**University of Birmingham**

School of Engineering

# Integrated Design Project 3

## FINAL INTEGRATED TEAM REPORT

**Sustainable Offshore Energy Island**

| | |
|---|---|
| **Team Number** | 3 |

# 1. Team Level Design

## 1.1 Problem/Context

Offshore Wind Turbines (OWTs) and Farms (OWFs) form the most prolific means of energy production in a bid to move away from carbon-positive and non-renewable energy sources, with the UK being the world's largest producer at 13GW, yet still aiming to expand and produce 40GW by 2030 [1], for example. However, a significant issue with OWTs, as with other renewable energy sources, is that the rate of energy production is entirely dependent on weather conditions and hence is incredibly inconsistent in its output.

This means that, in a battle of supply and demand, national infrastructure must resort to other sources of power – often fossil fuels – to compensate when OWTs are not providing sufficient energy production. Therefore, to truly diminish countries' dependency on fossil fuels, a support system is required such that the output from OWFs become much more, if not completely, consistent.

We shall focus on Australia, a country currently suffering from a national energy crisis and is still heavily dependent on fossil fuels; specifically, we shall be focusing on the Star of the South OWF currently in development.

## 1.2 Solution

Our solution is a network of floating platforms to be situated within the OWF, onto which the support system will be placed; the network will be formed of multiple 'clusters' of platforms, where each cluster can contain different systems, depending on their role within the network. Almost all of the clusters will feature power supply units consisting of 3 forms of renewable energy production: solar panels, rotational mass wave energy conversion (WEC), and point absorption WEC; this is to generate the necessary power to supplement the output of the OWF such that it is consistent.

One cluster will be responsible for the operation of the entire network, containing: a control centre, transformer(s), and power storage. Power storage is necessary to retain surplus energy produced when the OWTs are operating sufficiently and to assist in regulating the output to the mainland; the transformer(s) will be used for efficient power transmission to the mainland; and the control centre will monitor the output of the OWF as well as the regional/national power demand, and adjust the supplementary power output accordingly.

The system will be entirely modular, both within and between clusters; the number of power supply units, transformers and power storage units can all be varied, meaning that the system is scalable to any power supplement requirement over time and potentially compatible with any OWF globally.

Each group's contribution to the solution is as follows:

- Civil MEng 3 – Floating platforms and tethering
- EESE BEng 3 – Power Systems and Internet of Things
- Mech BEng 4 – Floating Photovoltaic System
- Mech Meng 3 – Rotational Mass WEC
- MSc 2 – Point Absorption WEC

## 1.3 Location

The team's choice to locate the sustainable offshore energy island in Bass Strait, Australia, was predominantly attributed to the fact it provides the resources for all three technologies to thrive – i.e., wave, wind, and solar. Figure 1 highlights the annual mean wave power density, with the southern region of Australia (where the island will be located) displaying good wave energy potential having ≈ 110 kW/m mean power density. In addition, Australia is a country that experiences high solar irradiance [2] which is directly linked to the yield of a Photovoltaic system. Finally, in 2028, the Australian government is to commission an offshore wind farm, Star of the South, with an energy capacity of 2.2 GW. The windfarm will benefit from support of the wave and solar technologies to help meet its baseline energy output, overcoming intermittency challenges associated with renewable energy production sources.

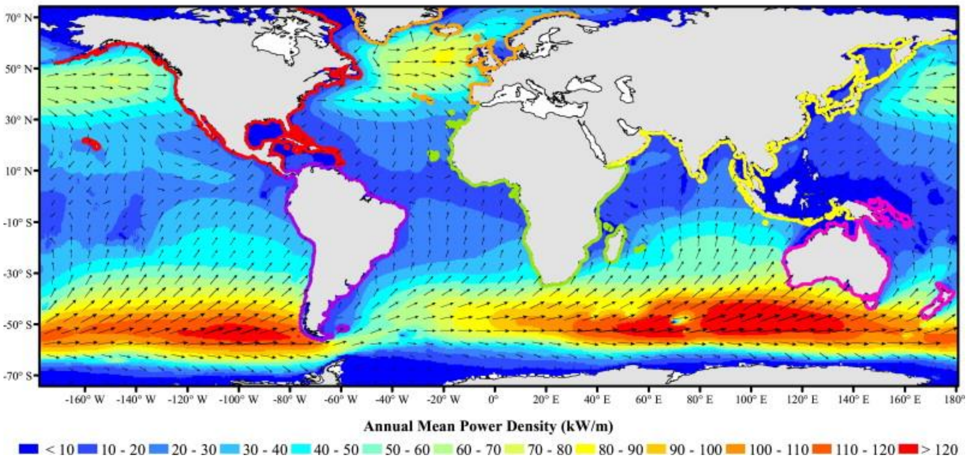



*Figure 1 - World map showing annual mean wave power density [3]*

Australia is a country that is still heavily reliant on fossil fuel for its energy production, with up to 93% of its electricity being generated from burning of coal [2]. The Russia-Ukraine war has further exacerbated the energy crisis, as sanctions have been placed on Russian produced oil and gas [4]. The fallout, is that Australian citizens have experienced surges in energy prices that have climbed up by up to 18 % [4]. However, the government is heavily involved in the transition away from fossil fuel dependency and actively investing in renewable energy sources [5]. The Australian Federal Government body, Clean Energy Finance Corporation have set the goal of net zero emission by 2050 and have so far invested a total of A$ 11.7 billion since 2012 [5]. Our project will help Australia overcome dependency on fossil fuel helping it meet its renewable energy goals and as a result also benefit from funding from the Australian government.

# 2. Wider Engineering Implications

*Table 1 - Wider Engineering Implications based on SDG goals*

| Factor | SDG No. & Definition | Project Relation |
|---|---|---|
| Sustainability | 7 - Affordable clean energy<br>11 - Sustainable cities and communities<br>12- Responsible consumption and production<br>13 – Climate action | The project aims to provide clean renewable energy to the local and regional area surrounding the Bass Strait using a variety of renewable generation methods. The energy will be clean, renewable and consistently provided to the grid allowing cities and communities to reduce their reliance on unconventional energy sources. This lessens the need for traditional energy generation thus reducing greenhouse emissions. |
| Commercial | 7 – Affordable and clean energy<br>8 - Decent work and economic growth<br>9 – industry, innovation and infrastructure<br>17 – partnerships for the goals | The project provides a blueprint for a modular component which can be used worldwide, allowing multi-renewable offshore power farms to be implemented elsewhere. As well as providing employment in construction and management in local areas in the renewable energy field the energy island project encourages further development and innovation of consistent clean energy supply through partnerships with local and regional governments, as well as TNCs. |
| Social | 3 – Good health and wellbeing<br>4 – Quality education<br>8 – Decent work and economic growth<br>10 – reduced inequalities<br>12 – responsible consumption and production | As well as the economic and environmental benefits, socially the energy island provides a global talking point in the innovation of renewables and will encourage education relating to ethical energy consumption. The surrounding areas will further benefit from cleaner air quality as traditional power generation methods are phased out. The new influx of employment opportunities will result in a positive multiplier effect throughout the community. |
| International | 17 – Partnerships for the goals | Once implemented on a larger scale, nations with access to offshore land will become self-dependant and will be able to use clean energy as a form of trade and revenue. |

*Table 2 - Ethical Principles*

| Ethical Principal [6] | Definition [7] | Project Examples |
|---|---|---|
| Honesty & Integrity | "Professional engineers and technicians should adopt the highest standards of professional conduct, openness, fairness and honesty." | All professionals involved will be licensed and qualified accordingly. An extensive health and safety plan including risk assessments will be used and a diverse workforce will be involved. Smaller suppliers will be offered the same opportunities for work, materials and contracting as large TNCs. |
| Respect for Life, Law, & the Public Good | "Professional engineers and technicians should give due weight to all relevant law, facts and published guidance, and the wider public interest." | All construction and design work will be in accordance to local and regional building codes. A survey will be taken prior to development where areas of concern from the public will be identified such as loud noise and closure of land. |
| Accuracy & Rigor | "Professional engineers and technicians have a duty to ensure that they acquire and use wisely and faithfully the knowledge that is relevant to the engineering skills needed in their work in the service of others." | Efficient working practices will be implanted with regular inspections and quality control measures. All engineers will be appropriately qualified in each respective field. |
| Leadership and Communication | "Professional engineers and technicians should aspire to high standards of leadership in the exploitation and management of technology. They hold a privileged and trusted position in society and are expected to demonstrate that they are seeking to serve wider society and to be sensitive to public concerns." | Many simulations and tests will be carried out before funding is acquired to ensure the feasibility of the energy island from an environmental and economic perspective. This ensures that there is. A justification for large amounts of greenhouse gases and the carbon footprint associated with constructing and assembling the island. Professionals and bodies from around the world will be used in research and development of the project. |

# 3. Risk Management

*Table 3 - Risk Assessments*

| Type of Risk | Risk | Effect(s) | Severity (1-10) | Reason | Occurrence (1-10) | Control(s) |
|---|---|---|---|---|---|---|
| Design | Design Oversight/ Underperformance after Validation | - Significant retrospective amendments<br>- Underperformance<br>- Specification not met<br>- Issues/Delays in manufacturing<br>- Subsequent costs<br>- Significant delays | 7 | - Inexperienced or underqualified staff<br>- Poor Requirements/ Specification<br>- Rushed/ Underfunded Project | 3 | - Thorough staff recruitment<br>- Sufficient time, funding, facilities and resources are provided<br>- Frequent review or evaluation of requirements and design |
| | Incorrect Tolerance/ Material Selection | - Underperformance<br>- Unsafe or unreliable product after commission<br>- Manufacturing / Assembly issues | 7 | - Design Oversight<br>- Poor Requirements/ Specification<br>- Contractor Miscommunication<br>- Imperial-Metric Conversions | 2 | - Correct standards will be followed/ adhered to<br>- Review of standards and materials |
| Planning | Poor Requirements/ Specification | - Underperformance<br>- Incorrect Tolerances<br>- Poor Material Selection<br>- Design Oversight | 7 | - Inexperienced or underqualified staff<br>- Insufficient Research<br>- Project expectations | 2 | - Thorough staff recruitment<br>- Review with stakeholders, consultants and contractors |
| | Specification Creep | - Eventual underperformance<br>- Project Delays<br>- Outdated designs<br>- Increased cost | 6 | - Contractor/ Stakeholder interference | 2 | - Sole responsibility of specifications lie with the designer<br>- Standards of planning and work also apply to contractors |
| | Environmental Impact Assessment | - Potential re-specification or re-design<br>- Project Delays | 5 | - Authority interference<br>- Subjective application of policy | 1 | - Environmental considerations were integral part of design process<br>- Frequent reviews throughout design process |
| | Progressive delays/Project Stagnation | - Missed deadlines<br>- Increased/Induced Costs<br>- Material/Supply Rescheduling | 4 | - Issues with payments or funding<br>- Re-designs or re-specification<br>- Lack of organisation | 3 | - Many causes for delay are external, but must still be accounted for |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | - Impact on logistical and operational efficiency | | | | - Project GANTT chart with critical path analysis<br>- Parallel tasks to prevent delay, or stagnation |
| Political/ Financial | Loss/Lack of Funding | - Halt of project<br>- Cancellation of project<br>- Significant increase in costs<br>- Lack of facilities or resources<br>- Reduced project quality | 9 | - Governmental change<br>- Lack of budget<br>- Lack of qualification due to underperformance | 2 | - Frequent performance reviews/ comparison to specification |
| | Quote-Cost Discrepancy | - Increased costs<br>- Delay in payment | 3 | - External Factors | 6 | - Most factors are external and so not the fault of the contractor or management, but a contingency must always be accounted for<br>- Contractual agreement of costs before work begins |
| | Loss/Lack of Cost Recovery | - Unable to pay off loans<br>- Product must run for longer than initially planned<br>- Subsequent reliability and maintainability costs/issues | 5 | - Governmental change<br>- Lack of budget<br>- Lack of qualification due to underperformance<br>- Initiatives cease | 3 | - In-service review of product and project to assess required service life duration; followed by subsequent overhaul, update, or obsolescence review, to extend service life, if necessary. |
| Manufacturing | Material Delay | - Overall project delay<br>- Logistical strain<br>- Possible reschedule | 3 | - Delay in payment<br>- Fault of contractor<br>- External Factors | 5 | - All contracts and payments are prepared well in advance of deadlines<br>- Regular progress checks with contractor |
| | Supply Delay | - Overall project delay<br>- Logistical strain<br>- Lack of resources; halted work<br>- Possible reschedule | 3 | - Delay in payment<br>- Fault of contractor<br>- External Factors<br>- Supply chain disorganisation | 5 | - All contracts and payments/cash-flow established in advance of implementation |
| | Substandard Material/Supply | - Reduced project quality | 8 | - Fault of contractor | 2 | - Only reputable contractors will |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | - Underperformance<br>- Work to be re-done<br>- Significant delay and subsequent costs<br>- Termination of contract; subsequent legal actions | | | | be considered, no cutting corners/costs<br>- Regular contact/progress checks with contractor; additional inspections if required |
| Operation | Worker Injury | - Legal action<br>- Project delay<br>- Damage to image/reputation<br>- Possible resignations | 6 | - Lack of health and safety rigour<br>- Worker malpractices | 3 | - Adequate health and safety rigour is enforced, as a minimum<br>- Necessary insurances are in place |
| | Worker Pay Dispute | - Halted project<br>- Possible protests; damage to image and reputation<br>- Legal action<br>- Increased costs | 4 | - Union action<br>- Inflation/national pay changes | 2 | - Contracts of employment are comprehensive, yet considerate of the worker<br>- Competitive pay, and subsequent pay rises/bonuses |
| | Missed Deadlines | - Project delay<br>- Logistical strain<br>- Subsequent costs | 3 | - Substandard work Disorganisation<br>- Delays | 4 | - Proficient and proactive planning and organisation<br>- Regular meetings, progress reviews, evaluations, etc. |
| | Change in Contractor | - Significant delays<br>- Significant costs<br>- Wasted resources<br>- Legal action | 8 | - Substandard contractor delivery<br>- Frequent contractor delays and issues<br>- Termination by mutual consent<br>- External factors | 2 | - Only reputable contractors will be considered<br>- Regular contact/progress checks with contractor; additional inspections if required<br>- Comprehensive contracts with necessary legal cover |

# 4. Team Management

As with any large team, particularly one of 33 people, communication can be complicated yet particularly important; therefore the designation of groups and group leaders (breakdown can be seen in Figure 2) acted as an integral means of streamlining organisation. Group leaders held weekly meetings to discuss the general progress of the project, actions from/for group meetings, queries from group level, and the integration between teams, as well as more general matters that may have arisen week-to-week. Initially, these meetings were also the primary opportunity for liaising between groups, before it was necessary to open communications between groups to allow for more targeted and immediate discussions to take place with regard to integration of designs, exchange of information and other areas. Progress tracking, continuity and evaluation was assisted through the use of a GANTT chart for each group, accessible to every group leader.

| Mech MEng 3 | Mech BEng 4 | MSc 2 | EESE BEng 3 | Civil MEng 3 |
|---|---|---|---|---|
| Team Leader: Adam Cheshire | Group Leader: Nathan Kairu | Group Leader: Benjamin Richards | Group Leader: Karun Dhindsa | Group Leader: Harry Sophocleous |
| Ewan Dunnett | Odysseus Bouziotis | Yicheng Chen | Michael Abram | Samuel Broadbent |
| Charles King | Afshin Kouhyar | Ryan Ennis | Mohammed Ali | Emma Buckingham |
| Adam Lokkerbol | Cameron Nagar | Jiyao He | Ahmed Al-Massry | Benjamin McIntyre |
| Joseph Roberts-Nuttall | Ching Ng | Didin Issac | Mate Lorincz | Benjamin Oubridge |
| David Shepherd | Alex Rankin-Landry | Gurparas Singh | Alexandru Spinu | Matthew Wilkinson |
| James Smith | Lois Stevenson | Zeyu Sun | | |

*Figure 2 2 - Team-Level Breakdown*

MS Teams became the foundation of the team's communications and organisation, allowing groups to stay connected but also demonstrate their own autonomy, as different disciplines and project areas result in different approaches, meaning that a strict, universal format for organisation across all groups would have been highly inefficient. Each group had a private channel to make best use of shared storage and live-access documents, ensuring that all group members are kept up to date on the latest versions of documents and files, such that accessibility and efficiency of workflow can be optimised. The group leaders also had a private channel intended for team-level co-ordination and workflow. Two open/team-wide channels were also made to encourage collaboration between groups and for publishing team-wide notifications. WhatsApp chats also ran parallel to each MS Teams channel, intended for less task-based, more immediate and informal communication; it also provided two separate means of contact for every team member, meaning that everyone could be present and involved, even if not in-person.

# 5. Integration

Figure 3 3 represents the flow of information between groups within the team. The diagram showed how each groups design had integrated with each other to ensure that consistency was kept throughout the project.  The information was requested during meetings and the communication channels that was set up to easily share information.

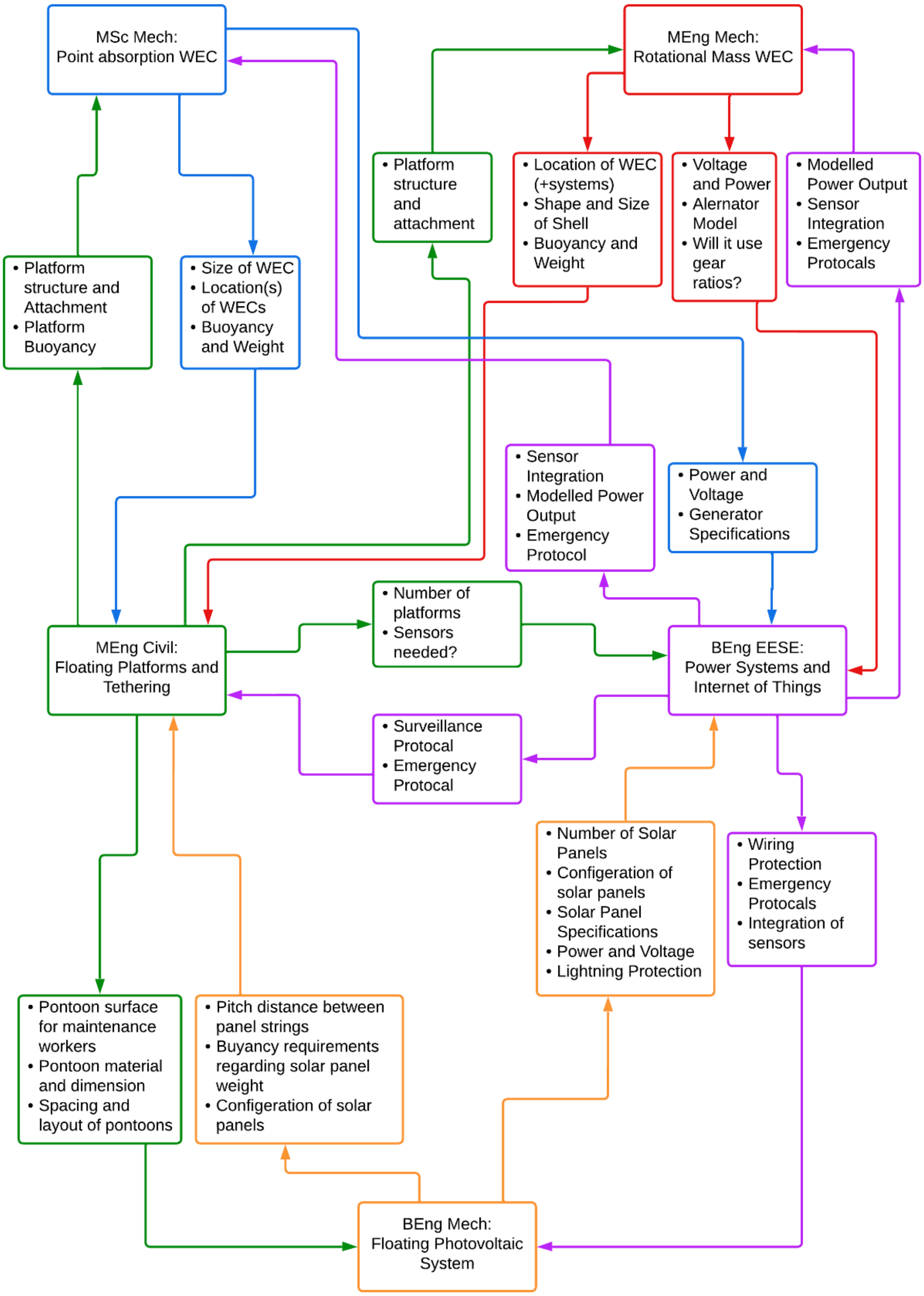



*Figure 3 3 - Information flow diagram between the different groups at a team level*

# References


[1] Department for Business, Energy and Industrial Stategy, “New plans to make UK world leader in green energy,” Department for Business, Energy and Industrial Stategy, 6 October 2020. [Online]. Available: https://www.gov.uk/government/news/new-plans-to-make-uk-world-leader-in-green-energy. [Accessed 3 May 2023].

[2] Department of Industry, Science, Energy and Resources, “Australian Energy Update 2021,” Department of Industry, Science, Energy and Resources, Canberra, 2021.

[3] K. Gunn and C. Stock-Williams, “Quantifying the Global Wave Power Resource,” *Renewable Energy,* vol. 44, pp. 296-304, 2012.

[4] P. Hannam, “Australia’s energy crisis explained: from price caps to the suspension of electricity trading,” The Guardian, 15 June 2022. [Online]. Available: https://www.theguardian.com/australia-news/2022/jun/15/australias-energy-crisis-explained-from-price-caps-to-the-suspension-of-electricity-trading. [Accessed 7 May 2023].

[5] CEIC Data, “Australia Electricity Prices,” CEIC Data, 7 May 2023. [Online]. Available: https://www.ceicdata.com/en/australia/electricity-prices. [Accessed 7 May 2023].

[6] Engineering Council, “Statement of Ethical Principles,” 2017. [Online]. Available: https://www.engc.org.uk/professional-ethics. [Accessed May 2023].

[7] R. Lawlor, “Statement of Ethical Principles,” *Engineering in Society,* no. 2, pp. 22-23, 2016.

**University of Birmingham**

School of Engineering

# Integrated Design Project 3

## FINAL GROUP REPORT

## Civil Engineering

## MEng

| | |
|---|---|
| **Team Number** | 3 |
| **Group Number** | 3 |

| Student Names | ID Numbers |
|---|---|
| Harry Sophocleous | 2170831 |
| Ben McIntyre | 2161955 |
| Matthew Wilkinson | 2196365 |
| Benjamin Oubridge | 2165531 |
| Emma Buckingham | 2183291 |
| Samuel Broadbent | 2170940 |

| Feedback (Compulsory Section) | | |
|---|---|---|
| Reflecting on the feedback that we have received on previous assessments, the following issues/topics have been identified as areas for improvement: | 1 | Communication and planning as a group through all stages of the project |
| | 2 | References and labels should be explicitly cited |
| | 3 | Equal delegation of teamwork |
| In this assignment, we have attempted to act on previous feedback in the following ways: | 1 | Using weekly meetings and cloud share software to share ideas and files |
| | 2 | Learnt as a group to use word reference manager to cite and label work |
| | 3 | Gantt chart and task split was discussed as a group |
| Feedback on the following aspects of this assignment (i.e. content/style/approach) would be particularly helpful to us: | 1 | |
| | 2 | |
| | 3 | |

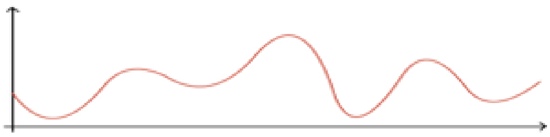
# Table of Contents

# Introduction to the Project

## Problem

Despite the many benefits of conventional sustainable energy infrastructure, a challenge which often limits the utilization of renewable energy is the inconsistency of power supply and the dependency on natural conditions such as sunlight, heat, marine currents, and wind.
As wind, water currents and sunlight vary in duration and intensity day-to-day and hour-to-hour, there is no way to ensure consistent and reliable power to the grid. This is an issue due to the current design of electrical grids. Most power grids were designed around the concept of large controllable energy generators and use a three-phase process to ensure power plants are optimised to produce the correct amount of electricity at precise times as to not overpower the grid and meet electric demand [1]. This is predominantly because power grids have extremely low storage capacity meaning a balance is always maintained to ensure problems do not arise.

