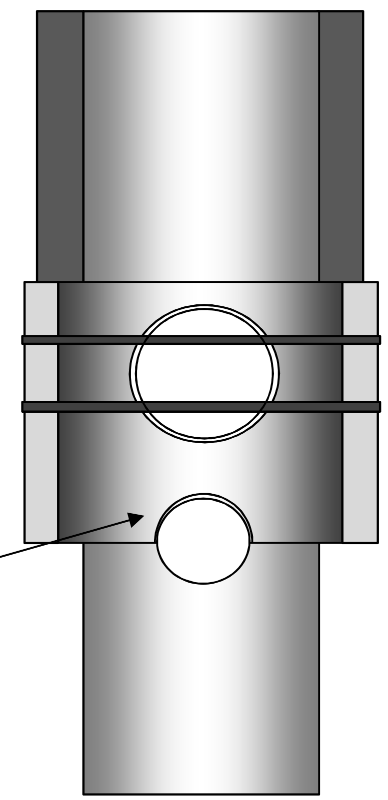




SECTION A-A



SECTION B-B

PRELIMINARY
NOT FOR CONSTRUCTION

No.	DATE	DRN	DESCRIPTION	CHKD	ENG	APPR
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WorleyParsons
resources & energy

TTR DEVICE CONCEPT STUDY