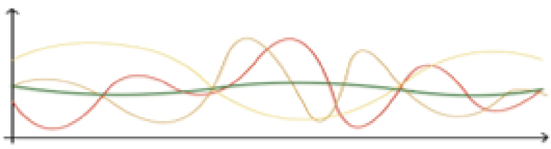
Currently, we cannot utilise energy efficiently from methods such as tidal, wind and solar power because energy storage technology has not been optimised to handle and store excess power in an efficient way. As the fluctuating power from these methods enters the grid, the operator is forced to adjust operating procedures at all times. For example, solar panels mean a grid operator is needed to adjust the day-ahead plan to accommodate the power influx which will not exist at night. Variability due to clouds also makes it extremely difficult to adjust the grid in accordance with fluctuations. Similar issues can be identified with other renewables such as wind, wave, tidal and thermal energy.



## Solution

The concept behind the project is integrating four sustainable offshore energy generation methods to create a renewable energy island which has a constant energy output. The infrastructure will be built within a wind farm and will consist of modular floating islands which encompass solar panels, rotating-mass wave generators, and floating wave generators. It has been theorised that having these various methods of renewable energy all working simultaneously in the same location will provide a consistent energy output with scaling and data control.

As the project is focused around a pre-existing or planned offshore wind farm, the space is readily available and the framework for transporting energy back to the mainland can be shared between all renewables. Furthermore, the 'islands' will be modular, meaning the quantity can be scaled up or down to ensure a perfect balance between all energy methods. The final goal is to have at least one of the energy generation methods working at all times, regardless of the climate, time of day, or other conditions.



## Project Objectives

The Civil Engineering group's objective is to design the infrastructure which will effectively and reliably support the renewable energy equipment. This includes the physical island itself and the mounting system(s). The list of design requirements is shown below:

*Table 1 : Requirements table*

| | Requirements |
|---|---|
| 'Must' requirements are those which will govern the design.<br>There must not be any compromises on these no matter what the cost. | Must be able to support all loads necessary |
| | Must be the correct shape, size, and material to produce enough buoyancy force to stay afloat |
| | Must be water resistant and salt water resistant |
| | Must be able to float for long periods of time (>100 years) |
| | Must be able to withstand wind and wave forces without sustaining damage |
| | Must be able to be easily and quickly constructed |
| | Must be constructed with readily available materials |
| | Must be produced using local or sustainable materials |
| | Must choose sustainable and environmentally friendly materials for the construction and design |
| | Must be designed for easy maintenance and servicing |
| | Parts must be easily replaceable if damaged |
| | Must be able to be maintained easily |
| | Must have a design life of >100 years |
| | Must directly be able to show how the project is suitable and effective at reducing greenhouse gas emissions |
| | Must consider the rights of all workers and involved personnel at each stage of the project |
| | Must avoid affecting marine life excessively |
| | Must not interfere with existing infrastructure (I.e., wind turbines) |
| | Must not affect the livelihood of workers with existing jobs in the prospective area |
| | Must not require excessive transportation due to carbon footprint |
| 'Should' requirements are extremely important design considerations in the project.<br>Where possible, all should be met, however, some may be overlooked if a better alternative is found or a good reason is identified. | Should be modular to improve fixability and constructability |
| | Should be accessible for workers |
| | Should have a back-up in the event of a failure of the modules |
| | Should make accessing affordable, clean energy easy for the respective country |
| | Should help to reduce emissions and improve air quality |
| | Should provide short-term jobs via construction |
| | Should provide direct, ongoing jobs via maintenance |
| | Should be innovative and prompt more forward-thinking designs |
| | Should help to reduce inequality in society by reducing energy costs so it is affordable for all |
| | Should make cities safer and more sustainable by reducing the amount of fossil fuels or nuclear reactors required in a community |
| | Should promote more responsible energy production and consumption |
| | Should help countries to reduce carbon emissions by providing an example to follow |
| | Should help to improve life on land by reducing land used for mining or power generation |
| | Should promote collaboration with other countries on innovation |
| | Should help to educate workers on sustainable building practises |
| | Should draw public awareness to the issue of climate change and ways in which it is being directly dealt with in this project |

## Teams and Integration

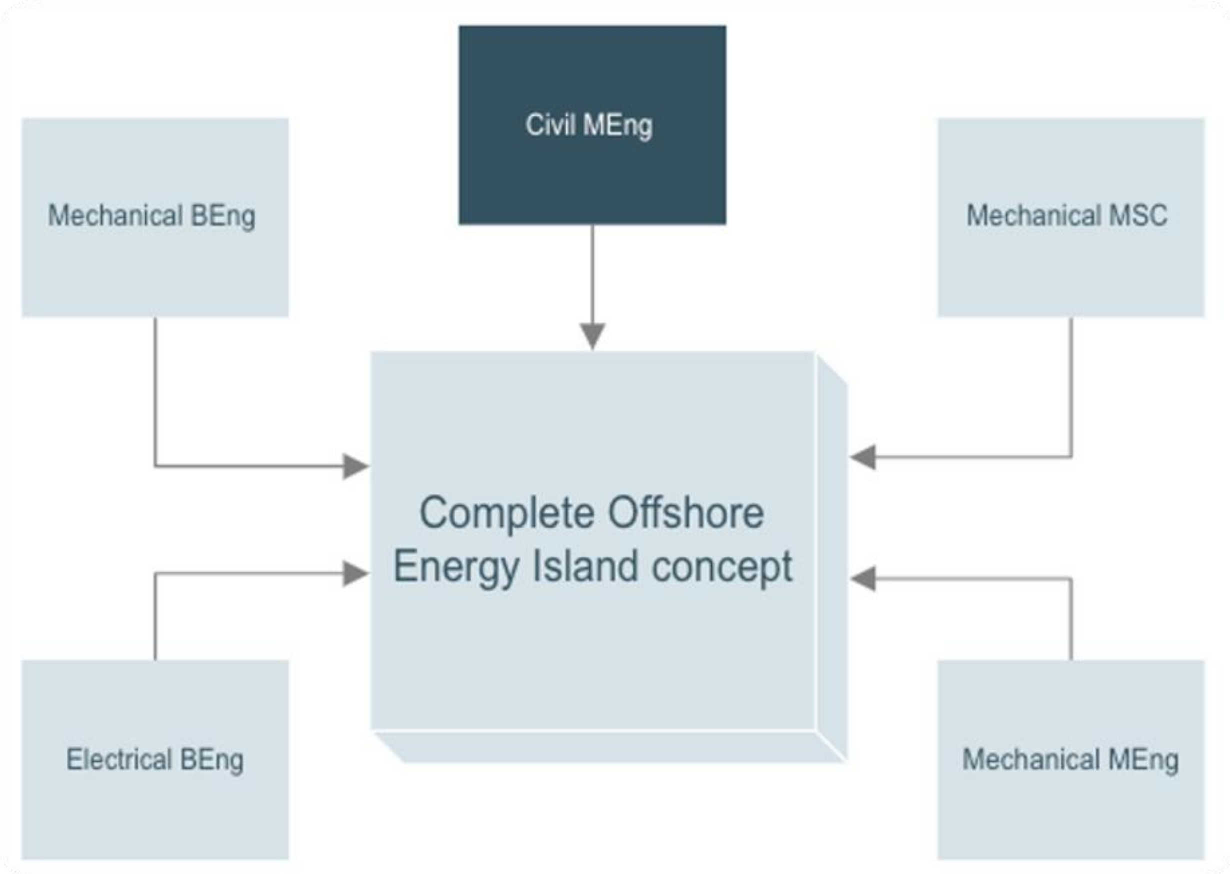



*Figure 1 – Team integration design*

To produce a design, such as Figure 1, which would function effectively and minimise obstacles throughout the planning and design stage, group integration was extremely important factor to get right. In the case of the offshore energy island, all groups have an equally important role to play. The mechanical groups focus on renewable energy methods, the electrical group on power delivery and control, and the civil group on infrastructure and the design of the 'island' itself. Naturally, there are many areas of interface between all of the groups. In particular, the civil group has several areas of concern including the loads from the other groups designs acting on the floating structure and general integration of all the different parts. Compromises must be made throughout the project by all groups to allow for the fairest way to meet each groups design requirements.

# Background Research and Literature Review

## Tethering Systems

There are 3 main types of floating platform requiring some form of tethering: tension leg platforms (TLPs), semi-submersibles and single point anchor reservoirs (SPARs). Many of these structures are designed and built with oil rigs in mind. However, this technology can be repurposed to be manufactured and redistributed for clean energy.

The main purpose of the tethering system is to allow a structure to float whilst also being suitably restrained against movement. While a fixed platform could work, its lack of adaptability to varying sea levels makes it an obsolete choice due to global warming and sea levels rising. However, if we were to repurpose an old oil rig, it could make environmental sense due to not needing to produce an entirely new structure.

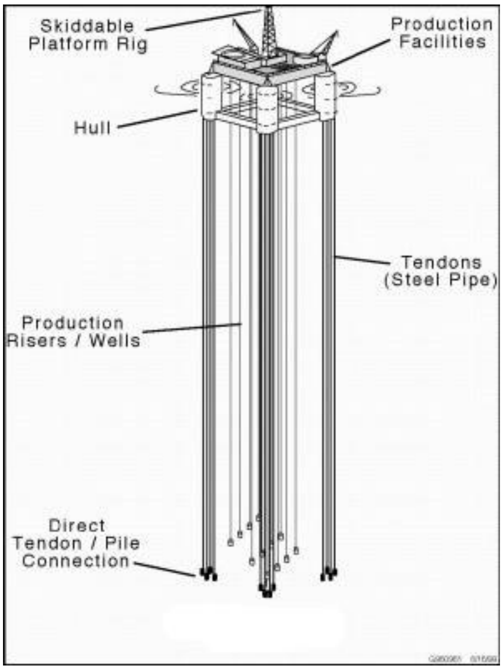



*Figure 2: Tension leg platform (Security n.d.)*

## Tension Leg Platforms (TLPs)

Designed for structures typically at depths of over 500 m to sea level [2]. TLPs have a very similar principle to boats in that a heavy anchor is dropped to the seabed. The platform is semi-submersible and relies on always maintaining positive tension in the cable by adjusting the buoyancy of the platform. As a result, this method of construction leads to almost negligible vertical sea response and very little rotational response.

Another version of this is the extended tension leg platform (ETLP), which works in the same way but with a greater depth, as the standard version is typically sensitive to increasing water depth. The tendons are connected beneath the vertical elements and in parallel to fixed pile foundations. They are also pre-tensioned to restrain the motions caused by tidal and wind forces. To be able to withstand such high forces for an extended period, a durable material such as high-strength steel is typically used. To ensure the materials maintain a suitable level of safety and reliability, they are routinely maintained and inspected to avoid catastrophic failure.

While the tethers appear to perform well under normal loading conditions, under extreme environmental conditions the reliability of the tethers may be significantly impacted. This could be because of extreme weather events such as a hurricane or tsunami [3]

## Catenary Mooring System

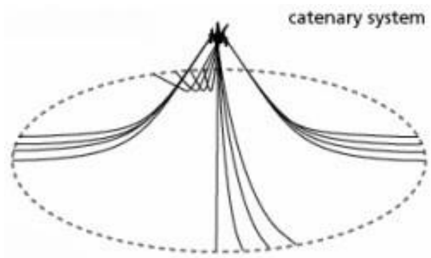



*Figure 3: Catenary Mooring system (Moorings n.d,)*

For shallower waters, this system is mostly used. The system looks like a free hanging line, which works to provide vertical stability by using the self-weight of the cable and provides horizontal stability thanks to the design of the line being horizontal at the seabed. The curve of this free hanging line helps to reduce the total forces acting on the foundations in the seabed and the floating structure. This works by allowing the slack from the cables, due to the cables being much longer than the depth of water, to absorb some of the energy caused by forces acting on the structure such as wind or wave energy [4]. To provide this vertical stability, the chains or wires are manufactured with a very high mass per meter, which also leads to higher costs due to the amount of material used.

The design of the mooring system works well to dissipate energy. However, it allows for greater displacements, making it unsuitable for the design of this offshore energy island due to the spatial restraint of being placed between wind turbines.

## Taut Leg Mooring System

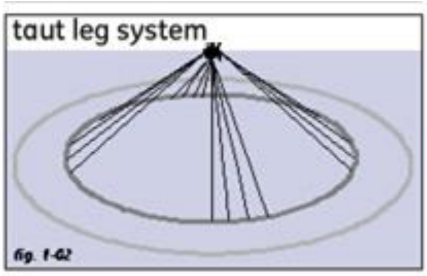



*Figure 4: Taut leg mooring system (Jermon, 2014)*

In a taut leg mooring system, instead of the cables hanging freely in the water, they are pre-tensioned. As a result, the cables are placed at an angle to the seabed, typically around 30 to 40 degrees. This leads to a difference in the way that the foundations work because in this design, the foundations must be able to withstand both horizontal and vertical loads. It also changes the mode by which the mooring system provides stability, as in this case it is the elasticity of the cable which provides the reactions to maintain the safety of the structure. [5]

A proposed improvement on the traditional steel cable involves the use of a polyester rope [6]. This design works in essentially the same way but with an improvement in the choice of material, which could lead to improvements over the historically used design such as reduced line length and improved performance at platforms with a higher load. The polyester material has a much lower modulus in comparison to the typical steel cables used, making it able to stretch further and withstand larger loads.

## Semi-Submersible


*Figure 5: semi-submersible platform (Modec, N. d)*

A platform typically consists of vertical columns risen above the water, connected to large volume pontoons to provide buoyancy. They perform poorly in terms of motion due to the large volume of the pontoons. Also, they do not perform well in environments which may experience extreme weather events such as hurricanes and typhoons. They are often moored using groups of mooring lines below the vertical columns. These lines are made up of 3 sections: the ground chain, polyester rope, and fairlead chain [7].

## Single Point Anchor Reservoir (SPAR)

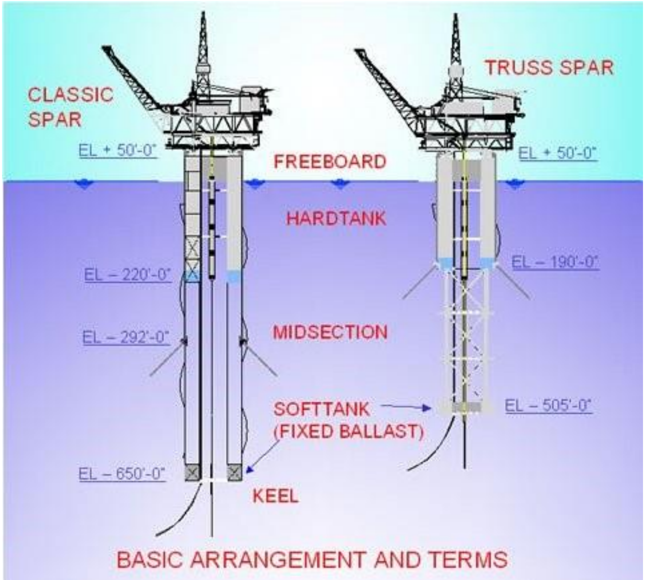



*Figure 6: Spar platform (security n.d)*

This type of platform is made from a large diameter buoyant vertical cylinder. Typically, this platform type is best suited to significantly deep waters in which it is perfectly adaptable and performs favourably against motion. This is similarly tethered to the semi-submersible, using 9 mooring lines composed of the same 3 sections. The mooring lines are divided into groups and placed equidistant from one another [7].

## Sea Level Rises

At present, it appears that not many offshore structures consider the issue of sea levels rising, this is mostly due to the design life consideration in comparison to predicted time scale of sea levels rising. For this offshore energy island, this issue could be considered via the introduction of length varying tethers, or the use of tethers connected to some form of vertically free, dampened column.

## Connections of Modular Offshore Structures and Bodies

The idea of multiple platforms operating as a single unit coupled with the unpredictable nature of open seas presents the problem of uncontrolled and erratic movement of the platforms individually and holistically. There are few examples of such offshore structures, however a similar problem is faced by large boats docking in stormy conditions so this is where the research will be initiated.

## Docking Boats in Rough Weather

The advice of BoatUS Hurricane Catastrophe Team (CAT) professionals is to always haul your boat assure in the event of a pending storm/hurricane. For some this isn't an option and securing the boat in the water must be done properly to ensure the boat and the dock aren't damaged by the mass movement of water. A storm surge of 10 feet or more is common in a hurricane or storm [8].

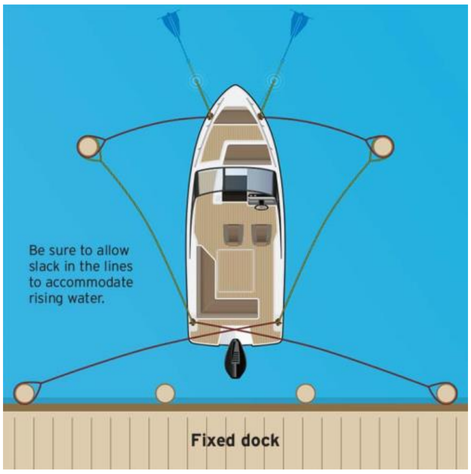



*Figure 7: Boat (US magazine)*

Figure 7 [8] shows that the bow (the strongest part of the boat) is orientated towards the storm. The boat is anchored in the direction of the bow away from the dock. The boat is then also secured to objects called pilings, two on the dock and two in the water.

Lines are used to secure the boat to these pilings, the size of line ranges from ½-inch to 1-inch depending on the size of the boat. A 60 ft boat (recommended to use a 1-inch line) can weigh 53,000 lbs [9] which is roughly 24 tons. It is recommended to loop the eye of the line around the piling and secure the loose end to the boat for adjustments and fastening [8].

[10] There are multiple types of rope used in boat docking, notably polyester, nylon and polypropylene. Nylon rope is commonly used as it has a relatively high degree of elasticity and shock absorption. However, they weaken when they are wet so they would need to be replaced if they are in contact with water too frequently. Polypropene rope floats, so is often used for safety lines and is only used on smaller boats. Polyester is the most used as it is the cheapest, has great strength as well as abrasion, and good UV resistance. It is also easy to splice. Splicing rope is the process of untangling strands and intertwining them into a new formation to create a joint in the rope. This is how the eyes of lines are created in polyester rope.

The strength of the rope is determined by the number of strands, usually either 3 or 8, and then by the diameter of the rope. [11] As shown in figure 2 the recommended 1-inch rope has a safe load of 7.34kN after a factor of safety of 12 has been applied. To convert a safe load to a safe mass the weight should be divided by the gravitational constant (g = 9.81).

| Rope Diameter | | Minimum Breaking Strength | | Safe Load (Safety Factor 12) | | Weight | |
|---|---|---|---|---|---|---|---|
| *(in)* | *(mm)* | *($lb_f$)* | *(kN)* | *($lb_f$)* | *(kN)* | *($lb_m$/ft)* | *(kg/m)* |
| 3/16 | 5 | 765 | 3.40 | 63.8 | 0.284 | 0.011 | 0.016 |
| 1/4 | 6 | 1315 | 5.85 | 110 | 0.487 | 0.020 | 0.029 |
| 5/16 | 8 | 2050 | 9.1 | 171 | 0.760 | 0.031 | 0.045 |
| 3/8 | 10 | 2900 | 12.9 | 242 | 1.07 | 0.044 | 0.065 |
| 7/16 | 11 | 3915 | 17.4 | 326 | 1.45 | 0.059 | 0.088 |
| 1/2 | 12 | 5085 | 22.6 | 424 | 1.88 | 0.077 | 0.115 |
| 9/16 | 14 | 6435 | 28.6 | 536 | 2.39 | 0.098 | 0.146 |
| 5/8 | 16 | 7825 | 34.8 | 652 | 2.90 | 0.120 | 0.179 |
| 3/4 | 18 | 11200 | 49.8 | 933 | 4.15 | 0.172 | 0.256 |
| 7/8 | 22 | 15225 | 67.7 | 1270 | 5.65 | 0.234 | 0.348 |
| 1 | 24 | 19775 | 88.0 | 1650 | 7.34 | 0.304 | 0.452 |
| 1 1/16 | 26 | 22225 | 99 | 1850 | 8.23 | 0.342 | 0.509 |
| 1 1/8 | 28 | 24800 | 110 | 2070 | 9.21 | 0.385 | 0.573 |
| 1 1/4 | 30 | 29800 | 133 | 2480 | 11.0 | 0.465 | 0.692 |
| 1 3/8 | 32 | 32500 | 145 | 2710 | 12.1 | 0.465 | 0.759 |
| 1 1/2 | 36 | 42200 | 188 | 3520 | 15.7 | 0.51 | 0.997 |
| 1 5/8 | 40 | 49250 | 219 | 4100 | 18.2 | 0.67 | 1.16 |
| 1 3/4 | 44 | 57000 | 254 | 4750 | 21.1 | 0.78 | 1.35 |
| 2 | 48 | 72000 | 320 | 6000 | 26.7 | 0.91 | 1.74 |

*Figure 8: (engineeringtoolbox.com)*

[12] These lines work in tandem with the fenders to ensure no damage comes to the boat or dock itself. Fenders are an essential accessory to a boat for if any sudden/unexpected movement occurs due to wind or tides, the boat won't end up crashing into the dock/jetty/pile but instead the fender will absorb the shock and the boat will 'bounce' off. There are important factors to consider when using fenders on a boat like the placement of the fenders around the boat as well as the number of fenders used. The most important thing to consider is the size of the fender used. Fenders can be used on the side of the boat/vessel or can be used on the dock, but it depends on the type of fenders being used.

[13] The first and most common is a cell fender (figure 9) which is normally cylindrical and hollow in the middle with a flat pad at the end. They are very effective at absorbing the force of moving boats from many directions. Similar to cell fenders, cone fenders have an almost identical shape except a narrower end pointing away from the dock. This allows them to absorb greater impact angles and helps them last longer than cell fenders.

*Figure 9: Cell fender (China rubber fender suppier, Pilotfits)*

[13] Pneumatic fenders look like rounded cylindrical fenders with a net of tires, attached with chains, wrapped around the main body of the fender. These are usually hung off the end of the edge of the dock with chain or rope, so they float semi-freely. This is useful in changing tides as their positions remain relative to the water level.

*Figure 10: Pneumatic Fenders (PALFINGER MARINE)*

[13] Pile fenders are made from plastic lumber rather than rubber. Plastic lumber is essentially 'synthetic wood' made from plastic and is highly durable and long lasting. It is completely waterproof as well as frost and rot proof making it a great alternative to rubber. [13] The use of plastic lumber means that the pile fenders can take a range of any shapes and sizes because of how they can be manufactured like wood. They are usually attached to docks or piles around docks and are often reinforced with fiberglass. They can protect the docks from impact just as well as rubber variants. They are unaffected by temperature, chemicals and decay so are perfect for marine applications.

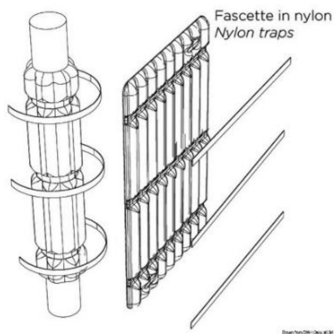



*Figure 11: Marina and pile fender 800mm (yachtshop.eu)*

## Material Analysis for Construction of the Island

There are 3 main structural components of the pontoon design, the framework, making up the structure of the pontoon, the sheet material used to provide the outer surface of the 'hull' section of the pontoon and the hull deck material. The following properties have been deemed to be critically important when selecting appropriate materials for both the framework and the pontoon's hull:

- Corrosion resistance (in sea water)
- Weight
- Strength
- Environmental impact

*Table 2: Material choice table*

| Material | Corrosion resistance | Density | Strength | Environmental impact |
|---|---|---|---|---|
| Steel | Susceptible to pitting corrosion when exposed to chlorides found in seawater. Effects may be lessened if chlorination alloys are present, e.g. Chromium, molybolenum, nitrogen. [14] | 7800 kg/m$^3$ [15] | Strength of structural steel is typically between 235-355Mpa | (For stainless steel) Global warming potential (GWP): 6.8 kg ($CO_2$) per kg (Steel) Solid waste Burden (SWB) 6.4 kg per kg (Steel) [16] |
| Aluminum | Susceptible to pitting attack, with increasing severity as water temperatures increase. AA1100 alloy provides good corrosion resistance, with a corrosion rate of 2mm per year after 49 days of immersion (at 23$^o$C) [17] | 2710 kg/m$^3$ [18] | The strength of aluminum is typically in the range of 86-170 MPa [19] | Global warming potential (GWP): 22.4 kg ($CO_2$) per kg (Aluminum) Solid waste Burden (SWB) 4.5 kg per kg (Aluminum) [16] |
| Wood (Tropical Hardwoods) | Wood is susceptible to both mechanical and biological weathering when applied in marine environments, for example living organisms may attack the wood if it is not properly sealed. [20] | 500-800 kg/m$^3$ [21] | Shear strength of 6-17 MPa and compressive strength of 3-16 MPa [22] | 1.2 kg ($CO_2$) per kg (wood), this value may be as low as -2.3 kg ($CO_2$) per kg (wood) if sustainable practices are enforced [23] |

| | | | | |
|---|---|---|---|---|
| Fiberglass | Glass fibers are damaged by sustained exposure to water, therefore if the resin fails, exposing the glass fibers, the structure may fail. Epoxy resin is a good candidate for marine fiberglass as, although the strength of the structure will degrade, it stabilizes after roughly 90 days and no further strength degradation as a result of saltwater exposure occurs. [24] | 2000 kg/m$^3$ [25] | Tensile strength of fiberglass typically ranged from 250-320 MPa when tested using low velocity testing [25] | Epoxy resins are generally considered to be environmentally safe as the raw materials used to produce it can be renewably sourced. However, epoxies do often contain toxic chemicals that can be harmful to the environment. [26] |
| Polyethylene | Sea water exposure may reduce the elasticity of plastic, in some cases, decreasing the residual elongation at break (REB) by 60+%. [27] This insinuates that the plastic is becoming more brittle after seawater exposure. | 900-950 kg/m$^3$ (polyethylene, used for making buoys) [28] | Tensile strength of polyethylene ranges from 10 (Low density)-30 (High density) MPa [29] | Roughly 110MJ/kg of energy is required to produce polyethylene [30], however this number reduces by 88% if the product is produced using recycled plastics [31] |
| Concrete | Sea water exposure vastly increases the chance of corrosion in concrete through both abrasion and chemical attack. The effects of chemical corrosion can be decrease by the use of pozzolanic materials in the concrete mix. [32] | C25 concrete has a desity of 2300 kg/m$^3$ [33] | Tensile strength rainges form 3 – 5 MPa [33] | It is predicted that for every 1 kg of concrete produce, 0.9 kg of $CO_2$ is produced. [34] |

# Concept Designs

During the brainstorming stage of project planning several concept designs were created which could represent the final design or contain elements which will be taken forward. Two of these are shown below.

## Concept design 1

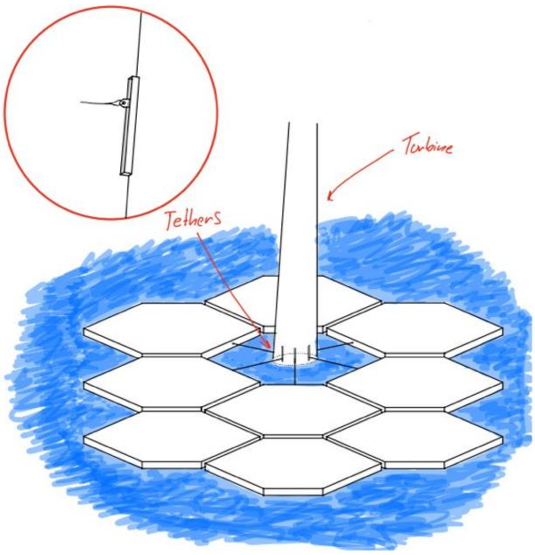



*Figure 13: Hexagonal modules*

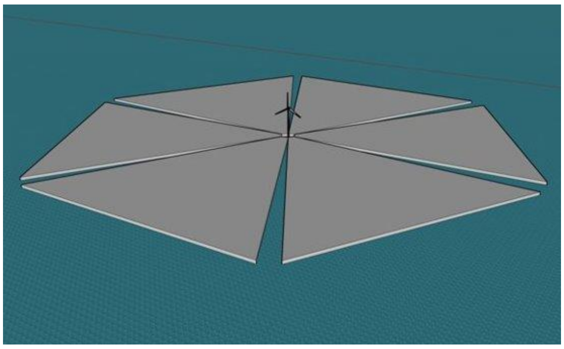


*Figure 12: triangular modules*

Concept design 1 was used to experiment with the modular aspect of the island. In this design the inner 'ring' would be anchored to the central shaft of a wind turbine as a mounting point and reinforced to the seabed using a catenary mooring system. The concept of a sliding channel was discussed, allowing the units to move vertically as tides change. This design presented several potential challenges, most importantly, the stress on the wind turbines themselves and potential corrosion between moving parts.

The issue of the individual modules colliding was solved with the addition of fenders that would likely to positioned on the shaft of the turbine in addition to in between the individual units. They would absorb the impact protecting all elements of this concept design.

## Concept design 2

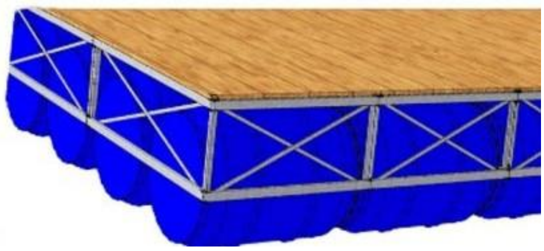


*Figure 16: Steel drum buoyancy system recommended in concept design 2*

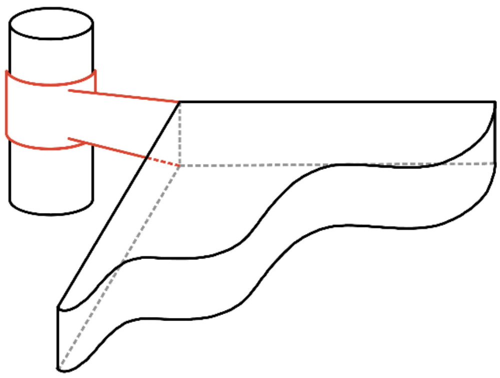


*Figure 15: Cables connecting second energy island concept design to turbine shafts*

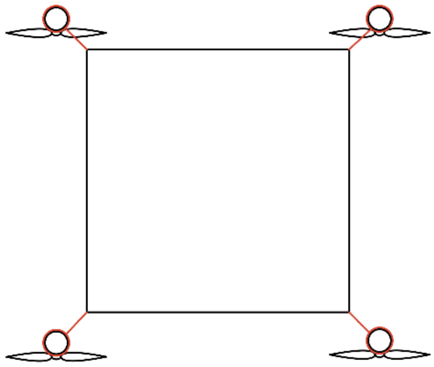


*Figure 14: : Arial View of concept design 2*

The second concept design, as seen in Figures 14 and 15, is a square or rectangle energy island, connected to the corresponding wind turbines via a cable and uses steel drums (Figure 16) or similar for buoyancy as they are economically viable with the option to reuse empty steel drums sourced locally to the energy island location.

For concept design 2, the connection of the module to the steel shaft of the wind turbine is such that it can slip in the vertical direction (Figure 15), similar to concept design 1. Importantly, this concept design overcomes any issues arising with the movement of the sea as if it were to be tethered to a fixed point on the wind turbine shaft as the sea levels differ the module would become submerged at parts, negatively impacting the amount of energy produced and potentially causing mechanical failures with submerging of the island not being expected.

The main potential challenge in this concept design is the additional lateral forces applied to the turbine shaft from the tethers, and therefore if this were to be the final design consideration would need to be made for this. Calculations would be required to find out if the turbine shafts could withstand the lateral forces instead of buckling. With this concept design, there is also an option to explore the idea of multiple square or rectangular modules coupled together within the original area shown on the diagram, as if the area is too large then one individual large island, such as depicted by Figure 14, will not suffice. This would allow for the entire system to move with the wave profile due to its interconnected modules. Configurations of rectangles or squares work best, scoring most highly in functionality and coupling scores according to a study by Ocean Solutions with triangles and hexagons also viable options however perhaps not as functional.

## Steel Drum Buoyancy Design (Alternative)

One design idea for the buoyancy of the offshore energy platform is to use steel drums for buoyancy. The envisaged design would look similar to that seen in Figure 16, and quite simply attach the steel drums beneath the platform, ensuring drums are located around the edge at the bare minimum to ensure the most stability. Steel drums would be an economically viable option for buoyancy with the opportunity to reuse empty steel drums sourced locally to the energy island location.

The standard size for the steel drum in both the UK and Australia would measure with a 580mm diameter and an 875mm height, these drums are often advertised as 44gallon or 205L drums for storage of a variety of fluids. The steel drums would weigh only 20kg when empty and provide significant buoyancy.

To calculate the buoyancy, volume must first be calculated, where a value of 0.231m$^3$ is calculated. With this known, along with the fluid density of the sea water (taken as an average between 1020 and 1050kg/m$^3$) and the value of acceleration due to gravity, the buoyant force can be calculated for an individual steel drum. A simple calculation is sued to find the displaced fluid mass and once the empty drum mass has been taken away, the carriable mass of each drum due to buoyancy is 219.1kg or approximately 0.22T.

The end result of the calculation provides the result that a platform approximately 50m x 50m platform with 40 drums supporting each edge provides a total carriable mass due to buoyancy of 35.0T. If all edges were however double lined the total number of drums proving buoyancy would be 320 and therefore have a carriable mass of approximately 70T. The reason this number of drums has been selected is to allow room for simple individual installation, required maintenance and/or easy replacement.

### Calculations (as above):

Volume = pi x r$^2$ x h = pi x 0.29 x 0.875 = approx. 0.231m$^3$

Volume = 0.231 m$^3$, Fluid density = 1035 kg/m$^3$, and Gravity = g = 9.81m/s$^2$

Buoyant Force = V x FD x g = 2.345kN

Displaced Fluid Mass = 239.1kg

Displaced mass - 20kg = Carriable Load = 219.1kg = approx. 0.22T

A 50x50m platform with 40 drums supporting each edge = 160 steel drums

Total carriable mass = approx. 35.0T

If all edges double lined (320 drums), carriable mass = approx. 70.0T

## Solution and Spec

Throughout the planning, research and design stages, constraints and limitations set by components and design challenges relating to other groups were identified and influenced the design process for the Civil Engineering group. In order to ensure the final product complies with the components and methods agreed upon on a team level, a detailed Civil Engineering specification list was created in order to ensure a final product in which all interfaces are satisfied:

*Table 3: Specification Table*

| Spec Point | Reason |
|---|---|
| The island must be comprised of modular sections which can be added and removed from the final location | Each modular component will produce a specific energy output. This means platforms must be added and removed to ensure the power output matches that of the wind farm. Platforms will also be added upon the potential upsizing of the wind farm. |
| The island must be connected to the sea floor using a pile and cable system | As highlighted in research, a catenary mooring system consisting of piles and cables is most appropriate for the size and scale of floating structure |
| The island must have a walkway section | A walkway will be necessary due to repairs and maintenance requirements |
| The platform must be able to resist tensile forces from the winds and wave conditions of the project location in the Bass Strait | The platform must not buckle or crack due to the forces acting upon it for it to be functional in its full design lifespan. |
| The island must be able to support a conservative load of 5000T therefore be designed with sufficient buoyancy to support this | The island must be sufficient in supporting all necessary equipment for renewable energy plus extra as a safety factor. |
| The island must be 56.56 x 56.56 metres squared | This value was found due to the number and size of rows of solar panels needed on each platform. |

# Risk Analysis

## Risk Management

*Table 4: Table of Associated Risks and Consequences*

| Risk Reference | Risk | Consequence |
|---|---|---|
| Risk Number 1 | Pipe damage | Any damage to the pipes or cables will cause the whole energy production system to shut down temporarily. This would result in missing out on the opportunity to convert any potential energy from the system whilst it was shut down. |
| Risk Number 2 | Solar panel damage | The solar panels will be exposed so individual solar panel damage could be commonplace. The consequence of any damage would be the need to replace the solar panel if efficiency was impacted. |
| Risk Number 3 | Machinery failure | The machinery will be set up in the best possible way to deal with any maintenance issues as quickly as possible, however, prior to maintenance it may be necessary to shut down the entire platform, or a certain section, in order to fix or replace parts. |
| Risk Number 4 | Imbalance in buoyancy | Any issues with buoyancy imbalances, possibly due to hull damage, could negatively harm the platform. Components situated on it could become water damaged  and could cause unexpected corrosion, consequently forcing the need to shut down due to machinery failure. This risk would require immediate solving however, the probability of this happening is low. |
| Risk Number 5 | Damage to platform or hull | The likelihood of platform damage is low due to regular inspections, replacement of parts and the resilience of the materials used. The consequence of any damage to the platform could require the entire platform to shut down whilst maintenance work is carried out, this could be lengthy but in the probability of damage worst than superficial corrosion, not picked up on during the regular inspections, is minimal. Damage to the bottom of the platform, or its hull, could result in the occurrence of Risk Number 4, likely resulting in partial submersion. |

| | | |
|---|---|---|
| Risk Number 6 | Electrical failure | Failures requiring maintenance could result in the need to shut down all electrical items to replace parts. All electrical parts would be ensured to have an outer shell protecting them. |
| Risk Number 7 | Hydro-electric generator damage | The energy output would decrease if a generator was to need fixing. The generator will be accessible separate from other parts and therefore the risk to the project is kept to a minimum. |
| Risk Number 8 | Emission of heat from machinery | With a project goal of producing as much energy as possible, energy loss should be kept to a minimum. The risk is low due to the regular inspection of parts for faults to be replaced if necessary. |

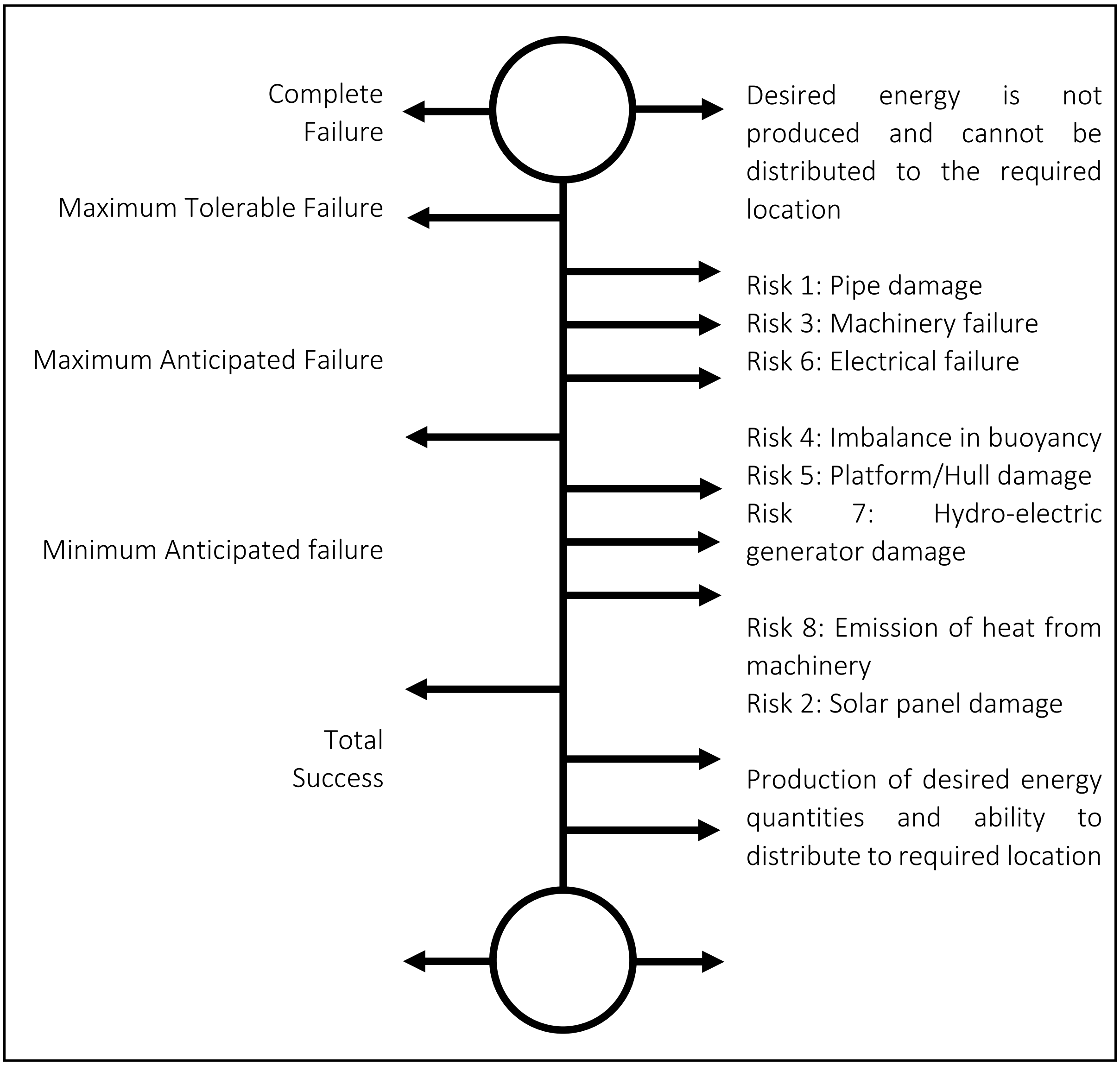



*Figure 17: Failure Space – Success Space Modelling*

*Table 5: Hazard and Operability Study*

| Intents | Guidewords | Deviation | Causes | Consequence |
|---|---|---|---|---|
| Storage | More | Storage device over filled | Continued addition of energy to storage device despite insufficient capacity available. | Increased energy being transferred to the grid with no storage capacity. |
| Pipe | Less | Decreased pipeline length | The transportation pipeline length is below that stated in the requirements for this project. | Increased chance of pipeline damage due to inadequate quality pipes needed. |
| Energy | More | Energy production above capacity/usage | There is insufficient usage and storage combined for the amount of energy produced. | When storage is full and usage is not adequate, energy is wasted. |
| Pipe | Part of | Low quality pipeline | The pipe quality is below the standard required by this design project. | The pipeline can become damaged causing no energy supply. |
| Hull/Buoyancy | Less | Decreased platform buoyancy | Lack of buoyancy to support the floating platform and equipment above it. | Damage to buoyancy devices could result in submersion of the platform. |
| Energy | As well as | Qualitative decrease in solar production | Salt build up or damage causing the solar panel  to work at a low efficiency. | Reduced energy production from solar panels due to damage is wated potential energy. |
| Energy | No | No energy production | Not enough energy being produced to meet the required production figures. | No energy production means no energy transfer to the grid is storage is full |

*Explanation for "Guidewords"*

No: This guideword shows complete negation of the design intent

More: A quantitative increase is represented by this guideword

Less: A quantitative decrease is represented by this guideword

As well as: This guideword represents a qualitative modification by an increase

Part of: This guideword represents a qualitative modification by a decrease

Reverse: A logical opposite of the design intent is represented by this guideword

Other than: A complete substitution is represented by this guideword

*Table 6: Failure Mode, Effects and Criticality Analysis*

<table>
<tr><td rowspan="2">Description</td><td>Name</td><td colspan="5">Process - Production of energy through solar and hydro-electric power on an offshore energy island</td></tr>
<tr><td>Function</td><td colspan="5">1) Production of energy in the desired quantities<br>2) Ability for distribution when necessary to the appropriate location</td></tr>
<tr><td rowspan="3">Description of failure</td><td>Failure Modes</td><td colspan="2">Platform Damage</td><td colspan="3">Damage to equipment</td></tr>
<tr><td>Failure Causes</td><td>Any damages impacting the structural integrity of the platform</td><td>Buoyancy imbalance – Damage to hull</td><td>Damage to solar panels</td><td>Hydro-electric energy generator damage</td><td>Electrical or mechanical fault</td></tr>
<tr><td>Detection of failure</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td></tr>
<tr><td colspan="2">Effect of failure</td><td>Potentially results in the shutdown of entire island to fix any key structural damages</td><td>Would require immediate solution or potential submersion</td><td colspan="2">Energy production from both forms of energy capture would decrease and consequently the efficiency of the island would decrease as a result</td><td>Immediate stoppage of all systems is required to fix any major electrical or mechanical failures</td></tr>
<tr><td colspan="2">Failure Type</td><td>Dangerous</td><td>Systematic</td><td colspan="2">Systematic</td><td>Dangerous</td></tr>
</table>

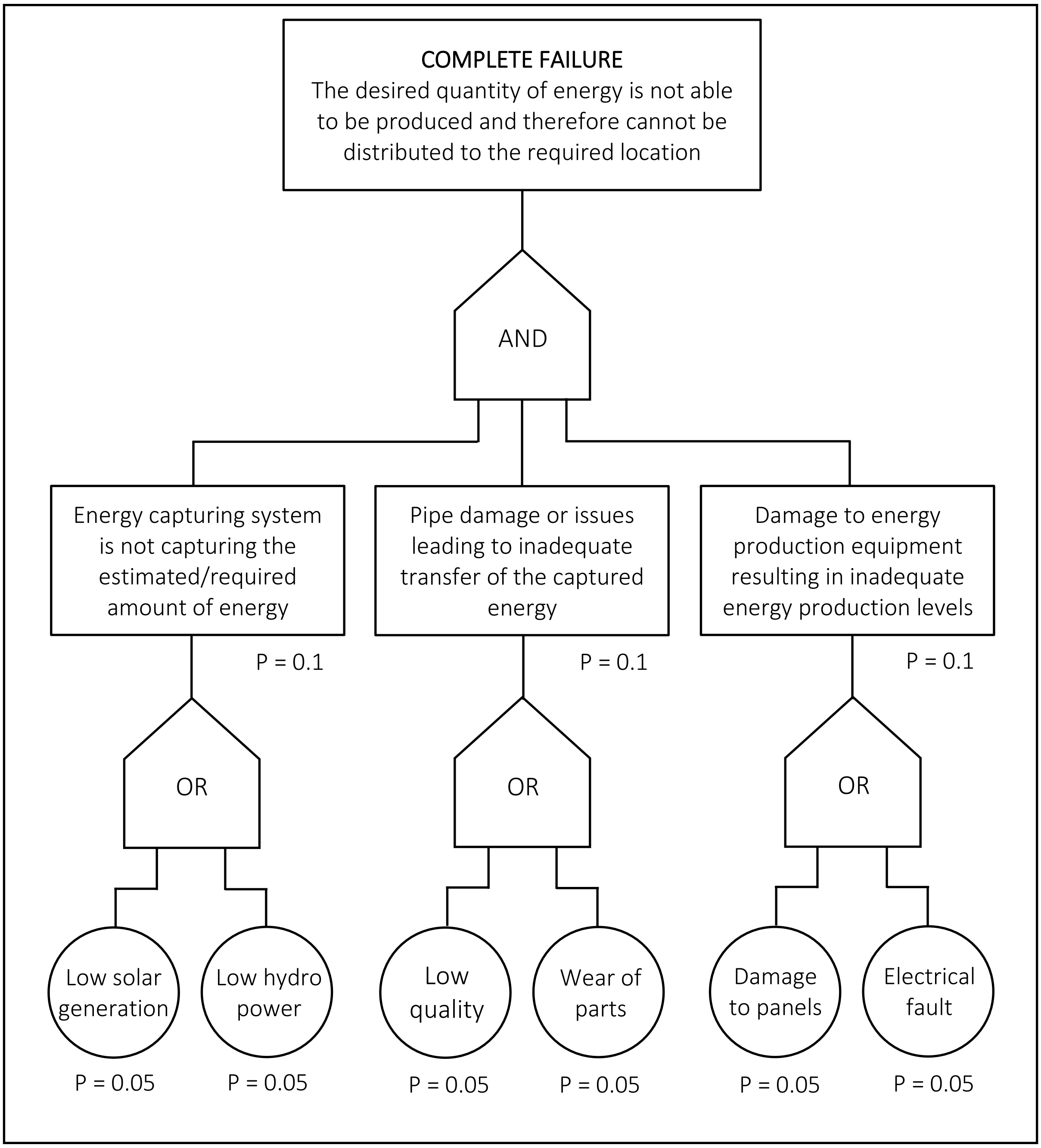



*Figure 18: Fault Tree Analysis*

**Probability Scale:**

1 in 10 (P = 0.1) represents 'Frequent'

1 in 100 (P = 0.01) represents 'Probable'

1 in 1000 (P = 0.001) represents 'Occasional'

Therefore, a probability of 0.05, lying between P = 0.01 and P = 0.1 represents Probable/Frequent.