STEEL COLUMN CONCEPT DETAILS

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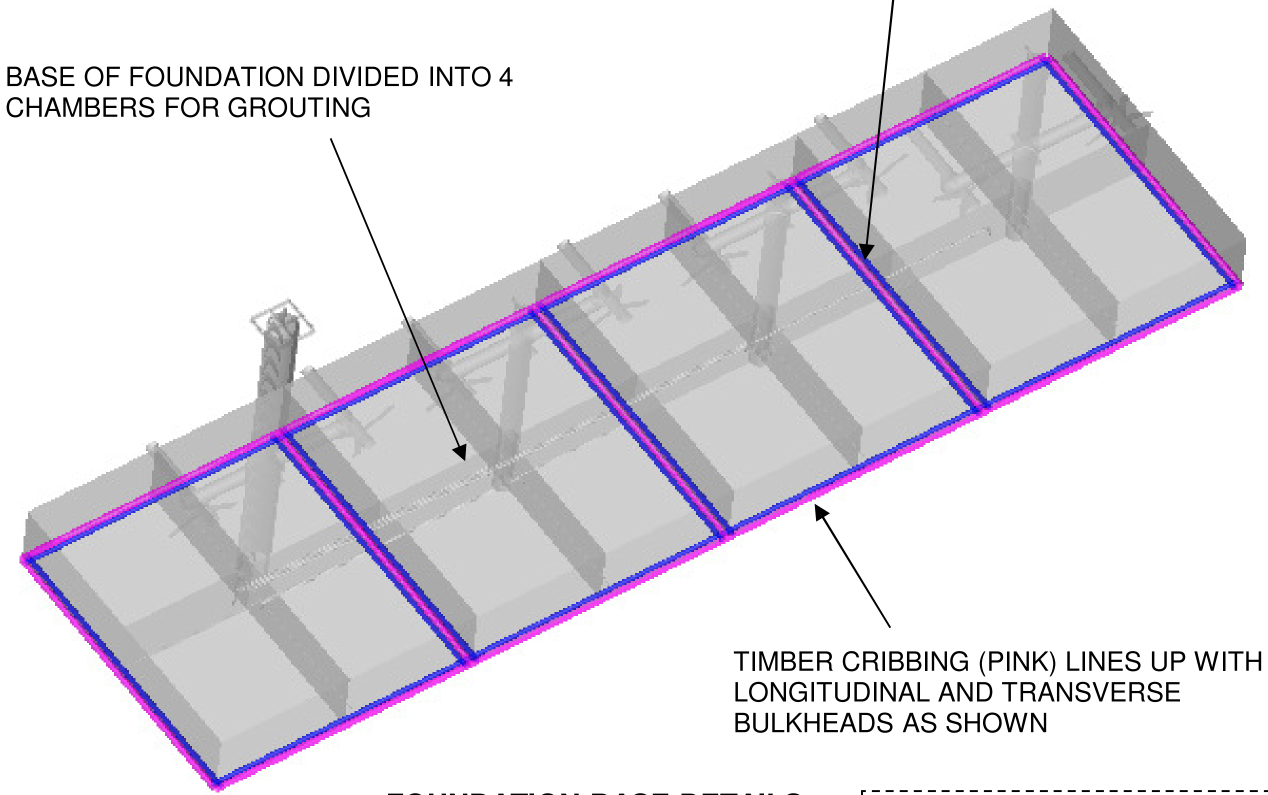
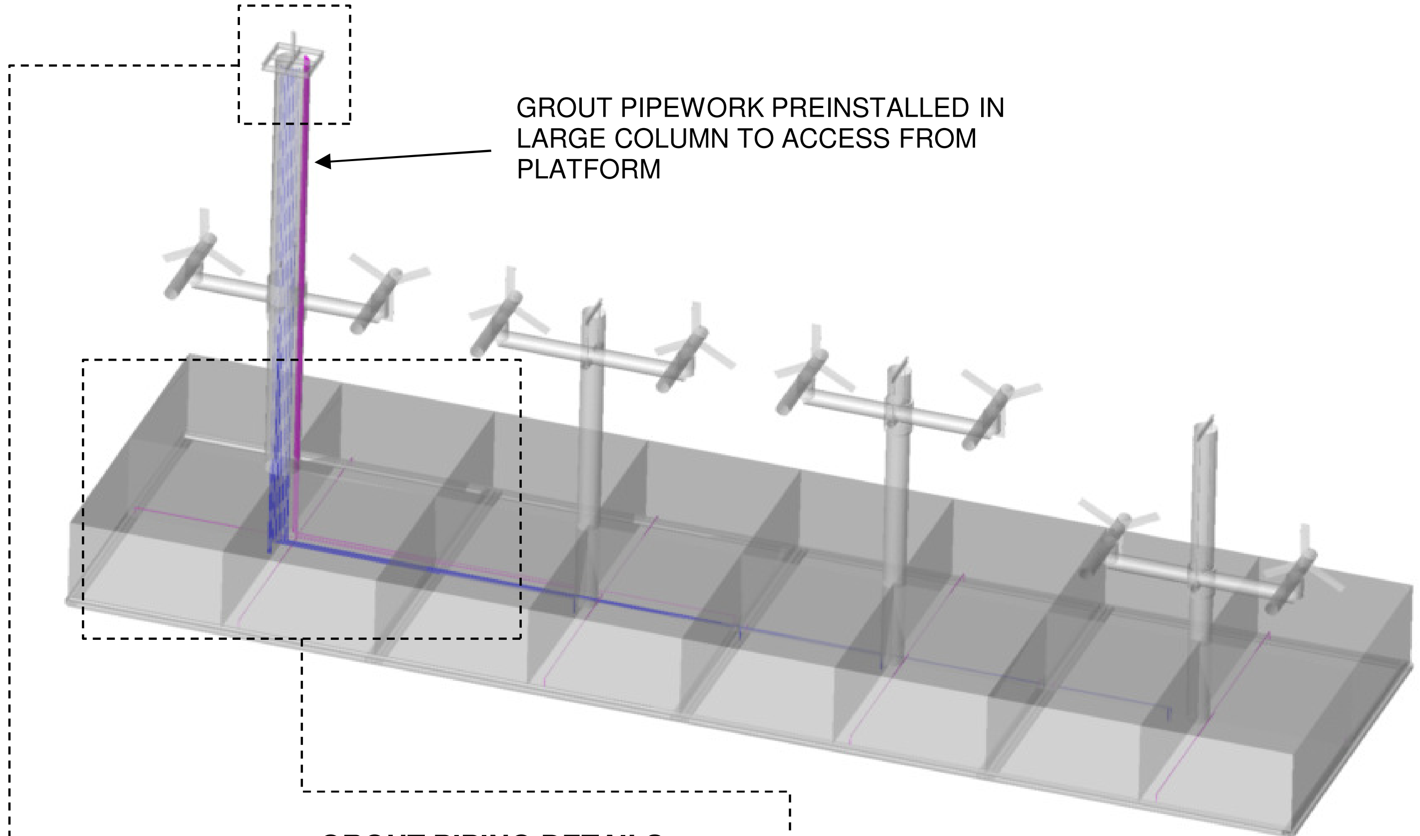
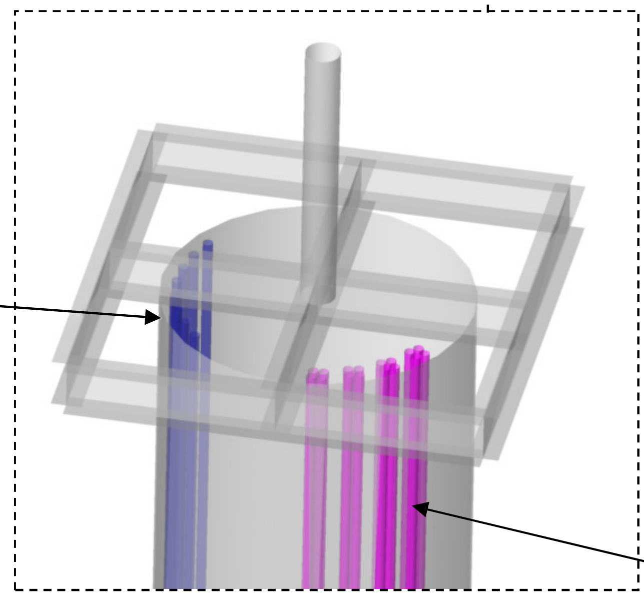
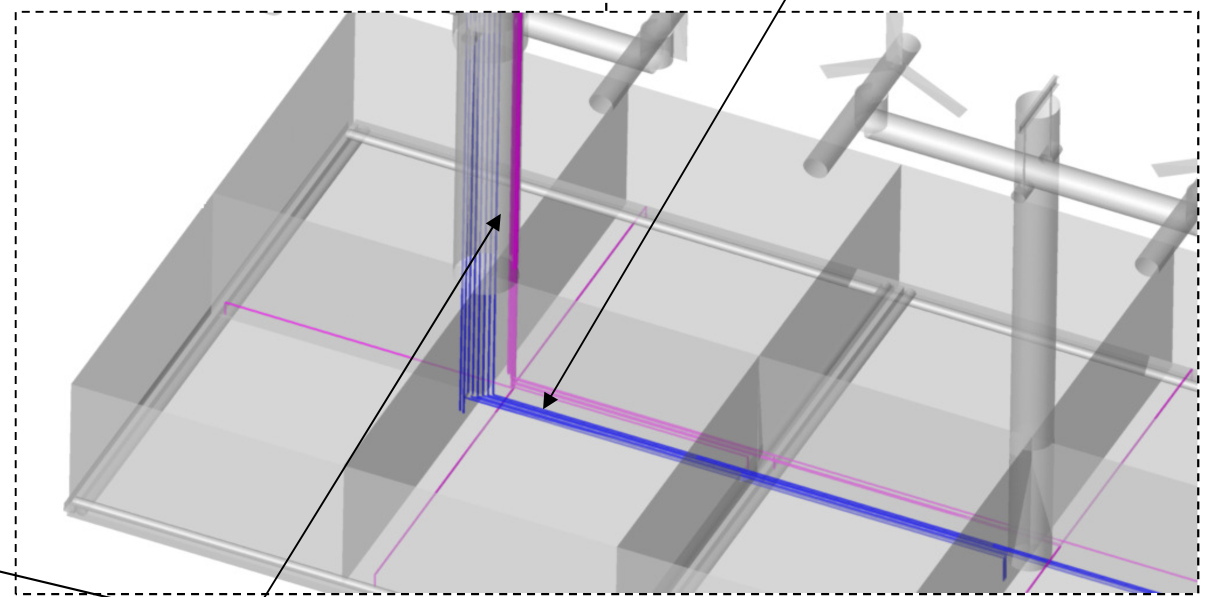