### Project Associated Risks and their Consequences

The risks stated above, numbered one to eight, show varying degrees of consequence. The impacts caused by these risks may be purely environmental or economic, meanwhile others may be a combination of the two. There are potential risks that even have a social impact, such as an impact on the welfare and safety of site workers, these social impacts may be exclusive but are often in addition to environmental or economic impacts. Using information from Table 4, two matrices can be produced, where likelihood is compared to consequence levels and severity is paired with the probability of the risks. These can be located in the following 'Risk Analysis' section. These matrices provide a valuable insight into the severity of each risk and for the more severe of the risks, making it visible if they are probable in likelihood or not, potentially causing concern and requiring further measures to be put in place to mitigate the risk effects.

### Failure Space – Success Space Modelling

When studying Figure 17, it can be seen that total success occurs when the offshore energy island produces the maximum quantity of energy efficiently and effectively distributes it to the appropriate location as stated in the requirements. Complete failure, however, occurs when the opposite happens, when the project does not produce the desired energy and cannot distribute it to the required location. There are three levels leading to complete failure, the first is minimum anticipated failure, the second is maximum anticipated failure and the final step before complete failure, is maximum tolerable failure. The various levels refer to the likelihood and severity of the risks and an effort has been made to order them in severity within their appropriate level, where for example an imbalance in buoyancy is listed higher than platform damage as it is more likely to lead to submerged sections, which can be very serious, as opposed to platform damage, more likely to be superficial.

Maximum tolerable failure refers to the risks of highest severity that do not cause complete failure, such as machinery failure, an immediate solution would need to be found but complete failure does not occur. Maximum anticipated failure refers to the risks that are uncontrolled yet remain low enough in terms of severity to be considered close to total failure. Minimum anticipated failure refers to risks which are mainly controllable, whilst there is no such thing as perfection, some risks are inevitable but due to predictable nature, they will be solved quickly and are far from causing complete failure.

### Hazard and Operability Study (HAZOP)

Table 5 shows a HAZOP study where intents are matched with causes and consequences. The consequences column of the table represents similar information to that of Table 4, however the consequences are specific due to the effect of the guideword. Prior to this table for example, the discussed consequences have not included when too much energy can be produced, this is discussed in Table 5 as a result of the intent, 'energy', matching with the guideword, 'more'. There is an explanation key for the guidewords as some are not as straight forward as others, whilst 'less' represents a quantitative decrease, 'as well as' represents a qualitative modification by an increase. The 7 intents listed in this table also precede their deviation, describing the hazard more precisely.

## Failure Mode, Effects and Criticality Analysis (FMECA)

The layout of Table 6 is useful for identifying and prioritizing potential failures in order to eliminate them from the design process in advance of production of the final design. The failure modes are shown clearly, with their causes and consequent effects listed beneath them. All failure causes for this design are able to be detected, with 'yes' applied to all. The objective of this failure mode, effects and criticality analysis is to improve the overall final product reliability and emphasize problem prevention. Any known failure modes can be worked on during the design process, hence eliminating any problems or at very least mitigating the effects of any related problems.

## Fault Tree Analysis (FTA)

This analysis is used as it is a clear diagram showing an investigation of a failure event, in this case complete failure, located in the top box. Figure 18 analyses and identifies the areas where hazard mitigation is necessary, these hazards are found during the planning phase of this offshore energy platform design and from the investigation an understanding of the hazard is found making it much more easily preventable.

The graphical nature of the fault tree analysis makes it extremely readable and easy to understand, however it should be noted that it has an underlying requirement for the failure event to be foreseen, which could be seen as problematic. If the failure event is not foreseen then it could be catastrophic to the final production of the offshore energy island.

## Risk Analysis

### Risk Matrices

*Table 7: Risk Likelihood Matrix*

| | | Consequence | | |
|---|---|---|---|---|
| | | Insignificant | Tolerable | Catastrophic |
| Likelihood | High | Risk 2 | | |
| | Moderate | | Risk 4 & Risk 5 | Risk 3 |
| | Low | Risk 8 | Risk 7 | Risk 1 & Risk 6 |

The risk likelihood matrix, Table 7, shows the probability of the risks, numbered 1 to 8, given in the 'Table of Associated Risks and Consequences'. The matrix has different areas representing the relationship between the risk likelihood and the resulting consequence. For example the bottom left area is unlikely to occur and has very little consequence on the offshore energy island project as a whole, meanwhile the top right area represents the risks with the highest chance of occurrence whilst also being highly consequential to the overall project.

*Table 8: RAG Matrix*

| | | Severity | | | |
|---|---|---|---|---|---|
| | | Catastrophic | Critical | Marginal | Negligible |
| Probability | Frequent | | | | |
| | Probable | | Risk 4 | | Risk 2 |
| | Occasional | Risk 6 | | | |
| | Remote | Risk 3 | | Risk 7 | Risk 8 |
| | Improbable | Risk 1 | Risk 5 | | |

The Red Amber Green Matrix (RAG Matrix), Table 8, is an extension of the 'Table of Likelihood and Consequence' located just above. The matrix has colour coded areas (red, amber and green) that represent the relationship between probability and severity of the risk. Where the matrix works much like a traffic light system with red being the most probable and severe risks and consequently very dangerous and green being the least serious and least common and consequently the least dangerous, orange and yellow straddle the gap between with orange representing risks more dangerous than those located in the yellow boxes.

# Wind and Wave analysis

## Wind Analysis

The Bass Strait is a stretch of water located between Australia and Tasmania. It has a mild and oceanic climate with cool to mild temperatures throughout the year. This area receives a significant amount of rainfall relative to the rest of the country, especially in the winter months, and is vulnerable to extreme winds and storms. The water temperatures are, like the climate temperatures, generally cool ranging from around lows of 12°C in winter up to highs of 18°C in summer.

[35] The winds in the area are predominantly westerly to south-westerly, which come from the Southern Ocean and head towards the east coast of Australia. These winds can hit speeds of 93-111 km/h and wind speeds tend to be greater in the winter months.

There are several weather stations that record data for the Bass Strait region. These include:

- Wilsons Promontory - located in Victoria on the southern tip of the Australian mainland.
- Hogan Island - located in the middle of the Bass Strait, 50 kilometres south of Wilsons Promontory.
- King Island - located in the western part of the Bass Strait, about halfway between Victoria and Tasmania.

[36] The weather station at Wilsons Promontory is located on the southern tip of a National Park in Victoria and is the primary weather station for observing and recording data around the Bass Strait. It is operated by the Australian Bureau of Meteorology and the weather station records a broad range of climate variables, including temperature, rainfall, wind speed and direction, humidity, and atmospheric pressure. The data collected at the station is used to produce weather forecasts and warnings, as well as to monitor longer-term climate trends in the region.

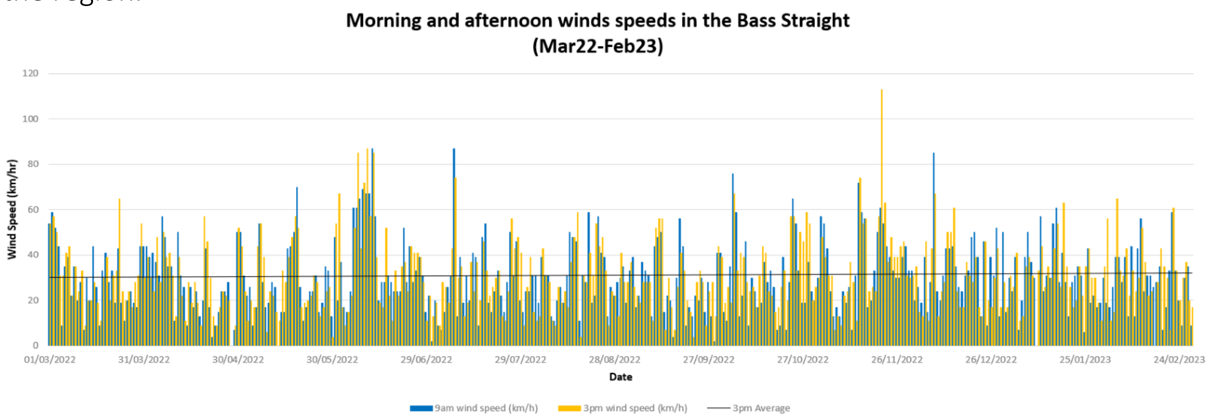



*Figure 19: Morning and afternoon wind speeds in the Bass Strait*

Figure 19 draws on data from March 2022 to February 2023 from the [36] Australian Bureau of Meteorology with climate and weather observations being taken from Wilsons Promontory Lighthouse, station #085096. Looking at the graph, on average the wind speeds are greater at 3pm than at 9am with most peak values occurring at 3pm including the largest value, 113 km/hr. The average of the 3pm wind speeds is 31.2 km/hr. Wind speed is an important parameter for determining the design wind loads on a structure. It is typically measured over a period of 10 minutes and is expressed in units of meters per second or kilometers per hour.

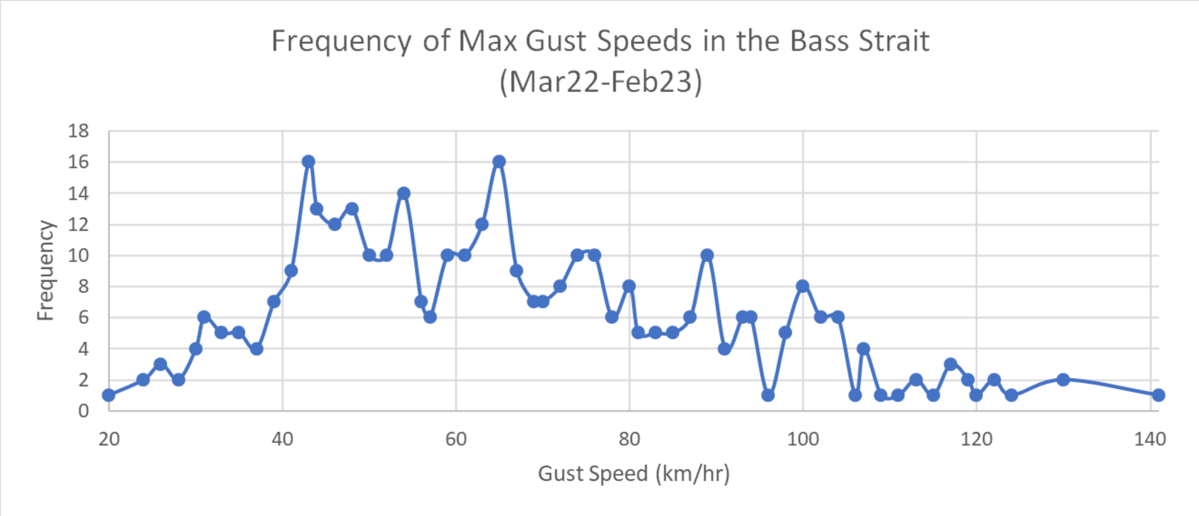



*Figure 20: Maximum gust speeds*

However, it is also important to consider the effect of gusts on any structure. Wind speed is the average speed of the wind over a given period, while gust is a sudden increase in wind speed that lasts for a short period. Gusts tend to be much larger than wind speeds and can cause oscillations and vibrations in the structure, which can lead to fatigue damage and eventually failure. Therefore, it is important to consider gusts when designing structures.
Figure 20 draws on the same data set used in Figure 1 but takes the maximum gust speed from each day rather than wind speeds in the morning and afternoon. The graph above is a frequency distribution of the maximum gust speeds everyday between March 2022 and February 2023. Most data points fall between 43 km/hr and 65km/hr. However, it is common for much larger gusts to occur with 41 days in the year experiencing gusts of 100 km/hr or more. The largest of these gusts was 141 km/hr.

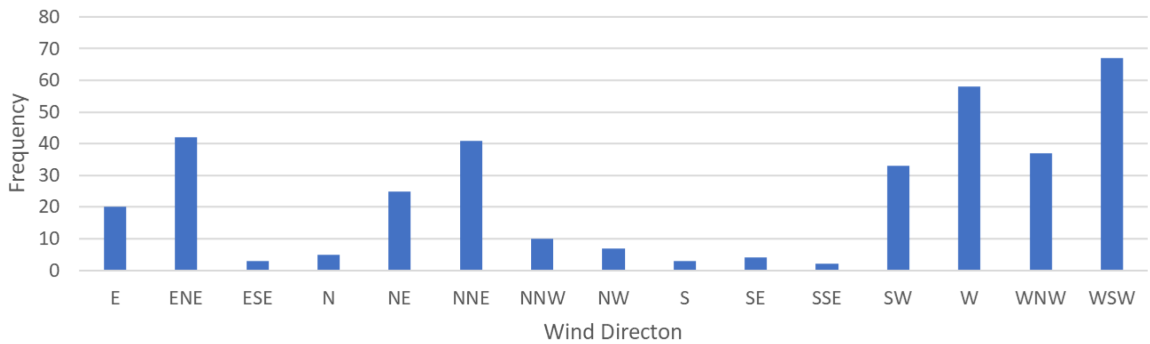



*Figure 21: Direction of winds/gusts in the Bass Strait (Mar 22 – Feb 23)*

Figure 21, also using the same data set, is another frequency distribution but instead of gust speed displays the direction of the wind/gusts for each day. The direction of the wind varies a lot daily, however, there are over 200 data points with western directions implying that most of the wind is moving from east to west through the bass strait. It is important to consider the most recent data however there may be outliers in terms of gust speed and wind speed that didn't occur in the last year.

*Table 9: Wind data*

| Location | Max Gust Speed (km/hr) | Max Mean 9am Wind Speed | Max Mean 3pm Wind Speed |
|---|---|---|---|
| WILSONS PROMONTORY LIGHTHOUSE | 171 | 33.6 | 35.8 |
| HOBART (ELLERSLIE ROAD) | 150 | 15 | 19.1 |
| HOGAN ISLAND | 180 | N/A | N/A |

Table 9 is a summary of data taken from the [36] Australian Bureau of Meteorology. It draws on observations from the 3 main weather stations surrounding the Bass Strait with data reaching back 150 years. The maximum gust experienced around the Bass Strait in the last 150 years was 180 km/hr. The table shows how the data varies from site to site despite all operating around the same channel of water. It is also important to consider the effect of climate change on the area.

One of the most significant ways in which climate change has affected the Bass Strait winds is changes in atmospheric pressure patterns. According to a study [37] climate models project a decrease in the frequency and intensity of high-pressure systems over the Tasman Sea, which would lead to a reduction in the strength of the westerly winds that pass through the Bass Strait. This is because high-pressure systems are responsible for creating a pressure gradient that drives the winds from west to east. As the frequency of these systems decreases, the pressure gradient weakens, and the wind speeds decline. It is safe to assume that the data of the last 150 years will be an accurate forecast for the foreseeable future and the wind data in the future will likely be less extreme than the last 150 years. Therefore, a value of 180 km/hr gust speeds and 31.2 km/hr average wind speeds moving east to west would be a fair approximation for the upper limit of wind data. However, in design it is important to include factors of safety to account for any unexpected circumstances.

The factor of safety for wind loading specified in AS/NZS 1170.2:2011 is 1.5 for most structures. This means that the design wind load should be multiplied by a factor of 1.5 to account for uncertainties in the design like material strengths and other factors that could affect the performance of the structure. This factor of safety is a minimum requirement and higher factors of safety may be used in certain situations or for more critical structures. Examples of critical structures may include hospitals, emergency shelters, power plants, telecommunications towers, and bridges. Therefore, it is unlikely that our design would fall under the category of critical structures.

## Wave Analysis

The wave climate surrounding our chosen area, the Bass Strait in Australia, is known to be very rough [38]. This leads to a challenging task when designing against wave loads. By using wave data found from the Victoria state government [39] and cross referencing with the mechanical engineering group, several parameters were found. This data was unfortunately limited, leading to our group having to use the data for one year only. This could affect the designs slightly as it may not account for extreme weather events with a return period greater than one year. As a result, in subsequent calculations, a safety factor was applied to minimise this impact on the design in future.

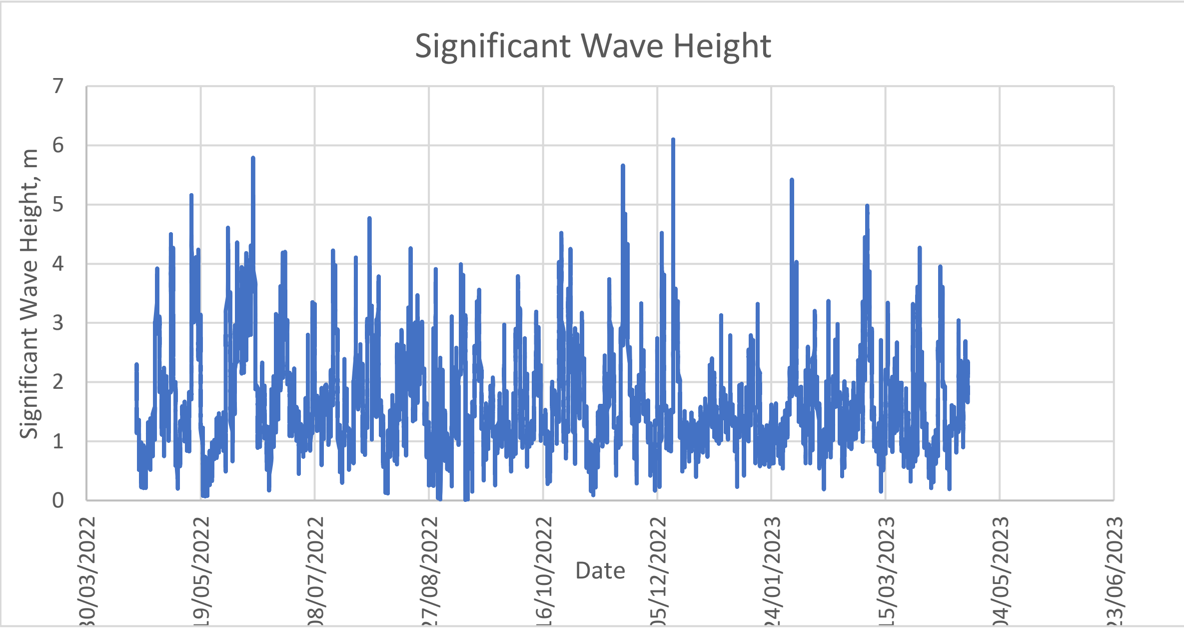



*Figure 22 : Significant wave height*

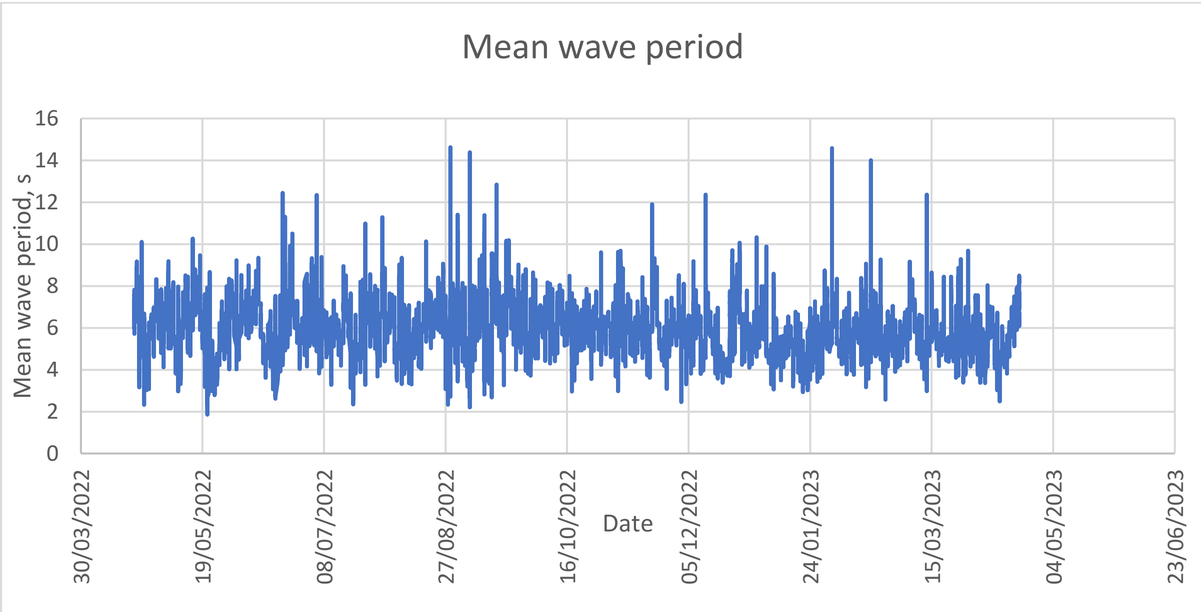



*Figure 23: Mean wave period*

Figure.22 and Figure 23, above, are graphs produced from the data that was found. Figure 22 shows significant wave heights over a one-year period; this provides some of the necessary information for calculating wave forces on a structure. Additionally, Figure .23 shows the mean wave period over one year, this is also necessary for wave force calculations. To ensure our structure is suitable and safe in as many conditions as possible, the wave forces were designed using worst-case scenarios from the available data. This led to choosing a significant wave height of 6.1 m, taken from Figure .22, as this was the maximum value in the data and a higher wave, hence higher amplitude, meaning it has more energy [40]. A period of 14.62 s was then taken from Figure .23, as it was the maximum in the range leading to a greater wavelength and a more powerful wave, as wavelength is directly related to wave speed [41].

Using the data taken from the figures, various other parameters were calculated, most notably the wavelength. This was calculated using a trial-and-error approach, using the solver function in excel and Equation 1 to ensure the correct value was found, which was 299.97 m.

$$\lambda = \frac{gT^2}{2\pi}\tanh(\frac{2\pi d}{\lambda})$$

*Equation 1 – Wavelength*

As our design is intended for offshore use, the relevant design code is the Det Norske Veritas (DNV). This was key for designing our structure again several offshore loads, which are typically not considered on land in other design codes (i.e., Eurocode). Due to designing against such large wavelengths, the wave forces are calculated for a small volume structure. This is done because the DNV considers a small volume structure as anything with a characteristic length less than one fifth of the wavelength, as shown in Equation 2 (DNV-RP-H103). Our pontoon and cables satisfy this equation, as the pontoon is only 56.56 m and the cables are only 0.05 m.

$$D < \frac{\lambda}{5}$$

*Equation 2 - Small volume structure check*

A few key assumptions were made when producing the following design loads. These were: the wave load decreases exponentially from its highest point at the surface to approximately zero at the ocean floor [42]; the maximum load occurs at one of the 4 key wave points (i.e., crest, trough and maximum acceleration points); current loads are negligible in comparison to wave loading; the cable can be modelled as a vertical cylinder and the pontoon can be modelled as a thin square plate (for the purposes of drag and inertia coefficients from the DNV).

Wave loads were calculated according to DNV-RP-H103, using a modified version of the Morison equation, as seen in Equation 3. Additionally, physical constants such as sea water density, drag coefficient and inertia coefficient were taken from the appendices of the same design code.

$$F(t) = \rho V(1 + C_A)\dot{v} + \frac{1}{2}\rho C_D S v|v|$$

*Equation 3 - Morison equation for wave loads*

*Table 10: Wave forces on structural elements of the platform*

| Element | Force Direction | Crest (kN) | Downward acceleration (kN) | Trough (kN) | Upward acceleration (kN) |
|---|---|---|---|---|---|
| Cable | Horizontal | 3.47 | 0.07 | -3.47 | -0.07 |
| | Vertical | -0.07 | 2.94 | 0.07 | -2.94 |
| Pontoon | Horizontal | 247.55 | 8203.94 | -247.55 | -8203.94 |
| | Vertical | -7553.87 | 209.88 | 7553.87 | -209.88 |
| Rotating mass generator | Horizontal | 50.01 | 24.25 | -50.01 | -24.25 |
| | Vertical | -12.27 | 12.80 | 12.27 | -12.80 |

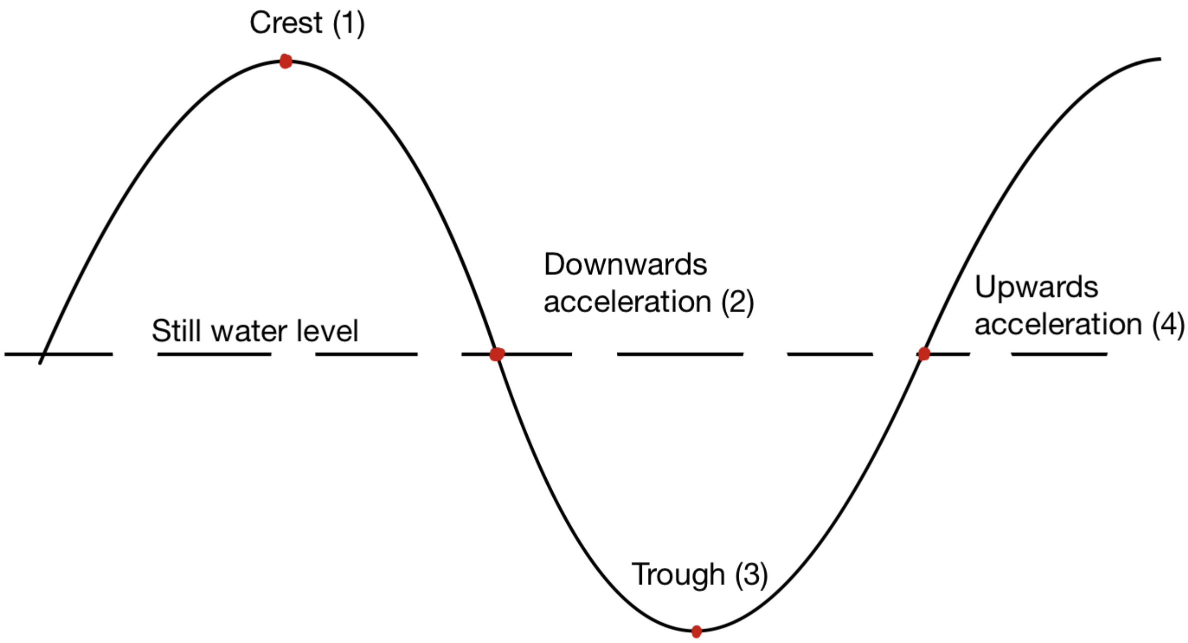
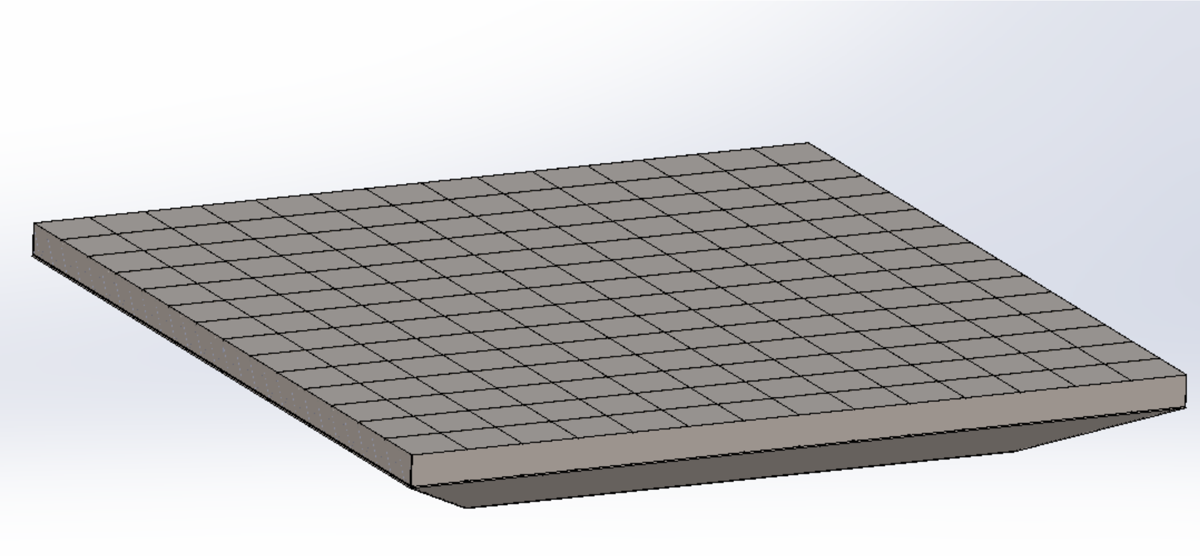
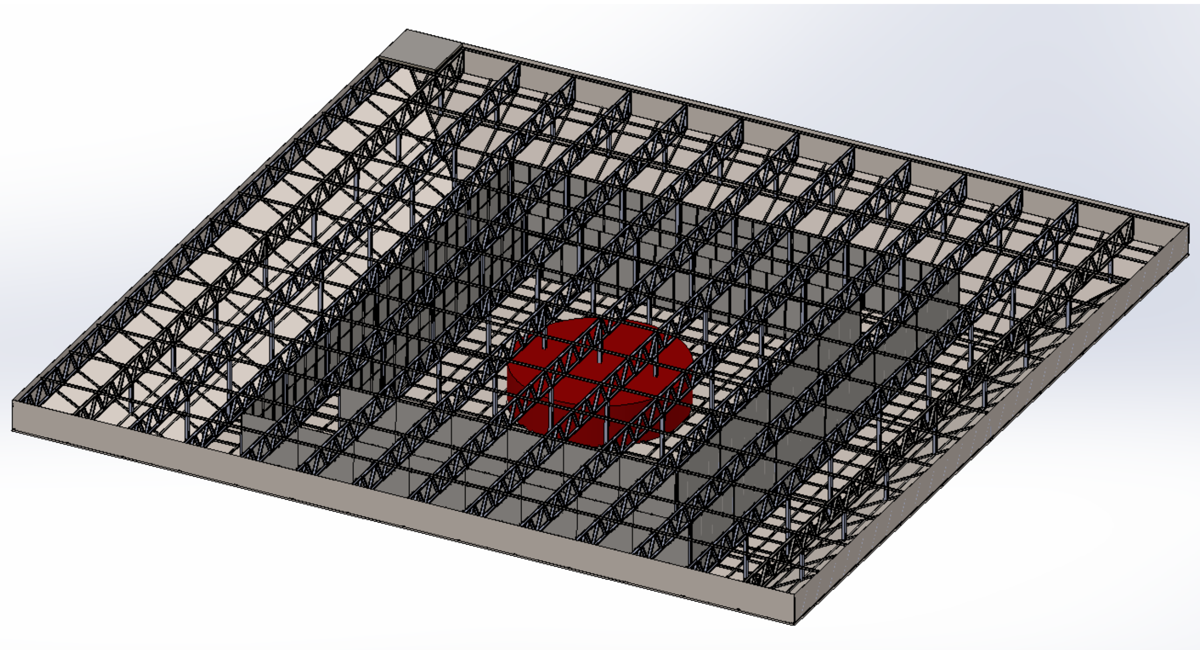



*Figure 24 - Wave diagram*

Table 10, above, shows the values for the wave forces on the three main structural elements, the pontoon, the rotating mass generator, and the tethering cable. It is important to note that a negative vertical force indicates the force acting down (towards the seabed). The point on the wave that the force corresponds to is labelled and can be examined using Figure 24

# Final Design





The figures above show the final design of one modular component of the energy island. As observed, a square shaped platform with a frustum shaped hull structure was selected due to the ability to connect each pontoon in a grid formation. The structure is designed to produce enough buoyancy to carry up to 10000 tons (including the self-weight of the pontoon). The red object in figure 26 represents the rotating mass energy generator and where it will be located on the platform. Safety has also been considered as shown by the inner panel layers. These provide redundancy and ensure the entire hull will not flood in the event of a collision. These inner panels also provide further structural support to the rows of steel trusses and allow outer or inner sections to be filled with ballast to alter the weight and buoyancy of the platform if more equipment is added/removed later in the product's lifespan. The design features an inner structural membrane comprised of s355 steel along with steel outer panels. The deck contains C25 grade concrete to allow for robust mounting of solar panels and other equipment. The concrete deck is completely encased in water sealed steel plating in order to prevent any degradation due to saltwater attack.

# Pontoon calculations

[All calculations are performed in accordance with Eurocode 3 [43]]

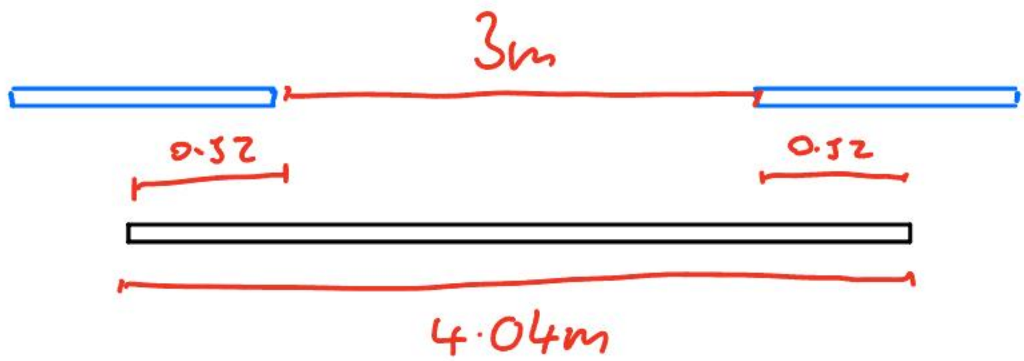
## Deck size:

The deck size was calculated based on the size of the solar panels (2.04x1.04m), the required gap between rows of solar panels (3m), the gap between panels in the array (0.05m) and the size of solar panel arrays (25 panels end to end). The deck must be a symmetrical square.

**Length of array:** (25 x (0.05+2.04)) + 0.05 = 52.3m

**Number of rows: ((**52.3 – 3)/(3 + 1.04)) + 3 = 12.2

The number of rows is to be rounded up to 13, the pontoon deck is to be constructed from square steel panels, solar panel will be mounted at the join between panels. The length of the panel will be such that the solar panels will be mounted with the required 3m gap between rows.




For there to be 13 rows of solar panels, there must be 14 rows of deck panels.

**Deck size:**
14 x 4.04 = 56.56m The deck will be 56.56 X 56.56m

**Pontoon buoyancy:** It was decided that the pontoon should float with the bottom surface of the hull at a depth of 4-4.5m. The hull is to be designed in the shape of a square bases frustrum with a top surface of 56.56m$^2$ (the required size of the dec to accommodate solar panels) and a bottom surface of 40m$^2$. The displacement of this design = (4.5 / 3) x (40$^2$ + (56.56 x 40) + 56.56$^2$) = 10592.2m$^3$
This displacement allows for a max weight of the pontoon = 10592.2 x 1025 = 10857 tons. This value is larger than the anticipated weight of the pontoon, which will allow for the addition of ballast to create variable buoyancy, effectively allowing the pontoon to be tuned once in use.

## Design of plates that make up the pontoon deck:

Each deck section will need to be able to take the load of 30 of concrete, a 5mm steel cover plate, the equivalent force of 10mm of water (spread over the area of the panel) and the force of 5 people stood on the panel (80kg per person). Safety factors of 1.5 are to be added as these are live loads [1]. The plate must be able to take this force with a maximum deflection of 10mm.

**5mm cover plate:** 0.005 x $4.04^2$ x 7850 = 604.6kg = 6284.5N

**Concrete:** 0.2 x $4.04^2$ x 2300 = 7507.9kg = 73652.9N

**Water weight force:** 1000 x (4.04$m^2$ x 0.01m) x 9.81 x 1.5 = 2401.65N (assume this is a point load acting at the center of the plate)

**Human weight force:** 80kg x 5 x 9.81 x 1.5 = 5886N (assume this is a point load acting at the center of the plate)

Total permanent load: (Assuming it acts as a point load at the center of the plate) = (73652.9N + 6284.5N) x 1.35 = 107914.3N

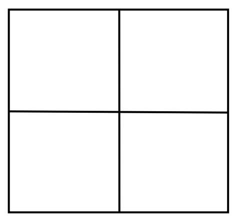
**Required plate thickness:** $\boldsymbol{t} = \sqrt[3]{\frac{\boldsymbol{K_1 P b^2}}{\boldsymbol{E y_m}}}$ [44]

Iterations were carried out to find the plate thickness, steel grade and required support system:

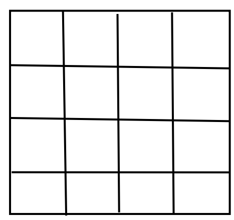
**Iteration 1:** (no supports)

$K_1$ = constant (0.061 [2])
t = plate thickness
P = concentrated point load
b = plate width
E = Young's modulus
$y_m$ = max allowable deflection
Total load per unsupported section = 5886N + 1601.1N + 107914.3N = 114600.9N
The required thickness of an unsupported plate was found to be 38.05mm, this was deemed too thick, and thus more iterations were carried out.

**Iteration 2:** (supports at half length and width)
Assuming the supports don't deflect, water is distributed evenly (therefor each Section take ¼ of the total water weight) and there is an equivalent weight of 3 People one quadrant.



Total load per unsupported section = (3 x 80kg x 9.81 x 1.5) + (2401.65+ 107914.3)/4 = 31110.5N
Required plate thickness = 15.45mm
This was also deemed to be too thick.



**Iteration 3:** (supports at quarter width and length intervals)
Again, assuming the supports don't deflect, water is distributed evenly across the Panel (therefore each section will take 1/16 of the total water weight) and there Is an equivalent weight of 2 people per section.
Total load per unsupported section = (2 x 80kg x 9.81 x 1.5) + (2401.65+ 107914.3)/16 = 9249.1N
Required thickness = 6.50mm
This thickness is deemed to be acceptable, a 10mm plate is selected.

**Required steel grade:** $f_y = \frac{6M}{bd^2}$ [43]

**Max moment:** (9199.1) x (4040/8) = 4.65x $10^6$ Nmm

$F_y$ = 276.2 N/mm$^2$ S355 steel is selected.

## Design of the plate supports:

### Loads acting on the supports:

Weight of 10mm plate: 0.01m x 4.04$^2$m x 7850 kg/m$^3$ x 9.81= 12569.0 N = 12.57 kN
12.57 / 4.04$^2$ = 0.77 kN/m$^2$
Weight of 5mm plate: 0.005m x 4.04$^2$m x 7850 kg/m$^3$ x 9.81= 6284.5 N = 6.29 kN
6.29 / 4.04$^2$ = 0.39 kN/m$^2$
Weight of concrete slab: .2 x 4.04$^2$ x 2300 x 9.81 = 73652.9N = 73.65 kN
73.65 / 4.04$^2$ = 4.51 kN/m$^2$

Water weight: 9.81 x 10$^{-5}$ N/mm$^2$ = 0.0981 kN/m$^2$
Human load: 80kg x 5 x 9.81 = 3924 N = 3.92 kN
3.92 / 4.04$^2$ = 0.24 kN/m$^2$

Total UDL over plate: ((0.77 + 0.39 + 4.51) x 1.35) + ((0.0981 + 0.24) x 1.5) = 8.16 kN/m$^2$
The load is spread evenly over the 6 beams therefore 8.16 / 6 = 1.36 kN/m$^2$
UDL along the beam = 1.36 x 4.04 = 5.50 kN/m

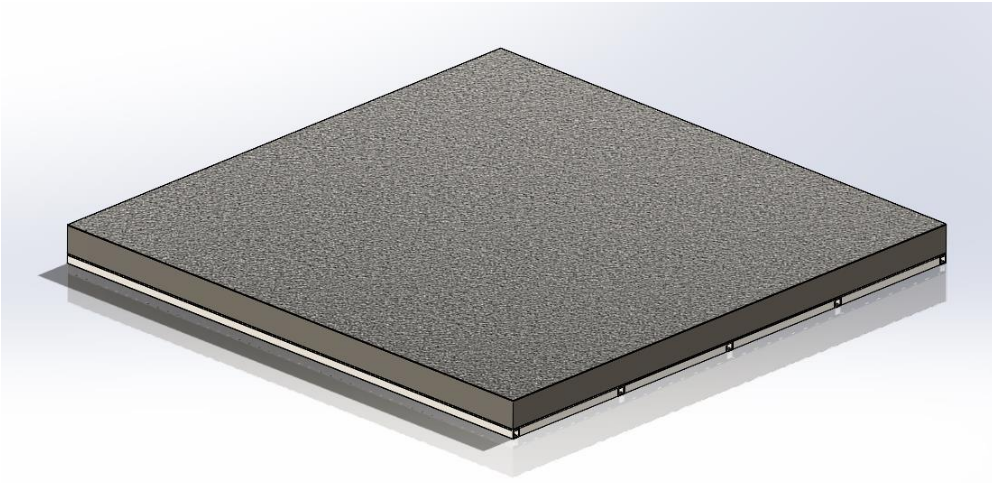
The beams are assumed to be fixed at both ends, therefore:
the maximum moment experience by the beam = (5.50 x 4.04$^2$) / 12 = 7.48 kNm
Maximum shear force experienced by the beam = (5.50 x 4.04) / 2 = 11.11 kN

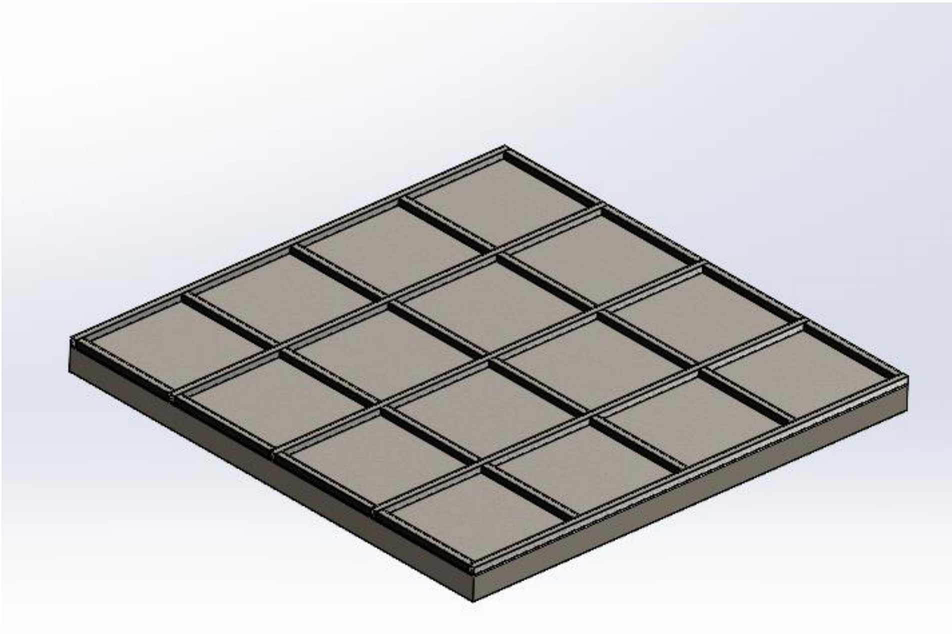
The section was then chosen using an excel calculator:

| Classification | |
|---|---|
| fy | 355 |
| C/t | 4.94 |
| class 1 | 58.58039 |
| class 2 | 67.53017 |
| class 3 | 100.8884 |
| section | class 1 |
| 60x60x8 | |

| bending | | |
|---|---|---|
| Med | 7.48 | kNm |
| Wpl | 30.4 | cm3 |
| YM0 | 1 | |
| Mc,Rd | 10.792 | kNm |

| Shear | | |
|---|---|---|
| Ved | 11.11 | kN |
| A | 16 | cm2 |
| b | 60 | mm |
| h | 60 | mm |
| $A_v$ | 800 | mm$^2$ |
| Vpl,Rd | 164 | kN |





## Support beam design:

Half of the combined permanent and live loads acting on the panel will be transferred on to support beams that run the length of the pontoon. These beams will be supported by trusses running perpendicular to them. The trusses are located directly below the solar panels and will take the other half of the deck loads directly, the solar panel loads directly and the load that is transferred from the support beams.