FOUNDATION BASE DETAILS



GROUT PIPING DETAILS





PRELIMINARY
NOT FOR CONSTRUCTION

No.	DATE	DRN	DESCRIPTION	CHKD	ENG	APPR
1F						

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TTR DEVICE CONCEPT STUDY

FOUNDATION BASE AND GROUT PIPEWORK DETAILS

DRN	CHK	DATE	SKETCH No.	REV
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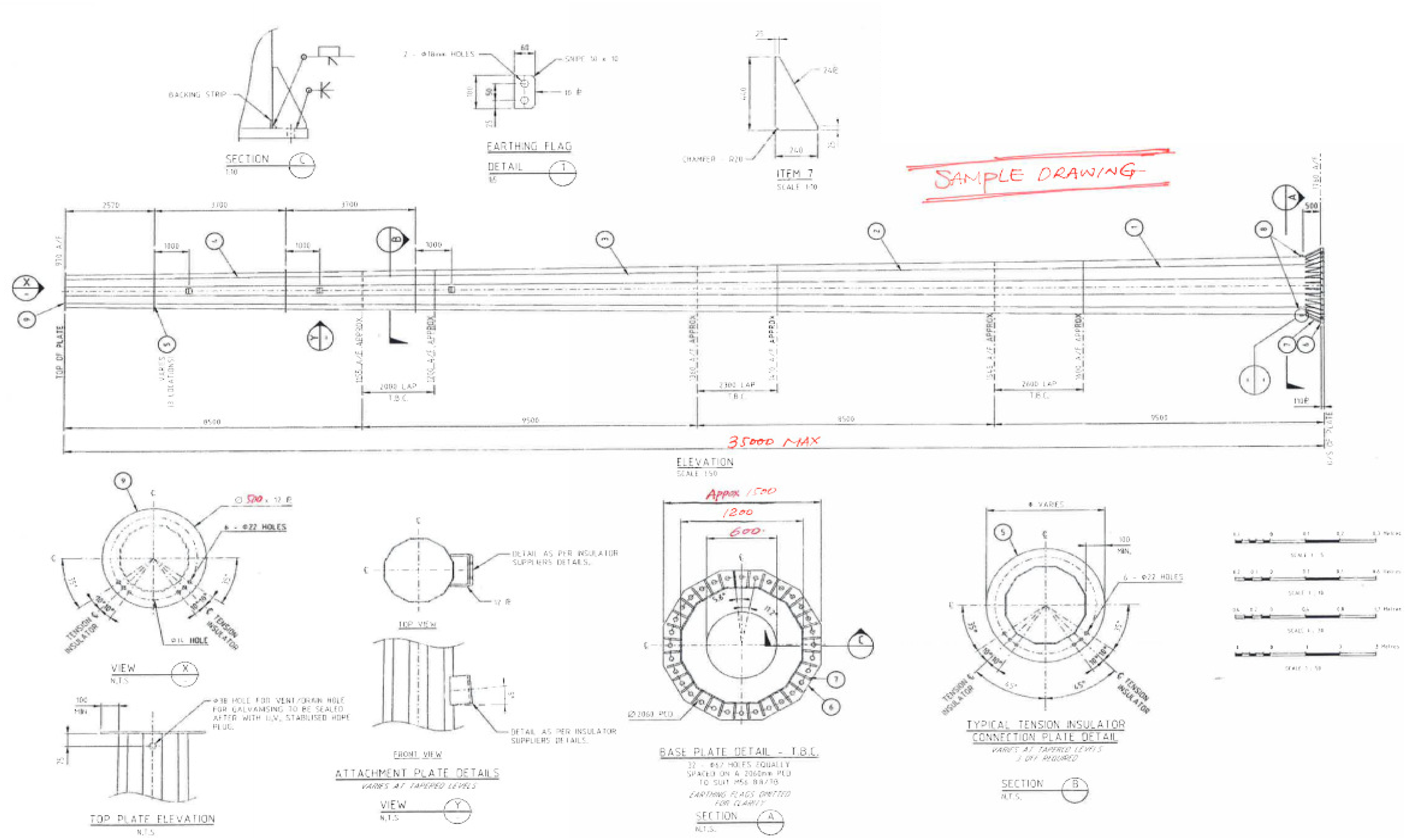