### Loads acting on support beam:

**Permanent load:** (604.6 + 7507.9 + 1281.2 + (10 x 4.04 x 12.5)) x 9.81 x 1.35 = 131093.4N = 131.1kN

**Water load:** $4.04^2$ x 0.01 x 1000 x 9.81 x 1.5 = 2401.65N = 2.4kN

**Human load:** 80 x 5 x 9.81 x1.5 = 5886N = 5.9kN

Each longitudinal support beam will take half the loads associated with the deck panel = (131.1 + 2.4 + 5.9) / 2 = 69.7kN

This force is distributed over the length of the member to give 69.7 / 4.04 = 17.3 kN/m

The longitudinal support is taken to be a simply supported beam, experiencing a UDL, therefore:

$M_{Ed} = (17.3 \times 4.04^2) / 8 = 35.3$ kNm
$V_{Ed} = (17.3 \times 4.04) / 2 = 34.9$ kN

A section was then chosen using an excel calculator:

| Classification | |
|---|---|
| | |
| fy | 355 |
| C/t (w) | 24.2 |
| C/t (t) | 3.74 |
| | |
| class 1 | 58.58039 |
| class 2 | 67.53017 |
| class 3 | 100.8884 |
| | |
| section | class 1 |
| | |
| 152x89x16 | |

| bending | | |
|---|---|---|
| | | |
| Med | 35.3 | kNm |
| Wpl | 123 | cm3 |
| YM0 | 1 | |
| | | |
| Mc,Rd | 43.665 | kNm |

| Shear | | |
|---|---|---|
| | | |
| Ved | 34.9 | kN |
| A | 20.3 | cm2 |
| b | 88.7 | mm |
| tf | 7.7 | mm |
| tw | 4.5 | |
| r | 7.6 | |
| $A_v$ | 815.7 | $mm^2$ |
| | | |
| Vpl,Rd | 167.2 | kN |

## Truss Design:

### Loads acting on truss:

### Force transferred by support beams (point load):

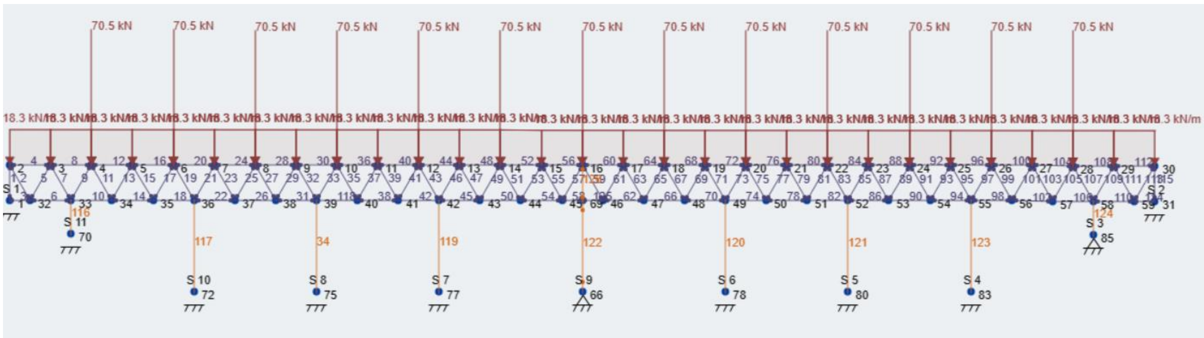
$(17.3 \times 4.04) + (4.04 \times 16 \times 9.81 \times 10^{-3}) = 70.5$ kN

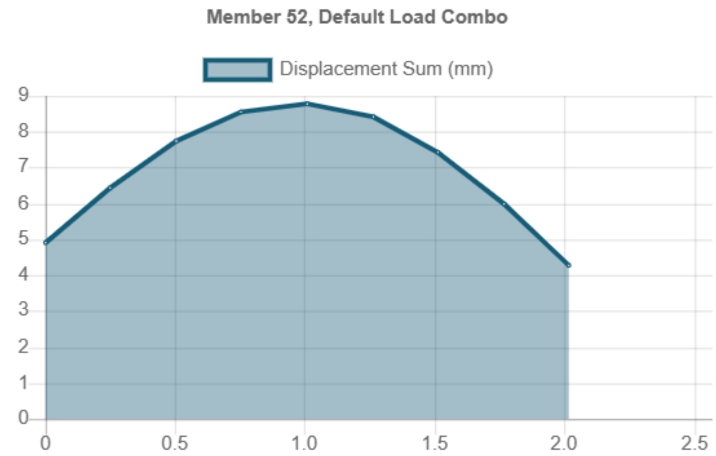
**Load from solar panels:** There are 25 panels per array, each weighing 22.7kg, the weight of the racks supporting the solar panels is 152.6kg per panel, therefore the total weight per array is:
$25 \times (22.7 + 152.5) = 5382.5$kg $= 43.0$ kN

It is assumed that this load is spread evenly over the length of the truss supporting it:
$43.0 / 56.56 = 0.76$ kN/m

### UDL on truss sections:

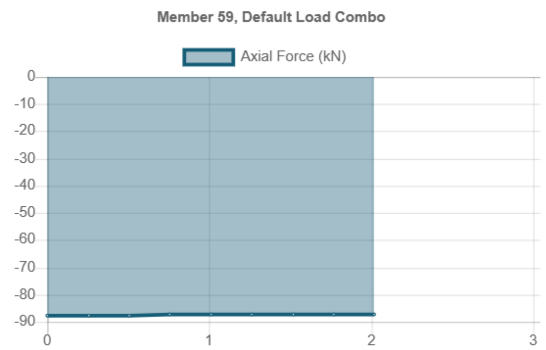
$(0.76 \times 1.35) + 17.3 = 18.3$ kN/m
A SkyCiv model was produced in order to find the axial forces in each member, as well as the deflections for each member of the truss (columns were not considered at this stage.

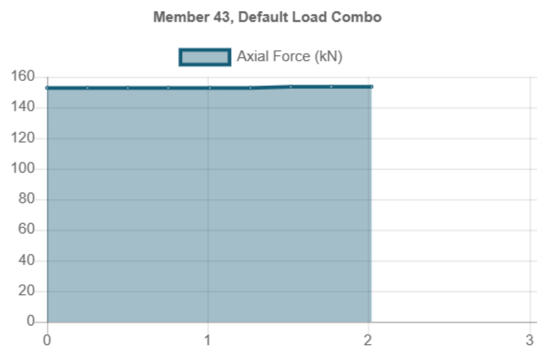





Initially, 127 x 76 x 13 UB sections were selected for the truss, however these sections experienced a large amount of deflection (max of 8.8mm) and so new sections were selected.

The new section chosen was, 203 x 133 x 30 UB. The maximum deflection found in this system was only 2.9mm which was deemed acceptable.
Next, the maximum axial forces experienced in the truss members and columns were found:




### Tension check for member 59:

The maximum tension force in a truss member was found to be 87.7kN, the member is assumed to have no fastening holes and is a 203 x 133 x 30 UB.

$N_{Ed}$ = 87.7kN

$N_{pl,Rd} = ((38.2 \times 10^2 \times 355) / 1) \times 10^{-3} = 1356$kN

### Buckling check for member 43:

The maximum compressive force in a member was found to be 153.3kN

$N_{cr}$ = 14730.4kN

$\bar{\lambda} = 0.3$

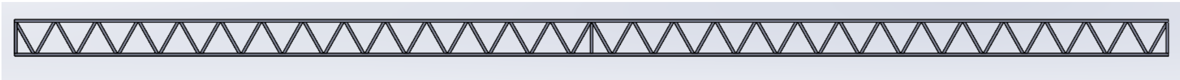
h / b = 1.54 > 1.2 $t_f$ < 40 y-y therefore, curve a is selected

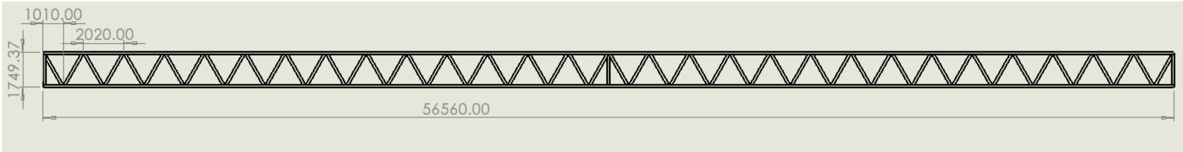
$\alpha = 0.21$

$\Phi = 0.56$

$X = 0.97$

$N_{b,Rd} = ((0.97 \times 38.2 \times 10^2 \times 355) / 1) \times 10^{-3} = 1315.4\text{kN} > 153.3\text{kN}$





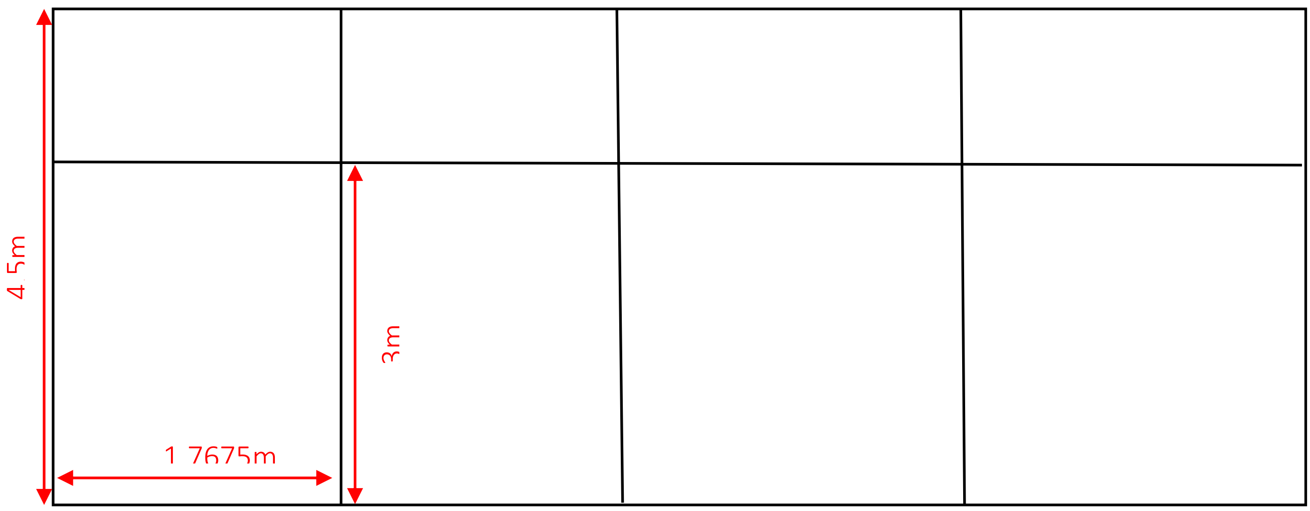

# Internal panel design:

## Panel sizes:

There are 3 size gaps that need to be spanned by panels to create an internal compartment, 7.07 x 4.5m, 6.06 x 4.5m and 4.04 x 4.5m.
Assuming the pontoon's outer hull has failed, the panels of the internal compartment must be able to withstand the water pressure applied to them.
Water pressure = $\rho \times g \times h = 1025 \times 9.81 \times 4.5 = 45.2 kN/m^2$
This value decreases linearly to zero at the water's surface.
It is assumed that the pressure can be converted to a line load acing at h/3 from the bottom edge of the internal panel:
Line load = (4.5 x 45.2) / 2 = 101.7 kN/m

## 7.07m x 4.5m panel:

The line load found to be acting on the panel is converted to a point load which is then used to work out the required panel thickness (assuming a max deflection of 10mm)
101.7 x 7.07 = 719.0kN
For this panel size (7.07 x 3m), $k_1 = 0.0789$
The required panel thickness = 110.6mm, this is far too large so extra bracing is to be added.
The panel is to be braced so that it is split into 4 equal spans of 1.7675m
For this panel size, $k_1 = 0.0785$
101.7 x 1.7675 = 179.75kN
The required panel thickness = 27.56mm, this is deemed to be acceptable and a 30mm S355 panel is selected.



**Panel supports:**

It is assumed that the load on each of the 4 panel sections is shared evenly between the supports. The UDL on the supports = 179.75 / (2 (3 + 1.7675)) = 18.9kN/m

The 3m members will experience a force of 2 x 18.9kN/m as it is supporting part of the load from the panels on either side.

**Bending:**

3m member: (2 x 18.9 x $3^2$) / 12 = 28.35kNm

1.7675m member: (18.9 x $1.7675^2$) / 12 = 4.92kNm

**Shear:**

3m member: (2 x 18.9 x 3) / 2 = 56.7kN

1.7675m member: (18.9 x 1.7675) / 2 = 6.7kN

**Support section selection:**

100 x 100 x 6.3 section for 3m member

| Classification | | | bending | | | | Shear | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| fy | 355 | | Med | 28.35 | kNm | | Ved | 56.7 | kN |
| C/t | 12.9 | | Wpl | 80.9 | cm3 | | A | 23.2 | cm2 |
| | | | YM0 | 1 | | | b | 100 | mm |
| class 1 | 58.58039 | | | | | | h | 100 | mm |
| class 2 | 67.53017 | | Mc,Rd | 28.72 | kNm | | $A_v$ | 1160 | $mm^2$ |
| class 3 | 100.8884 | | | | | | | | |
| | | | | | | | Vpl,Rd | 237.8 | kN |
| section | class 1 | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| 100 x 100 x 6.3 | | | | | | | | | |

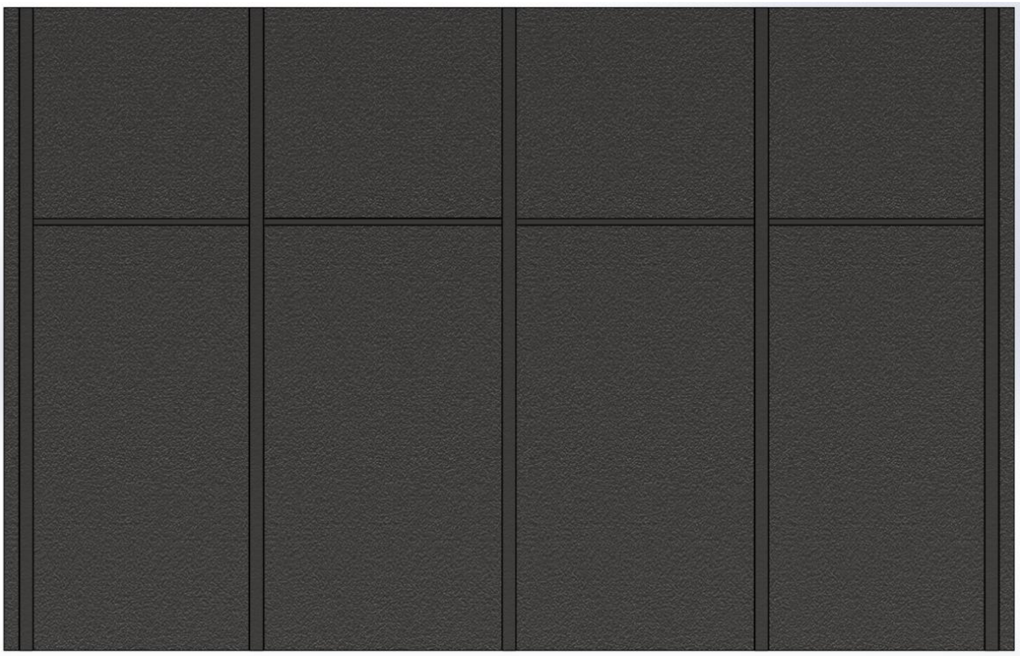
50 x 50 x 5 for 1.7675m panel

| Classification | | | bending | | | | Shear | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| fy | 355 | | Med | 4.92 | kNm | | Ved | 16.7 | kN |
| C/t | 3.25 | | Wpl | 14.5 | cm3 | | A | 8.73 | cm2 |
| | | | YM0 | 1 | | | b | 50 | mm |
| class 1 | 58.58039 | | | | | | h | 50 | |
| class 2 | 67.53017 | | Mc,Rd | 5.1475 | kNm | | $A_v$ | 436.5 | $mm^2$ |
| class 3 | 100.8884 | | | | | | | | |
| | | | | | | | Vpl,Rd | 89.46 | kN |
| section | class 1 | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| 50 x 50 x 5 | | | | | | | | | |

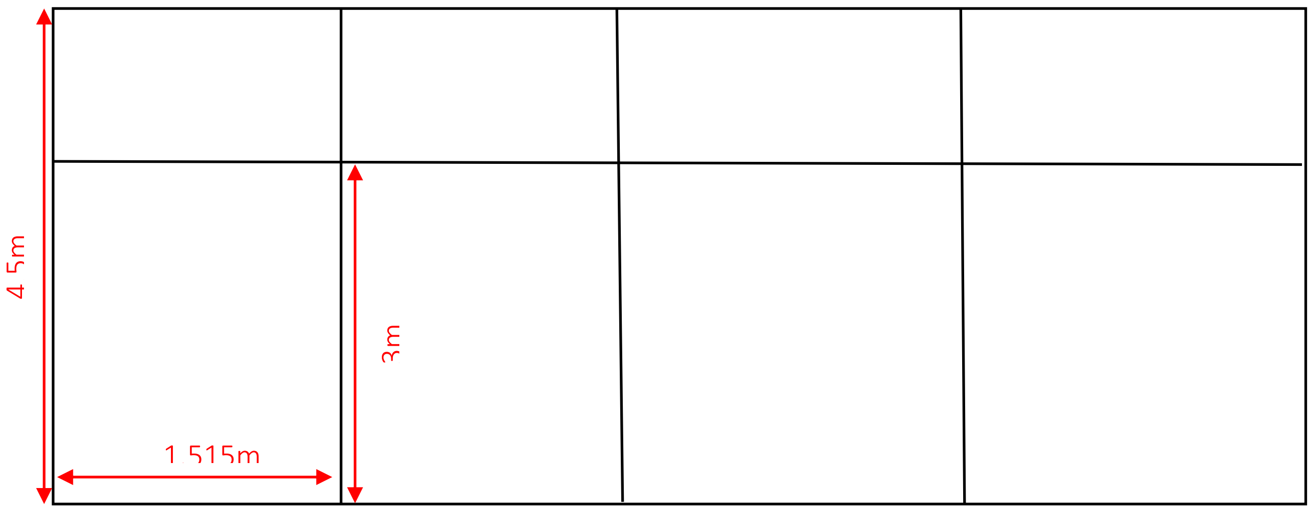
**Weight of panel:** 0.03 x 7.07 x 4.5 x 7850 = 7492.4 kg = 73.5kN

**Weight of supports:** (4.5 x 3 x 18.2) + (1.7675 x 4 x 10) = 316.4 kg = 3.10kN

**Total weight:** 7808.8 kg = 76.6kN



**6.06 x 4.5m panel:**
101.7 x 6.06 = 616.3kN
For this panel size (6.06 x 3m), $k_1 = 0.0788$
The required panel thickness = 94.8mm, this is far too large so extra bracing is to be added.
The panel is to be braced so that it is split into 4 equal spans of 1.515m
For this panel size, $k_1 = 0.0788$
101.7 x 1.515 = 154.08kN
The required panel thickness = 23.7mm, this is deemed to be acceptable and a 25mm S355 panel is selected.



**Panel supports:**

It is assumed that the load on each of the 4 panel sections is shared evenly between the supports. The UDL on the supports = 154.08 / (2 (3 + 1.515)) = 17.06kN/m

The 3m members will experience a force of 2 x 18.9kN/m as it is supporting part of the load from the panels on either side.

**Bending:**

3m member: (2 x 17.06 x $3^2$) / 12 = 25.6kNm

1.515m member: (17.06 x $1.515^2$) / 12 = 3.26kNm

**Shear:**

3m member: (2 x 17.06 x 3) / 2 = 51.18kN

1.515m member: (17.06 x 1.515) / 2 = 12.9kN

**Support section selection:**

100 x 100 x 6.3 for 3m panel

| Classification | |
|---|---|
| fy | 355 |
| C/t | 12.9 |
| class 1 | 58.58039 |
| class 2 | 67.53017 |
| class 3 | 100.8884 |
| section | class 1 |

| bending | | |
|---|---|---|
| Med | 28.35 | kNm |
| Wpl | 80.9 | cm3 |
| YM0 | 1 | |
| Mc,Rd | 28.72 | kNm |

| Shear | | |
|---|---|---|
| Ved | 56.7 | kN |
| A | 23.2 | cm2 |
| b | 100 | mm |
| h | 100 | mm |
| $A_v$ | 1160 | $mm^2$ |
| Vpl,Rd | 237.8 | kN |

100 x 100 x 6.3

50 x 50 x 3.2 for 1.515m panel

| Classification | |
|---|---|
| fy | 355 |
| C/t | 12.6 |
| class 1 | 58.58039 |
| class 2 | 67.53017 |
| class 3 | 100.8884 |
| section | class 1 |

| bending | | |
|---|---|---|
| Med | 3.26 | kNm |
| Wpl | 10.2 | cm3 |
| YM0 | 1 | |
| Mc,Rd | 3.621 | kNm |

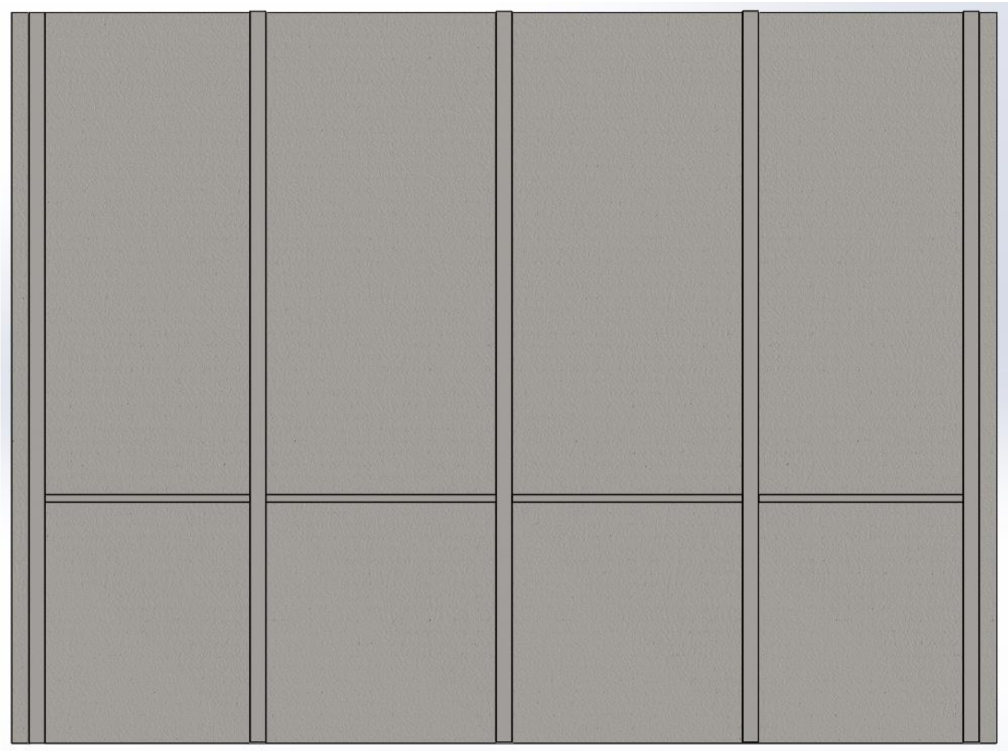
| Shear | | |
|---|---|---|
| Ved | 12.9 | kN |
| A | 5.88 | cm2 |
| b | 50 | mm |
| h | 50 | |
| $A_v$ | 294 | $mm^2$ |
| Vpl,Rd | 60.26 | kN |

50 x 50 x 3.2

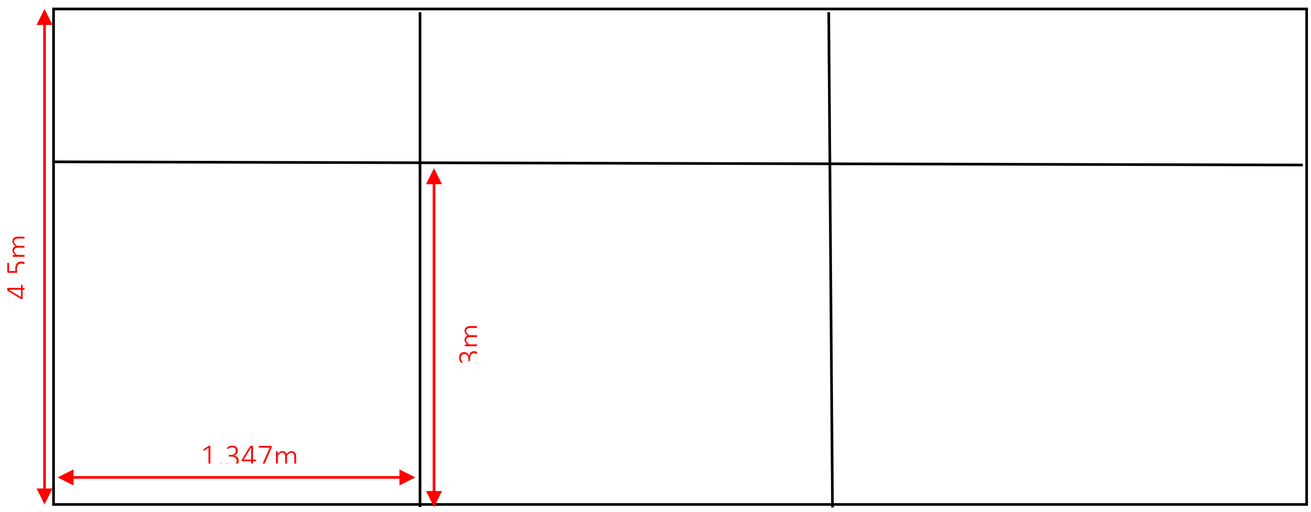
**Weight of panel:** 0.025 x 6.06 x 4.5 7850 = 5351.7 kg = 52.5kN

**Weight of supports:** (4.5 x 3 x 18.2) + (1.515 x 4 x 4.62) = 273.7 kg = 2.7kN

**Total weight:** 5625.4 kg = 55.2kN



**4.04m x 4.5m panel:**
101.7 x 4.04 = 410.9kN
For this panel size (4.04 x 3m), $k_1 = 0.074$
The required panel thickness = 61.8mm, this is far too large so extra bracing is to be added.
The panel is to be braced so that it is split into 3 equal spans of 1.347m
For this panel size, $k_1 = 0.0789$
101.7 x 1.347 = 137.0kN
The required panel thickness = 21.1mm, this is deemed to be acceptable and a 25mm S355 panel is selected.