PRELIMINARY
NOT FOR CONSTRUCTION

No.	DATE	DRN	DESCRIPTION	CHKD	ENG	APPR
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TTR DEVICE CONCEPT STUDY

ONSHORE POWER POLE DETAILS

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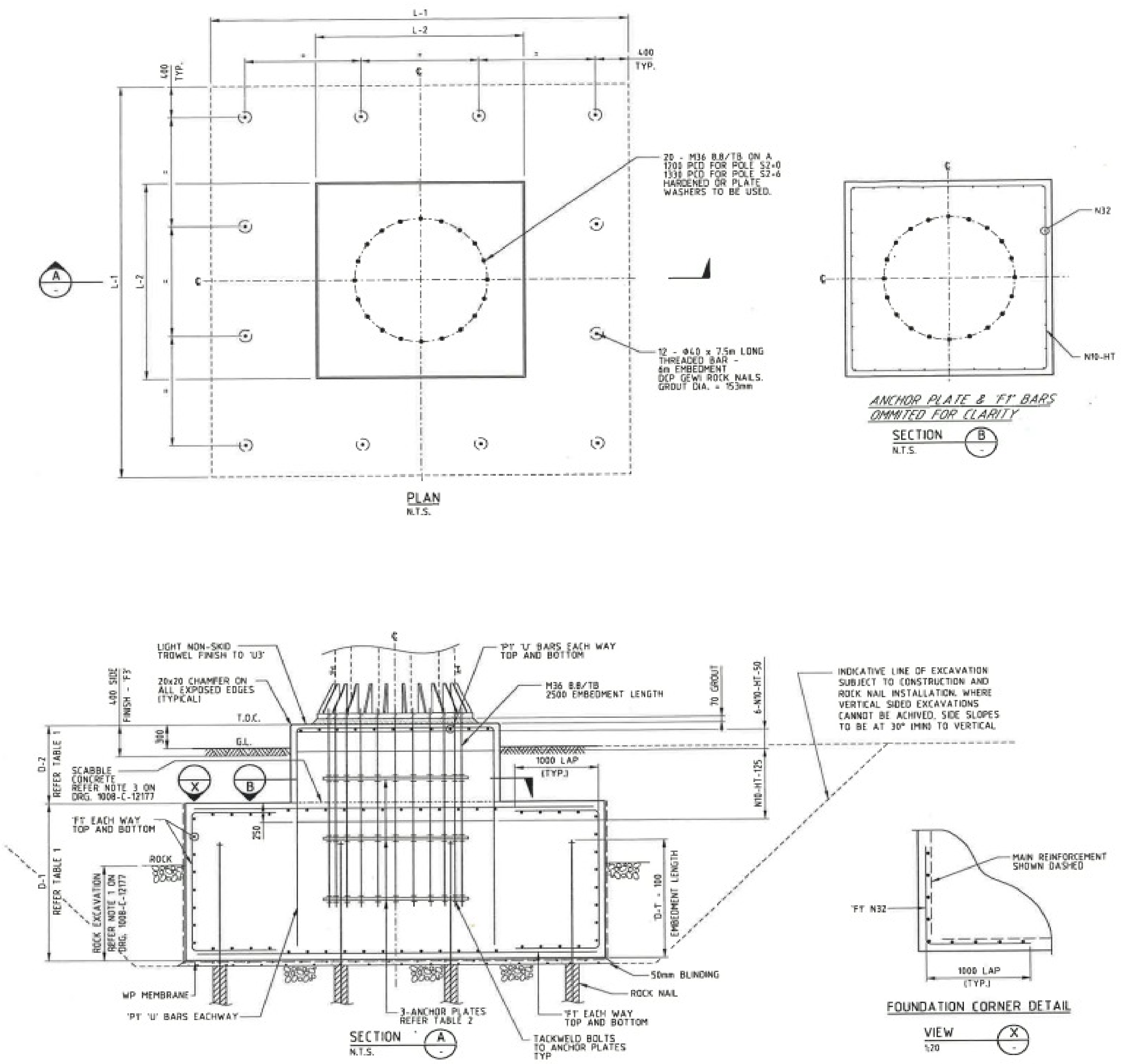

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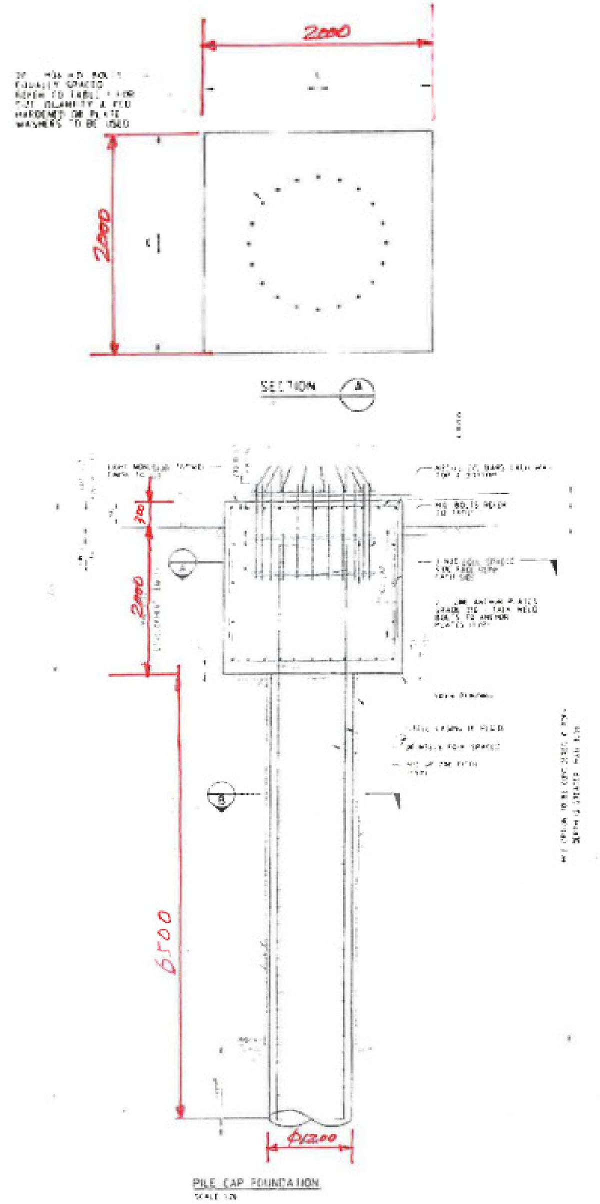

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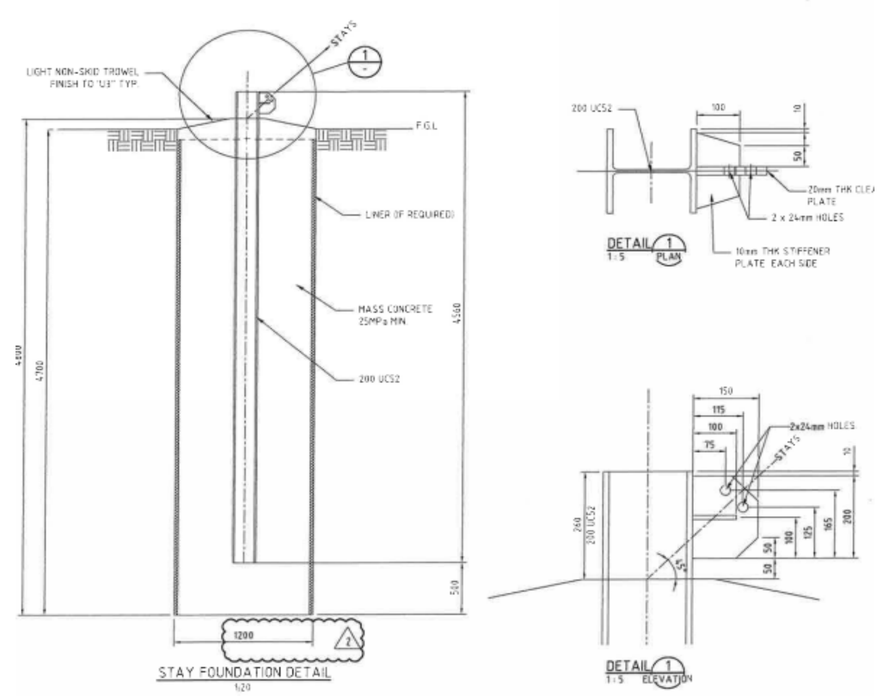

STAY FOUNDATION DETAIL

PRELIMINARY
NOT FOR CONSTRUCTION

1F						
No.	DATE	DRN	DESCRIPTION	CHKD	ENG	APPR

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TTR DEVICE CONCEPT STUDY

POWER POLE FOUNDATION DETAILS

DRN	CHK	DATE	SKETCH No.	REV
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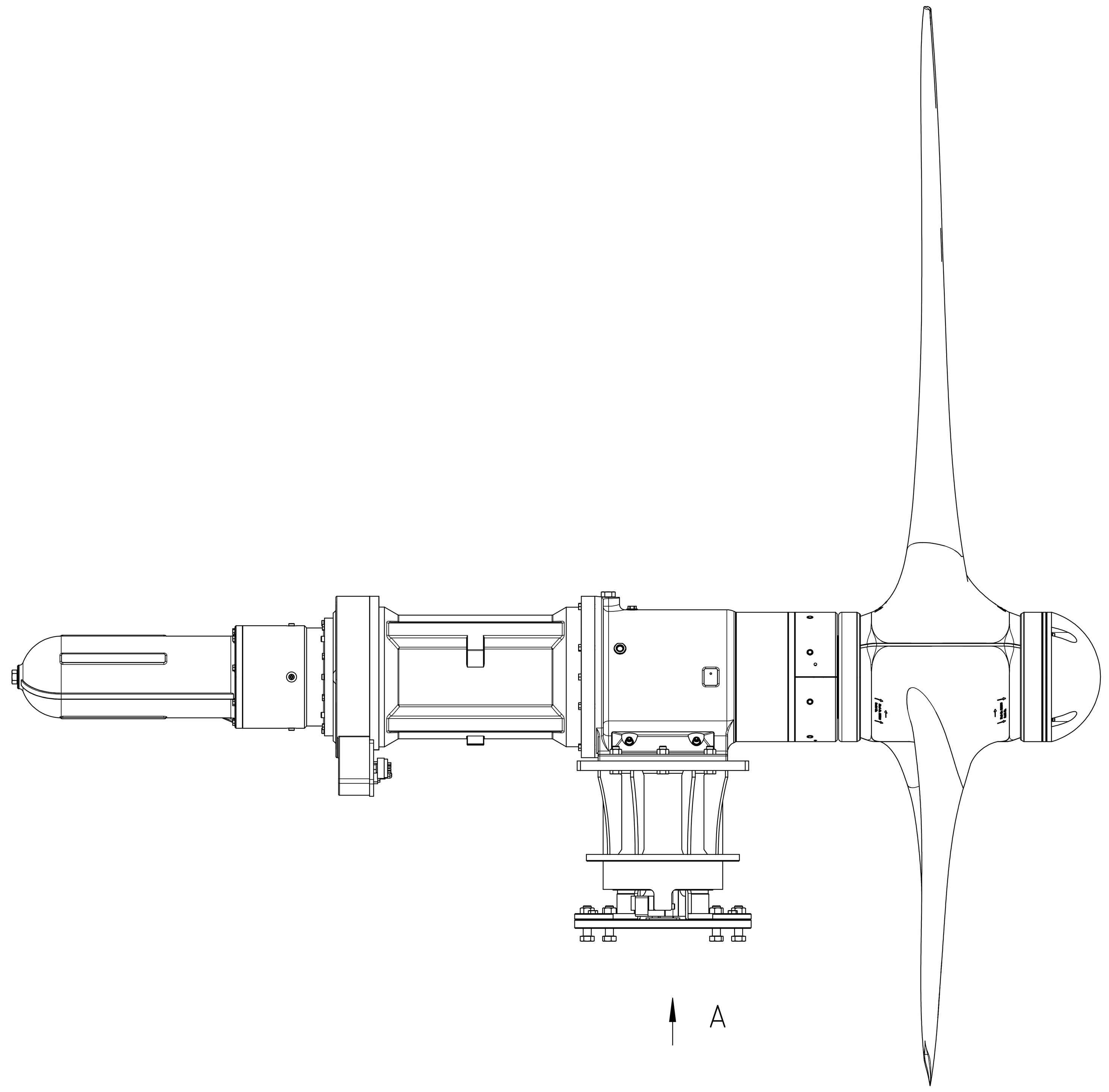