**Panel supports:**

It is assumed that the load on each of the 4 panel sections is shared evenly between the supports. The UDL on the supports = 137.0 / (2 (3 + 1.347)) = 15.72kN/m

The 3m members will experience a force of 2 x 18.9kN/m as it is supporting part of the load from the panels on either side.

**Bending:**

3m member: (2 x 15.72 x $3^2$) / 12 = 23.58kNm

1.347m member: (15.72 x $1.347^2$) / 12 = 2.38kNm

**Shear:**

3m member: (2 x 15.72 x 3) / 2 = 47.16kN

1.347m member: (15.72 x 1.347) / 2 = 10.59kN

**Support section selection:**

90 x 90 x 8 for 3m panel

| Classification | |
|---|---|
| fy | 355 |
| C/t | 8.25 |
| class 1 | 58.58039 |
| class 2 | 67.53017 |
| class 3 | 100.8884 |
| section | class 1 |

| bending | | |
|---|---|---|
| Med | 23.58 | kNm |
| Wpl | 77.6 | cm3 |
| YM0 | 1 | |
| Mc,Rd | 27.548 | kNm |

| Shear | | |
|---|---|---|
| Ved | 47.16 | kN |
| A | 25.6 | cm2 |
| b | 90 | mm |
| h | 90 | mm |
| $A_v$ | 1280 | $mm^2$ |
| Vpl,Rd | 262.3 | kN |

90 x 90 x 8

40 x 40 x 4 for 1.347m panel

| Classification | |
|---|---|
| fy | 355 |
| C/t | 7 |
| class 1 | 58.58039 |
| class 2 | 67.53017 |
| class 3 | 100.8884 |
| section | class 1 |

| bending | | |
|---|---|---|
| Med | 2.38 | kNm |
| Wpl | 7.44 | cm3 |
| YM0 | 1 | |
| Mc,Rd | 2.6412 | kNm |

| Shear | | |
|---|---|---|
| Ved | 10.58 | kN |
| A | 5.59 | cm2 |
| b | 40 | mm |
| h | 40 | mm |
| $A_v$ | 279.5 | $mm^2$ |
| Vpl,Rd | 57.29 | kN |

40 x 40 x 4

**Weight of panel:** 0.025 x 4.04 x 4.5 x 7850 = 3567.8 kg = 35.0kN

**Weight of supports:** (4.5 x 2 x 20.1) + (1.347 x 3 x 4.39) = 198.6 kg = 1.9kN

**Total weight:** 3766.4 kg = 36.9kN

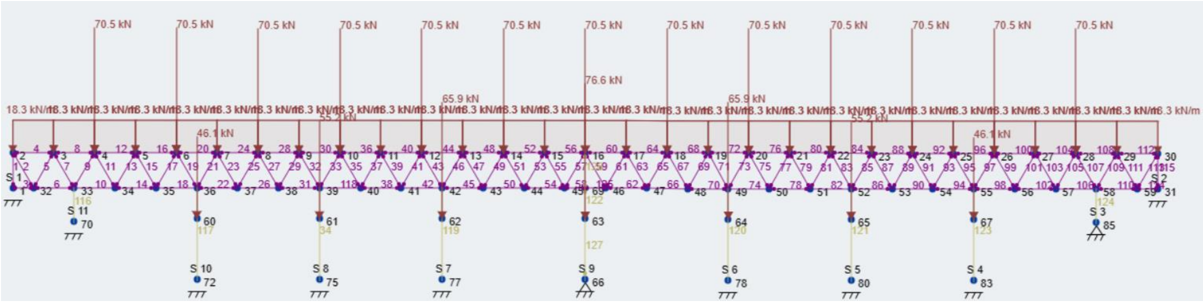
The purpose of the internal compartments are 2 fold, firstly, they can be used to hold ballast in order to stabilize the pontoon in rough conditions, and secondly, the outer compartment can provide buoyancy for the pontoon in the event of a catastrophic failure of the outer hull panels:

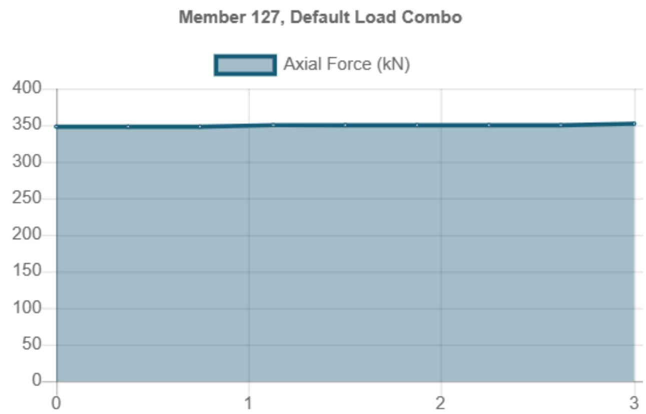
**Buoyancy provided by the outer compartment:**
((7.07 x 2) + (6.06 x 4)) x (4.04 x 8) x 4.5 = 5582.0m$^3$
5582 x 1025 = 5721.5 tons of buoyancy

## Loads on supports due to panels:

Center: 76.6kN
Center but one: (76.6 + 55.2) / 2 = 65.9kN
Mid span: 55.2kN
End: (55.2 + 36.9) / = 46.1kN

**SkyCiv model:**
The SkyCiv model was then updated with the new loads acting on the truss supports.






The largest compression force experienced was 351.3kN in the central support.

**Buckling check for section with new loads (203 x 203 x 46):**
The maximum compressive force in a member was found to be 351.3kN
$N_{cr}$ = 23213.1kN
$\bar{\lambda}$ = 0.3
h / b = 1.0 < 1.2 $t_f$ < 40 y-y therefore, curve b is selected
α = 0.34
Φ = 0.56
X = 0.97
$N_{b,Rd}$ = ((0.97 x 58.7 x $10^2$ x 355) / 1) x $10^{-3}$ = 2021.3kN > 351.3kN

**Bending and axial check for new loads (203 x 203 x 46):** (take the central column as the worst-case scenario.

**Axial force:**

$N_{Ed}$ = 351.3
$N_{pl,Rd}$ = 2083.85
$N_{pl,Rd}$ x 0.25 = 520.96 > 351.3 therefore bending resistance is unaffected by axial force.

**Bending:**
Assume the force on the beam is a point load acting at 3m from the top of the column,
101.7 x 7.07 = 719.0kN
$M_{Ed}$ = 479.3kNm
$M_{pl,Rd}$ = 176.5kNm
A larger section is required.
203 x 203 x 127 is selected (only bending checks are required as this is the critical component)
$M_{Ed}$ = 479.3kNm

$M_{pl,Rd}$ = 539.6kNm
203 x 203 x 127 is selected.

## Design of hull panels:

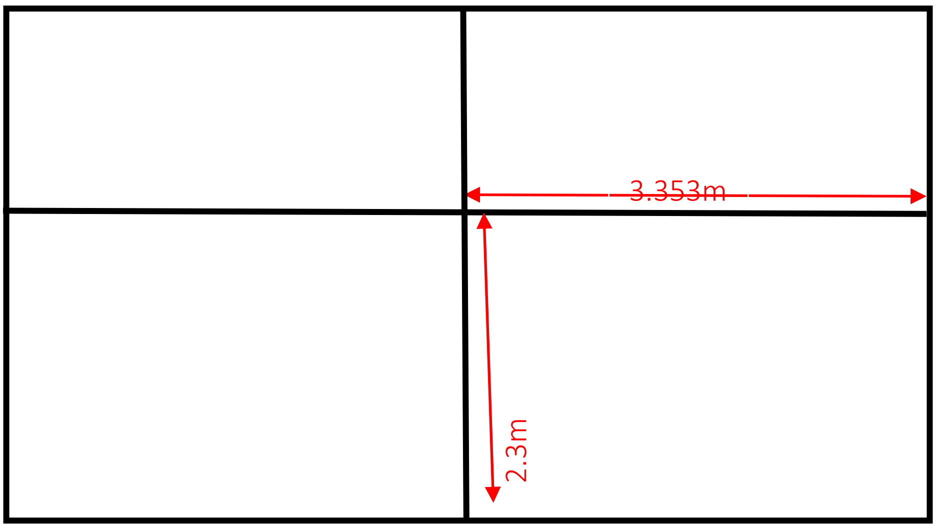
[The panels and supports in the deck are all the same thickness and the sections are all identical.]
[All calculations were performed for a critical hull panel span]
The deck side panels are inclined at 28.52° to the horizontal, it is assumed that the water pressure acts normal to the plate. The pressure varies from 45.2kN/m$^2$ at the bottom edge of the panel (4.5m depth) to 0kN/m$^2$ at the surface of the water. For the purposes of these calculations, it is assumed that a pressure of 45.2kN/m$^2$ acts over the whole panel, this gives a large degree of redundancy to the calculation, making the pontoon safer.

### Side panels, parallel to the trusses:

Sections supporting the side panels are placed between each of the support columns, creating a grid of supports. The largest unsupported span the deck panel must cover in this configuration is 7.07m (the distance between the central truss column and the next column along) x 4.6m (The distance, along the plane of the hull panel, between 2 adjacent trusses).
Equivalent point load for water pressure on panel = 45.2 x 7.07 x 4.60 = 1470kN

### Panel thickness and supports:

Calculations are carried out to find the required panel thickness and support sections to withstand this load, giving a panel thickness of 105mm and required sections of 220 x 220 x 10. The sections are deemed to be too large and so more supports are to be added to the design to decrease the size of the critical span.
Supports are added in order to half the span of the panel in both directions:




This gives new span dimensions of 3.353m x 2.3m
Equivalent point load for pressure on unsupported span = 45.2 x 2.3 x 3.535 = 367.5kN
3.535 / 2.3 = 1.5 therefore $k_1$ = 0.077

t = 55.22 there 60mm plate is selected

**Support calculations:**

The load on the plate is shared equally between the supports: 367.5/ 2(3.535 x 2.3) = 31.5kN/m
This value is multiplied by 2 as all support members contribute to supporting 2 panel spans.

**Bending:**

3.535m support: (2 x 31.5 x 3.535$^2$) / 12 = 65.6kNm
2.3m member: (2 x 31.5 x 2.3$^2$) / 12 = 27.8kNm

**Shear:**

3.535m support: (2 x 31.5 x 3.535) / 2 = 111.4kN
2.3m support: (2 x 31.5 x 2.3) / 2 = 72.5kN
The section is selected to support the critical member (3.535m)

Using an excel calculator, a 120 x 120 x 12.5 section was selected.

| Classification | |
|---|---|
| | |
| fy | 355 |
| C/t | 6.6 |
| | |
| class 1 | 58.58039 |
| class 2 | 67.53017 |
| class 3 | 100.8884 |
| | |
| section | class 1 |

| bending | | |
|---|---|---|
| | | |
| Med | 65.6 | kNm |
| Wpl | 207 | cm3 |
| YM0 | 1 | |
| | | |
| Mc,Rd | 73.485 | kNm |

| Shear | | |
|---|---|---|
| | | |
| Ved | 111.4 | kN |
| A | 42.9 | cm2 |
| b | 120 | mm |
| h | 120 | mm |
| $A_v$ | 2145 | $mm^2$ |
| | | |
| Vpl,Rd | 439.6 | kN |

120 x 120 x 12.5

# Structural Considerations and Design

## Loads

*Table 11: Load table*

| Material Name | Mass (kg) | Mass (T) |
|---|---|---|
| S355 Steel Longitudinal Support UB | 13574.40 | 13.57 |
| S355 Steel Truss UB | 102924.00 | 102.92 |
| S355 Steel UC | 54608.25 | 54.61 |
| S355 Square Hollow Deck Support | 98980.00 | 98.98 |
| S355 Square Hollow Section 2 | 819.00 | 0.82 |
| S355 Square Hollow Section 3 | 361.80 | 0.36 |
| S355 Square Hollow Section 4 | 387.44 | 0.39 |
| S355 Square Hollow Section 5 | 335.97 | 0.34 |
| S355 Square Hollow Section 6 | 496.60 | 0.50 |
| S355 Square Hollow Section 7 | 104432.02 | 104.43 |
| S355 Steel Grip Plate | 125560.75 | 125.56 |
| S355 Steel Plate | 251121.50 | 251.12 |
| S355 Steel Plate | 164065.00 | 164.07 |
| S355 Steel Plate | 59659.22 | 59.66 |
| Concrete Deck Panel | 1471540.00 | 1471.54 |
| Steel Hull Plate | 1620221.16 | 1620.22 |
| Steel Side panels | 31079.72 | 31.08 |
| ANSI 316 Steel Fender Cables | 28.32 | 0.028 |
| Pneumatic Fenders | 736.00 | 0.74 |
| Concrete Pile Foundations | 212434.50 | 212.43 |
| AISI 1045 Steel 390QT Cable | 38841.87 | 38.84 |
| Total | **4352207.49** | 4352.21 |

# Engineering drawings

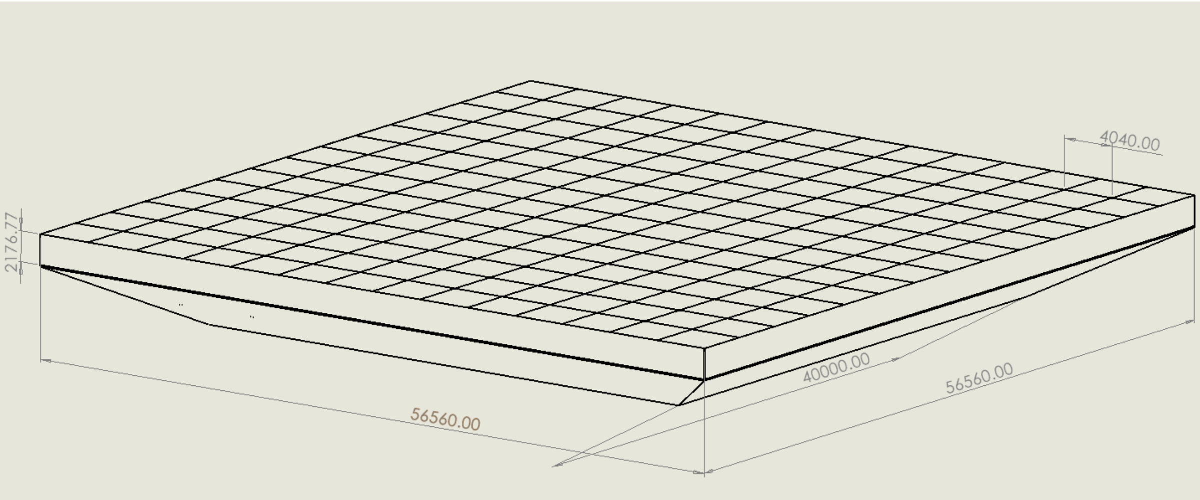



*Figure 25: Engineering drawing of the platform and hull structure (isometric)*

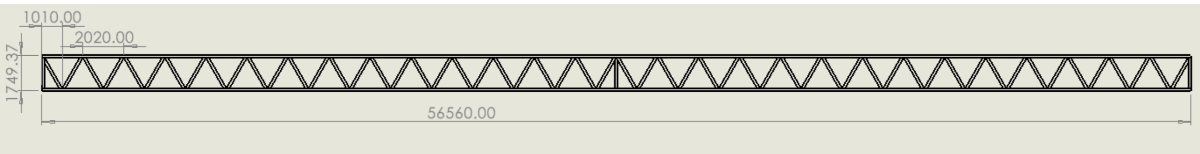



*Figure 26: Engineering drawing of truss used in the platform deck (side angle)*

## Justification for Design Decisions

The platform will weigh approximately 4352 tons, as per the analysis given in the project's business case, with only civil specific materials contributing to the total value. However, with all additional mechanical and electrical components, this value is likely to be larger, potentially close to 4500 tons. This calculated weight value is much too large for that of leisure boats and rather small for that of large cargo ships or other large ocean-going ships, but for the purpose of comparison the platform is to be compared to a cargo ship or similar. When fully loaded, a traditional cargo ship sits about two-thirds underwater [45], consequently, with an overall platform height of 6.25m, the estimation of 4.5m below the surface that has been used for this project produces a ratio not too dissimilar to a cargo ship.

Cargo ships enable a system called ballasting for emergency situations, providing better protection for the ship. Ballasting is the process by which the ship adjust its trim, or inclination, and therefore its stability by taking on or removing water from ballast tanks. These tanks are ship compartments designed to hold seawater or other liquids for the purpose given. Cargo ships are designed to undergo terrible weather conditions and extremely large waves; however the floating offshore energy island does not need to be designed for this as the sea conditions at the situated location are not as bad. Any bad weather events will be foreseen and actions can be taken. Instead of taking on or removing sea water, there would be an option of adding concrete or heavy natural rocks, to the hull in order for the platform to sit lower in the water. If this variable buoyancy system was implemented this would result in either a change in the platforms inclination or an increase in the depth below the water surface equally. This increases the protection of the platform if it were to be subject to more intense sea conditions, due to decreased buoyancy level provided by the hull with the additional weight.

## Foundation Design

The cables tethering the platforms to the bottom of the seabed require foundations to be anchored to restrict the movement of the platforms at the water's surface. Contrary to conventional foundations, these foundations will require to resist forces in the vertical upward direction. These forces come from the vertical uplift the platforms experience due to the effect of the waves.
From the wave analysis the critical uplift force is 7566.3 kN. This is the design load I designed the foundations to take. I decided to design a pile foundation to resist the vertical upward force based off the skin friction between the soil and pile surface. The safe skin friction capacity of the pile is determined by equation 1:

$$F_f = \frac{C_u \times A_s \times \alpha}{FOS}$$

*Equation 4: Safe skin friction capacity of a cylindrical pile*

Where Ff is the frictional resistance, Cu is the undrained shear strength of the soil, As is the active area of the side of the pile and $\alpha$ is a dimensionless parameter determined from Figure 27.

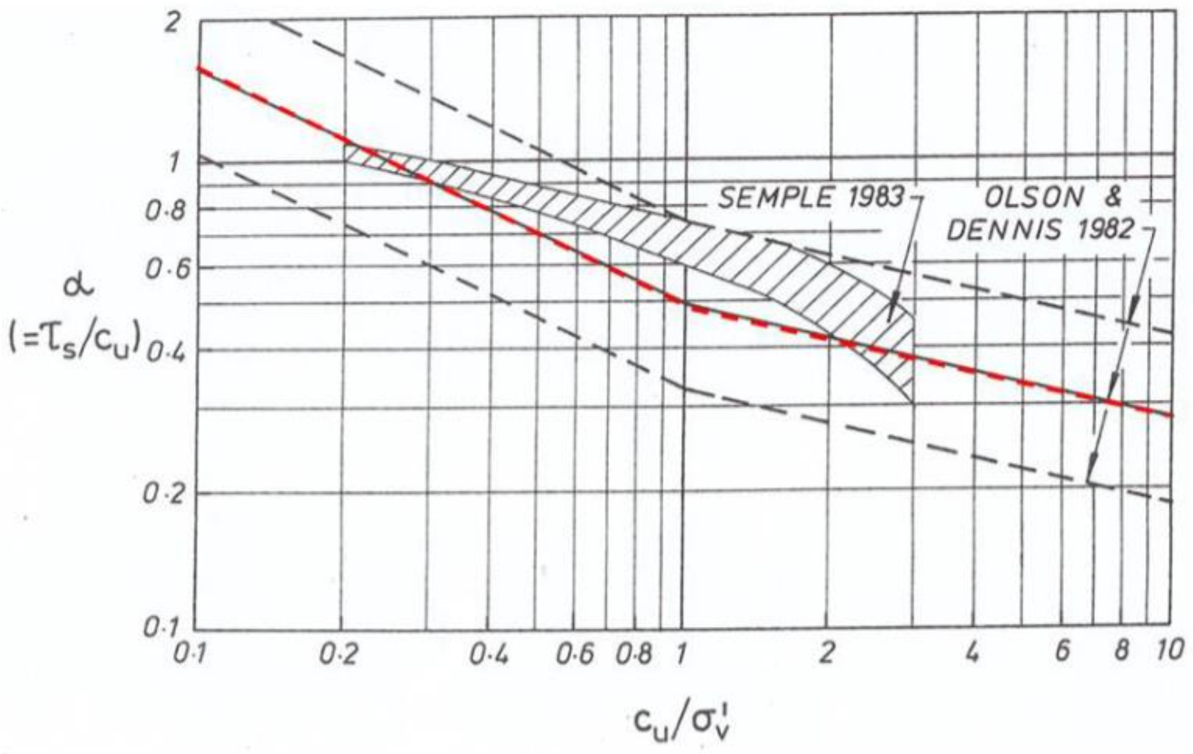



*Figure 27 - Graph to determine alpha*

As well as the skin friction resisting the upward force the water pressure above the foundation also resist it. Equation 5 details how to calculate the amount of force due to water pressure above the pile foundation:

$$F_p = \rho g h A_E$$

*Equation 5– Force on pile due to water pressure*

Where Fp is the force from water pressure, rho is the density of sea warer (1.025 kg/m3), h is the height of water above the foundation (70 m) and AE is the area of the end of the pile.

Combining equation 4 and 5:

$$F_T = F_f + F_p = \frac{C_u \times A_s \times \alpha}{FOS} + \rho g h A_E$$

*Equation 6– Total resistance of an underwater pile foundation to upward force*

Where FT is the total resistance to upwards force. Due to the nature of the sea floor the only way to accurately design foundations in our chosen location would be to carry out in situ testing to determine the undrained shear strength and unit weight of the soil the foundation will be built in. However this is not possible, and due to a lack of data available for the region we are working with I had to make assumptions based off of the most similar, readily available research.

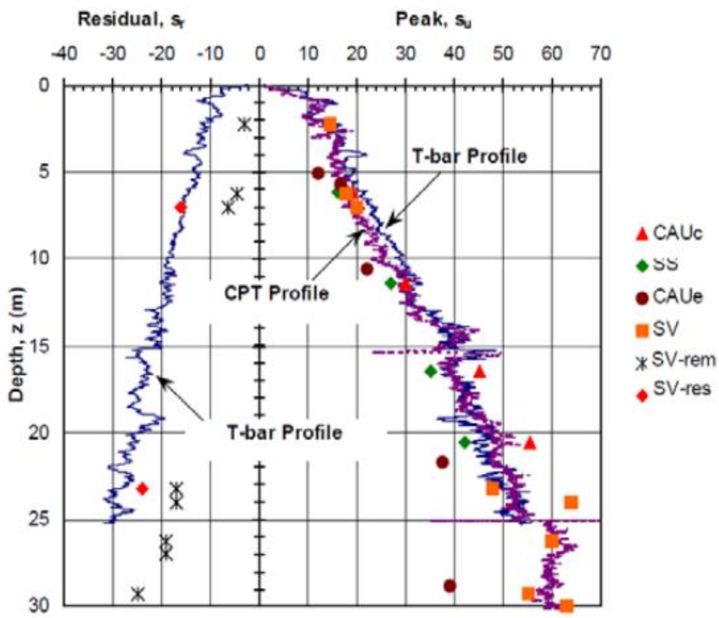



*Figure 28- Undrained shear strength of off-shore Australian soil*

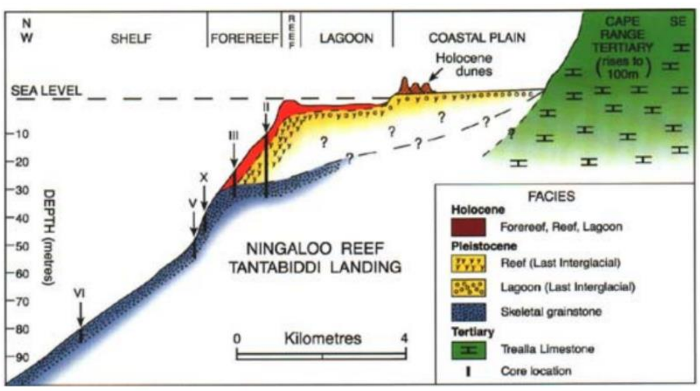



*Figure 29 - Typical soil profile of Australian sea bed*

Figure 28 is what was used to determine the shear strength off the soil in the bass strait. Figure 29 [46] shows that 30 metres below sea level is typically made up of skeletal grainstone. Skeletal grainstone is a type of carbonate rock and is essentially a coarse grained limestone. Limestone is a sedimentary rock and [] states a range of 16 kN/m3 – 35 kN/m3 for the saturated unit weight of rocks. It is more conservative to take a smaller value of unit weight and due to large assumptions being drawn I decided to work with a unit weight of 17 kN/m3 to be safe.

The design load of 7566.3 kN is shared across four foundations per platform so the actual design load is a quarter of the previously stated value (1891.6 kN).

Due to the nature of the sea floor I assume 2 metres of redundancy at the top of the pile that offers no resistance to skin friction. I also used a factor of safety of 2.5 for the foundation design.

The dimensions of each foundation are a length of 15 metres and a diameter of 1.4 metres.

$$A_s = \pi D(L-2) = \pi \times 1.4 \times (15-2) = 57.2\, m^2$$
$$A_E = \pi \frac{D^2}{4} = \pi \frac{1.4^2}{4} = 1.54\, m^2$$

The effective stress, σv', is the weight of the soil above the base of the foundation. This is equal to 15 m x 17 kN/m3 = 255 kN/m2. I took the Cu value for the soil at 7.5 m depth to achieve the average strength of the soil surrounding the pile. From figure 28 a depth of 7.5 m returns an undrained shear strength of 25 kPa. Cu/ σv' is therefore equal to 25/255 = 0.098 ≈ 0.1. From figure 27 a Cu/ σv' value of 0.1 returns an α value of 1.6. Inputting all of these value sinto equation 3:

$$F_T = \frac{C_u \times A_s \times \alpha}{FOS} + \rho g h A_E = \frac{25 \times 57.2 \times 1.6}{2.5} + (1.025 \times 9.8 \times 70 \times 1.54)$$
$$= 1997.3\, kN$$

1997.3 kN is greater than the design load of 1891.6 kN therefore the foundation is safe and capable of taking the critical load.

## Cable and Tension Calculations

As part of our design, we found it necessary to use steel cables for tethering the floating structure. These cables connected from our foundation piles in the seabed to the platform, as well as connecting platforms together. These cables can perform in unpredictable ways, especially in the water due to the complexity of the environment and how the structure they are connected to moves.

We designed our cables to abide by Eurocode 3 1993-1-11 as the Australian design standards were not available for educational use. As a result, we chose a spiral strand rope 1x19. This means there is a central steel cord, surrounded by a further 18 cords spiraling around the central cord. Furthermore, we used Equation 7 to calculate the minimum required diameter for withstanding a breaking force, where the breaking force was found using a summation of vertical forces and dividing by the number of proposed cables per structure.

$$D = \sqrt{\frac{\gamma F_{min} 1000}{R_r K}}$$

*Equation 7 - Diameter of a 1x19 cable given a minimum breaking force*

Where D is the diameter, $\gamma$ is a safety factor (1.25), $F_{min}$ is the minimum breaking force, $R_r$ is the grade of steel rope and K is the break force factor (taken from the appendix)
There are 2 different structural objectives of the cables, tethering to the seabed and tethering platforms together. Each of these was required to be analyzed separately to ensure they could perform their task safely and efficiently.

Tethering to the seabed required the strongest of the two types of cables, due to the significantly larger forces induced. As a result, the cables were made from a much stronger material – AISI 1045 Steel 390QT. This material's tensile strength and yield strength are much higher than typical steel (I.e., 316L Stainless steel), making it the ideal choice where these much larger forces were employed. This greater strength material also reduced the need for more cables where there was already a large number. Additionally, the diameter of these cables was larger than the cables tethering platforms together. In order to produce a satisfactory response to the loads without inducing unsafe deflections, 9 cables were placed at each corner of the platform, each with a diameter of 50 mm (in total as the cable used was a spiral strand of 1x19). Each 50 mm cable has a minimum breaking force of 1650 kN which is sufficient, as this means each corner can safely withstand nearly 15,000 kN which provides a safety factor of approximately 2 against possible critical loads.

The inter-platform connections require a smaller cable as the forces they are required to withstand are much less than the forces of the cables tethered to the seabed. From the analysis of wave data around the region the design value for the horizontal force exerted on the pontoon due to the waves is 303.3 kN. However, this doesn't account for the effects of the wind. I used Equation 2, along with information from the wind analysis to calculate the design load due to the horizontal force exerted on the platform from the wind.

$$F = \frac{1}{2}\rho v A C_D$$

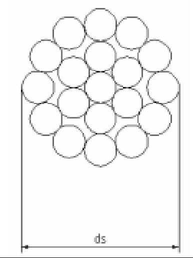
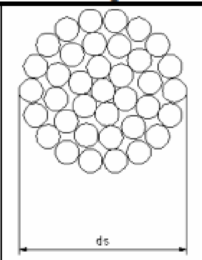
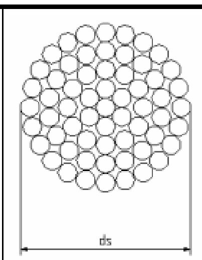
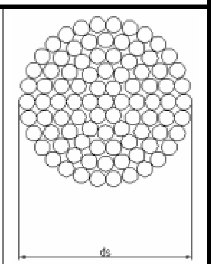
*Equation 2 – Force exerted by a gust of wind*

Where ρ is the density of air (1.2754 kg/m3), v is the wind speed (180 km/hr = 50m/s), A is the area the wind acts on, and $C_D$ is the drag coefficient of the platform.

*F = 0.5 x 1.2754 x 50 x 113.12 x 1 = 3.6 kN*

Combining the load from the wind and wave (3.6 kN and 303.3 KN) gives 306.9 kN which is the design load of the inter-platform cables. Figure 1 is from 1x19 Marine Grade Stainless Steel Wire Rope | Marine Grade and provides the break force factor (0.525) for the 1x19 steel cables.

*Figure 30*

| Spiral strand rope | | | | |
|---|---|---|---|---|
| |  |  |  |  |
| Construction | 1 × 19 | 1 × 37 | 1 × 61 | 1 × 91 |
| Diameter $d_s$ [mm] | 3 to 14 | 6 to 36 | 20 to 40 | 30 to 52 |
| Strand | 1 | 1 | 1 | 1 |
| Wire per strand | 19 | 37 | 61 | 91 |
| Outer wire per strand | 12 | 18 | 24 | 30 |
| Nominal metallic area factor *C* | 0,6 | 0,59 | 0,58 | 0,58 |
| Breaking force factor *K* | 0,525 | 0,52 | 0,51 | 0,51 |

The grade of steel rope for these specific cables is 1570 MPa which is the industry standard for marine grade steel cables. Inputting these values into equation one gives the minimum diameter of the cable required to take the design load of 306.9 kN.

$$D = \sqrt{\frac{1.25 \times 306.9 \times 1000}{1570 \times 0.525}} = 21.57\, mm$$

Therefore, a cable of 22 mm is required for the inter-platform connections. These cables are required to stop the platforms from drifting from each other and are therefore designed to withstand the tensile forces discussed earlier. However, they offer no resistance under compression. Platforms will displace in the water due to tidal forces and the effects of the wind, so measures were required to stop platforms colliding into each other when the cables won't be effective. As a result, we chose to make use of fenders. Fenders are commonly used in the marine industry to absorb large compressive forces, for example a boat knocking into the dock. It is highly unlikely any platforms will come into contact with each other due to the extensive cable tethering. However, the use of fenders is a preventative measure to minimize any damage the platforms may suffer due to a collision.

*Table 12 - Performance of P80 Pneumatic Fender Standard Sizes*

| Nominal Size Diameter x Length | Initial Internal Pressure | Guaranteed Energy Absorption (GEA) | Reaction Force at GEA | Hull Pressure at GEA | Safety Valve Setting | Testing Pressure |
|---|---|---|---|---|---|---|
| (mm x mm ) | (kPa) | ( kNm) | (kN) | (kPa) | (kPa) | (kPa) |
| 500 x 1000 | 80 | 8 | 85 | 174 | . | 250 |
| 1000 x 2000 | 80 | 63 | 338 | 174 | . | 250 |
| 2500 x 4000 | 80 | 925 | 1815 | 180 | 230 | 300 |
| 3300 x 10600 | 80 | 4281 | 6907 | 208 | 230 | 300 |
| 4500 x 12000 | 80 | 9037 | 10490 | 202 | 230 | 300 |

Table 1 collates the parameters of different sized pneumatic fenders. The 1 m x 2 m fenders have a guaranteed energy absorption (GEA) of 338 kN which is in excess of the design load for horizontal forces acting on the platform. On top of this the fenders will be placed around the corners of the platform uniformly; therefore, platforms would be colliding fender to fender so the max combined reaction force of the two fenders colliding would be 676 kN. Each fender has a mass of 92 kg and there would be two placed at each corner of the pontoon.

## Deflection Testing

In order to ensure the cable design performs safely even under the most critical loading conditions, a simulation was performed to check how the design reacted. This simulation was performed in Fusion 360 using the built-in finite element analysis software.

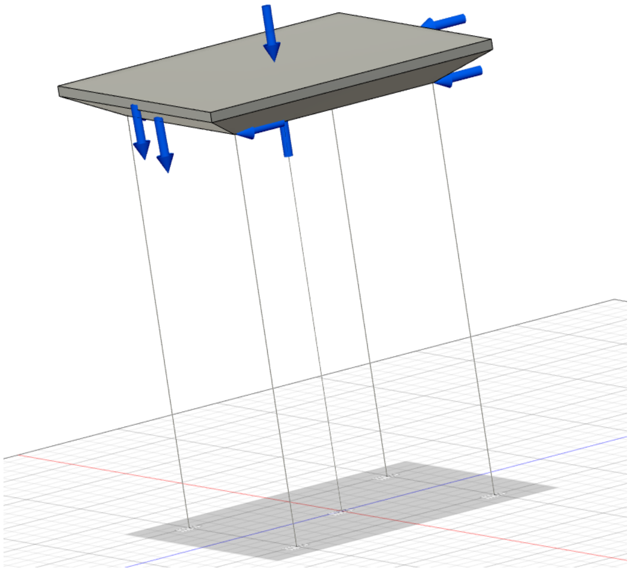


*Figure 31 - Load configuration*

The forces were applied to the points in the model which they would most likely act upon. This included things such as the wave force on the cable being applied only at the top, as per the wave analysis. The above figure shows where the forces acted on the model and the load table mentioned earlier shows the magnitude and direction of loading. It is important to note that these are the most critical values calculated in our analysis, which occur when the structure interacts with the wave at wave position 1, as shown in the wave analysis. Additionally, these values have also all been factored in accordance with DNV load combinations as stated earlier. Furthermore, these loads have been simplified in their distributions, due to the complexity of simulating cables. As a result, some values may not be perfectly accurate, however, they should be a relatively suitable reflection on reality.

The method was set up according to all preceding analysis. This includes the platform's dimensions (56.56x56.56 m for the top 1.74 m then tapering down to 40x40 m over 4.5 m) and the cable's dimensions 0.05 m each. Due to issues with such a small cable being used, the initial idea of using 9 of these on each corner was simplified into a single 0.15 m cable on each corner. This allows for the same area of steel to be stressed, producing a result which should be relatively similar. In order to produce a value for the displacement, the bottom face of the cables were fixed against all motion, while the face of the cable connecting to the platform is assumed to be pinned. The cables were assumed to be 70 m long due to the depth of water in the region, in reality this would be adjusted to ensure all cables maintain tension to provide the most effective support against rotational movement. The platform was allowed to move freely, with the only constraints being caused by the attached tethering cables. Finally, the materials used are as described in the relevant design sections.

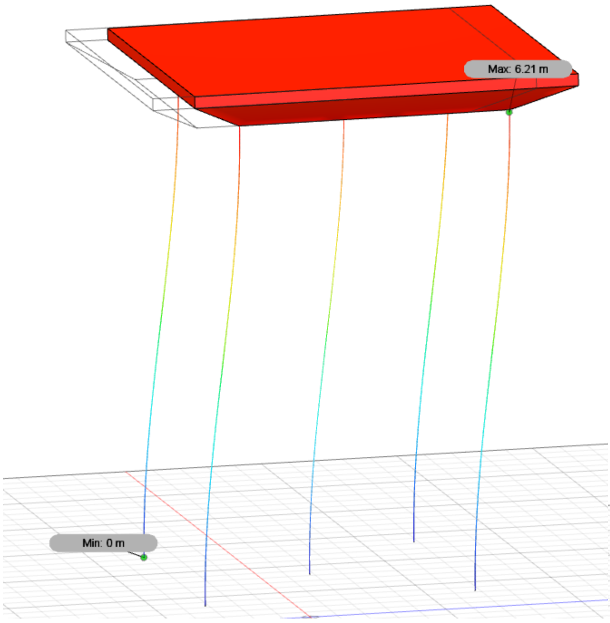



Figure 32 - Horizontal displacement

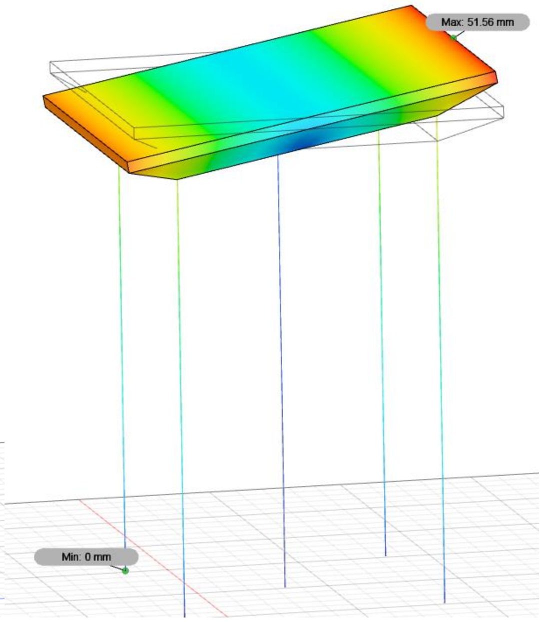



Figure 33 - Rotational displacement

The results above show the displacement of the platform both rotationally and horizontally and are adjusted to provide an enhanced view of the displacement. Due to the nature of the tethering system, the vertical displacement is negligible. The areas of greatest displacement are shown by the red in the figures above. These values are in line with what you would expect a structure of this size to move by due to the extreme weather events. This simulation shows the worst case possible, and these displacements would be very unlikely in normal daily operation. However, as our platform does not have workers on it full time, only the occasional maintenance worker, these displacements should not be an issue.

The design could be further improved to reduce the horizontal displacements induced by extreme weather conditions. This could be done in a number of ways, such as: increasing the number of tethers, increasing the size of the tethers, using a stronger material and tethering the platform to other fixed objects (i.e., a fixed wind turbine). Furthermore, the design is intended to be able to tether to other platforms to increase stability, however, as they are designed to be modular, it is important for individual platforms to be able to withstand the forces they may receive.

The simulation has some limitations which make it less accurate than it could be, however due to the software, these limitations cannot be avoided. These include not being able to simulate the correct size of cable and having to use an equivalent area, not being able to distribute forces according to an equation and not showing what could have caused failure in the designs leading up to the final iteration. Finally, it was assumed that there was some drag force acting in the opposite direction to the main horizontal loads (i.e., wind and wave). This would have been caused by the relative velocity increase as the forces applied cause the platform to move through the ocean. Additionally, it would have been proportional to the relative velocity This reduces the effect of the environmental loads, hence reducing the displacement induced.

## Manufacturing and Construction

Most of the manufacturing stages for this offshore energy island will take place onshore, somewhere along the coast, and as close to the final location as possible. The individual components will be manufactured on land, potentially in various locations, and once they are ready can be either shipped or towed out to sea. Some construction will be able to take place on land such as the floating pontoons which will be able to be towed out to sea easily one constructed.


*Figure 34: location of the Star of the South wind farm*

Figure 25 shows the location of the Star of the South windfarm. To reduce the carbon footprint of the project and increase efficiency, cost, and time, the components will be manufactured and assembled in a shipyard on the Southeast coast as close to the location of the offshore energy island as possible. Since the island is being installed during the manufacture and installation of the wind turbines of the Star of the South, construction and towing equipment can be reused and may be used to carry multiple components in one trip, reducing the carbon footprint of each journey.

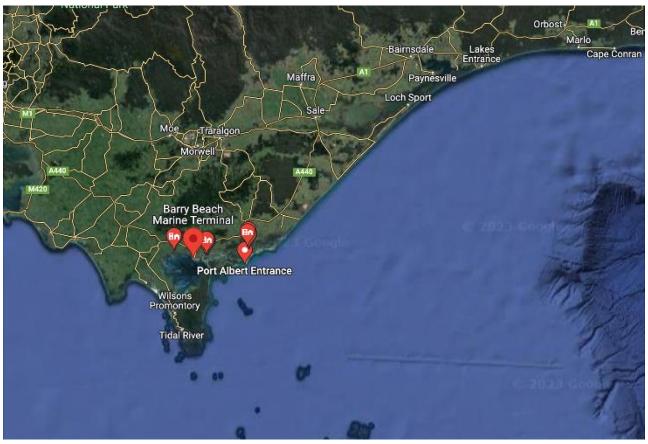



*Figure 35: Location of proposed manufacture location (Port Albert)*

Figure 26 above shows the proposed location for manufacture of the platforms. This location is near Port Albert which will allow the components to be fastened and towed to the final location from here.

## Health and Safety

Any offshore structure is going to come with many complicated health and safety risks. Here are some of the main hazards associated with this offshore energy island and some of the precautions that have been taken and will be taken to mitigate the risks.

With around 70 m of sea sitting just below the platform, it is vital that workers are safe on the island and there is no chance of them falling overboard and drowning. Barriers and caution signs will be put in place and life jackets will be provided to everyone who enters the island.

Heavy operating machinery is a large part of the island which, if left in the wrong hands, could become a major health and safety risk. All workers will be properly trained and educated on the use and maintenance of all equipment aboard the island. There will also be implementation of strict safety protocols and procedures.

Although design measures have been put in place to minimise water landing on the pontoons as much as possible, it is inevitable that during particularly harsh environmental conditions the surface of the structure could become slippery. To account for this, the walkways have been designed in a corrugated fashion to increase the friction under the workers feet. Workers will be educated on how to move around the structure in the safest possible manner.

Electrical systems in offshore energy structures can be a source of hazard if not installed, maintained, or used correctly. Therefore, the appropriate protective materials have been used surrounding the cables and other sources of electricity. Workers will be informed of the location of these systems and the safest way to interact with them. Caution signs can be used as an additional reminder.

Harsh environmental conditions can cause structural damage or failure which can lead to catastrophic accidents. All aspects of the structure have been designed to withstand the worst-case scenarios, so in theory it should be able to last the entire working life without failure. Regular maintenance checks will take place on the island to make sure everything is in working order and if any parts are sub-standard, they will be replaced or repaired.

The island could potentially pose health hazards to workers who spend copious amounts of time there. For example, loud noises and high temperatures from machines could potentially have a negative impact on workers. Noise and temperature levels will be monitored regularly to ensure they don’t reach extreme and harmful levels. All workers must wear personal protective equipment (PPE) to protect themselves and limit their exposure to dangerous situations.

Enforcing health and safety regulations remains the most important objective when considering all features of the offshore energy island and will be continuously implemented throughout the lifetime of the island.

# Sustainability

## Causal Maps for SDG 7 and 11

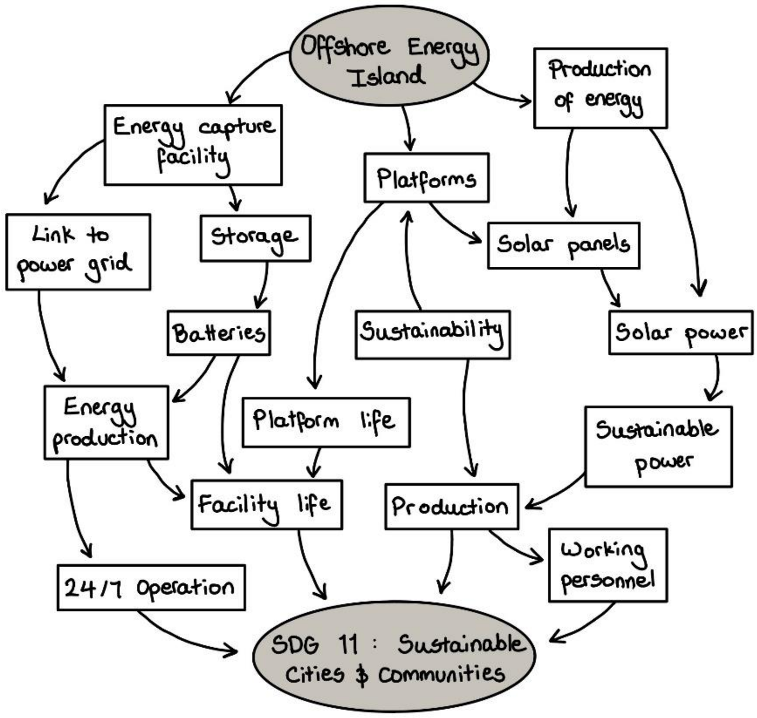



*Figure 36: Causal map for SDG7*