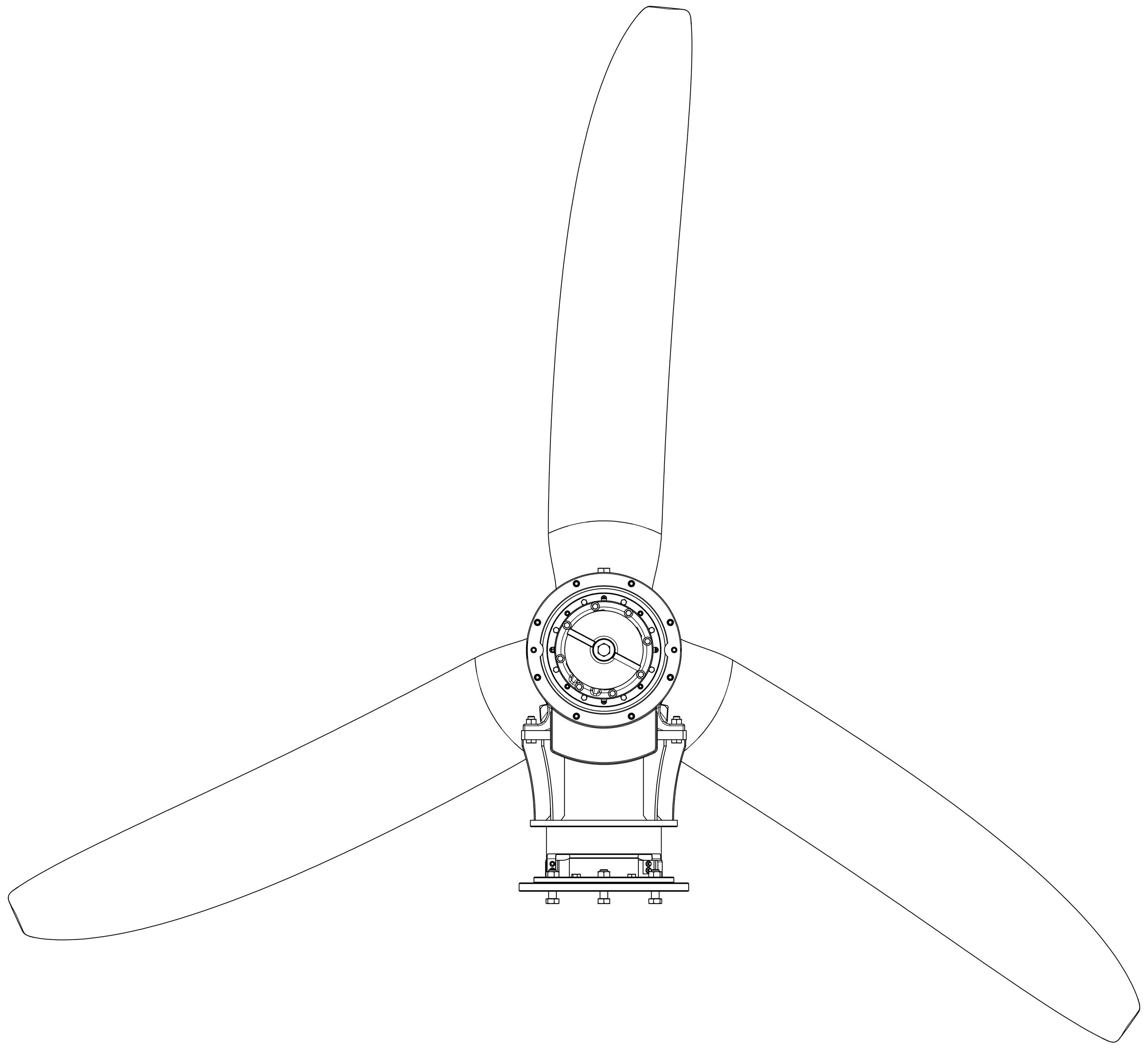

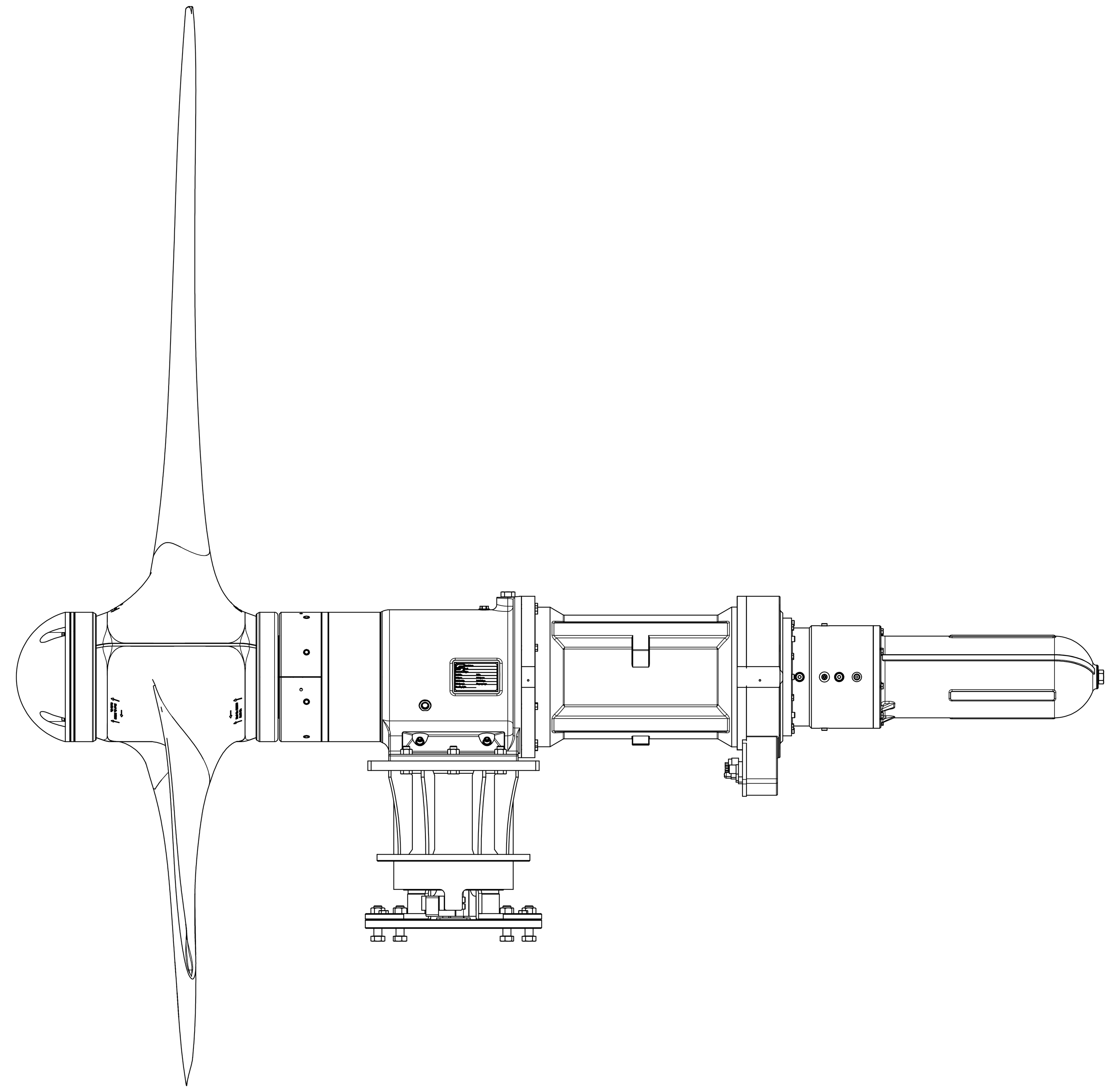

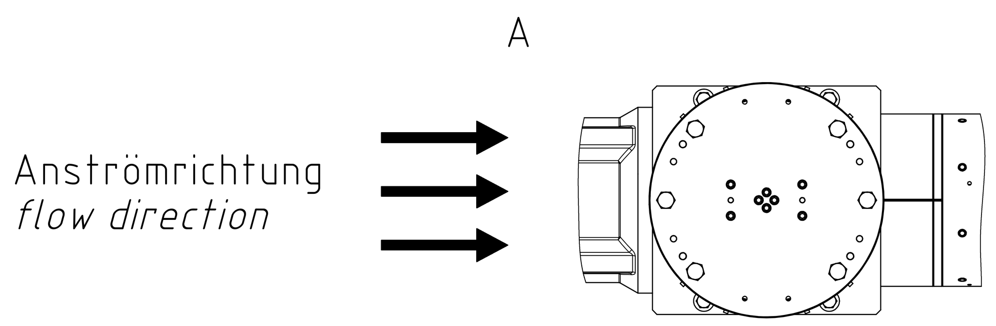

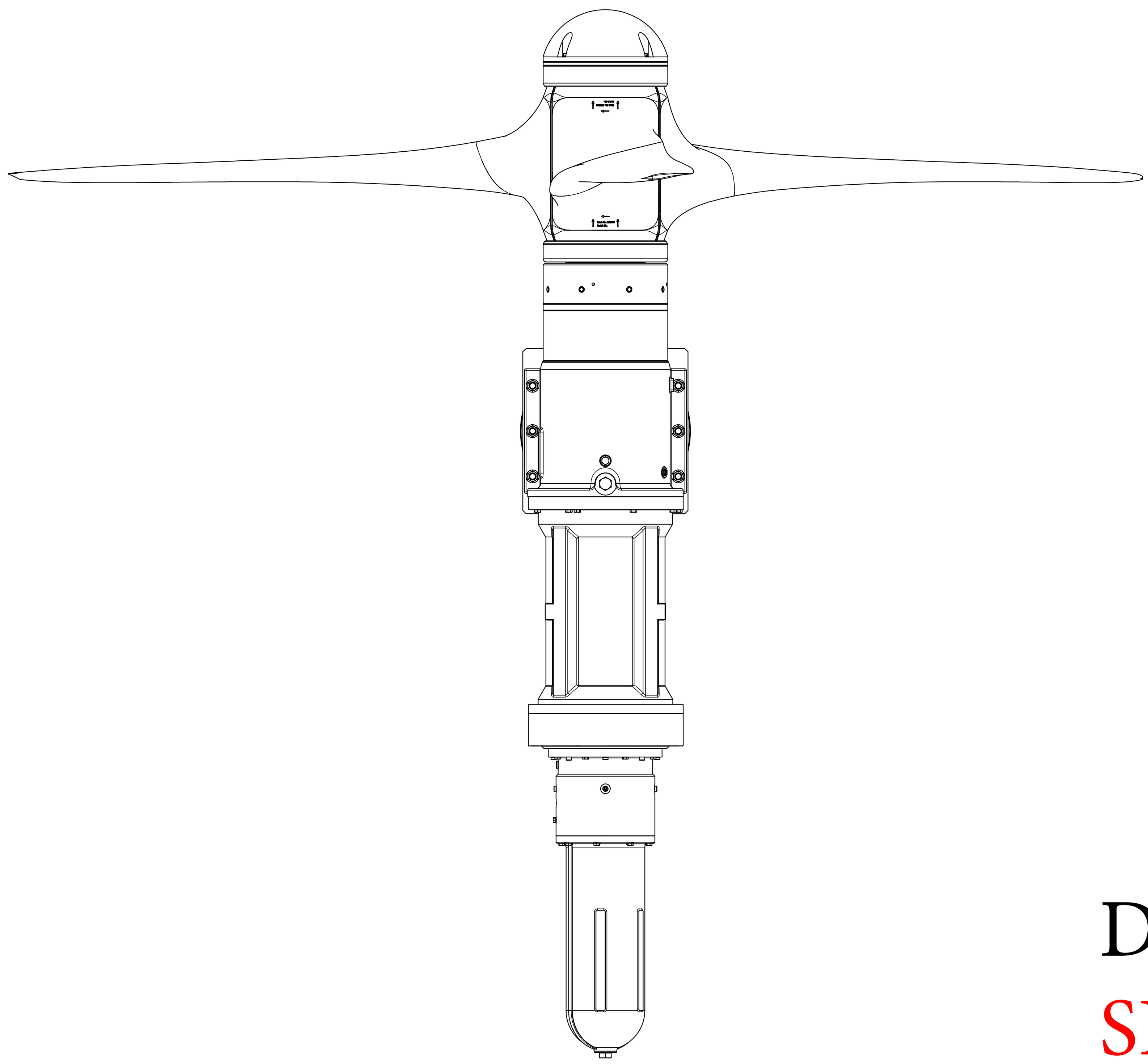

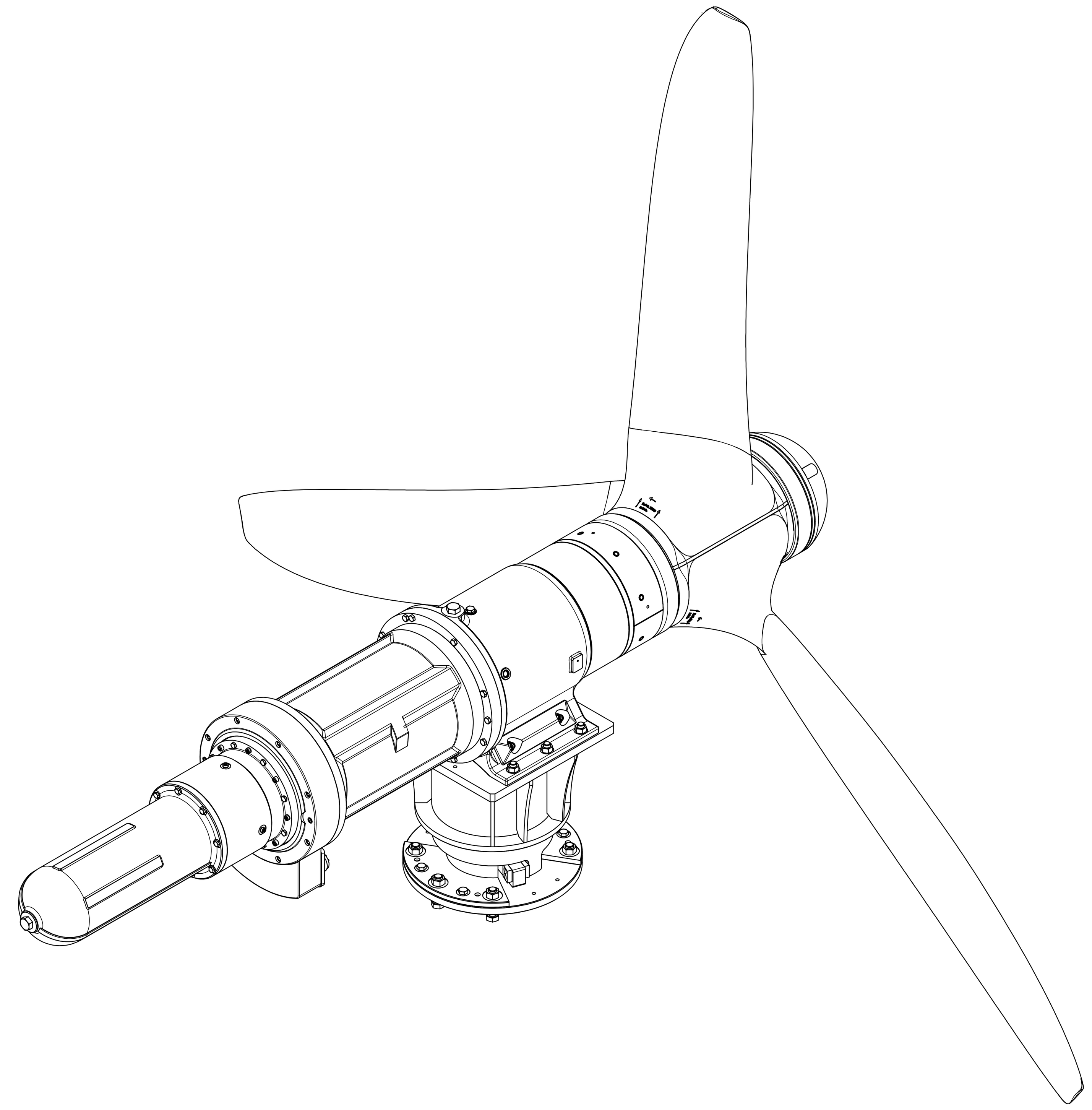

Drawing Number
SH-DSK-0001

ACHTUNG; CAUTION!
Zeichnung ist nicht freigegeben,
keine Gültigkeit für die Produktion!
Preliminary drawing,
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CONFIDENTIAL

Dieser Entwurf ist geistiges Eigentum der SCHOTTEL HYDRO GmbH	Schutzvermerk DIN ISO 16016 beachten	CAD-ZEICHNUNG Manuelle Aenderung verboten !	Typ:
Werkstueckkanten DIN ISO 13715 (-0.3, +0.8) / Projektionsmethode 1 DIN ISO 128-30	Allgemeintoleranz DIN ISO 2768-mK Schweisskonstr. DIN EN ISO 13920-CF Tolerierung DIN EN ISO 8015 Oberflaechenangaben DIN EN ISO 1302	Massstab: 1:10	Gewicht: 1841.68 kg
		Werkstoff:	
		Rohteil-Nr.:	
		Modell-Nr.:	

	Datum	Name
Bearb.		
Gepr.		
AV		
Norm		
Abt.		

Benennung: Tidal Turbine Reef (SIT250)

Zust.	Aenderung	Datum	Name

SCHOTTEL HYDRO GmbH
Mainzer Strasse 99
D-56322 Spay/Rhein
Ein Unternehmen der SCHOTTEL-Gruppe

Zeichnungs-Nr.	Index:		Format
		Bl.Nr.: 1 von 1	0

Urspr.: | Ers. f.: | Ers. d.: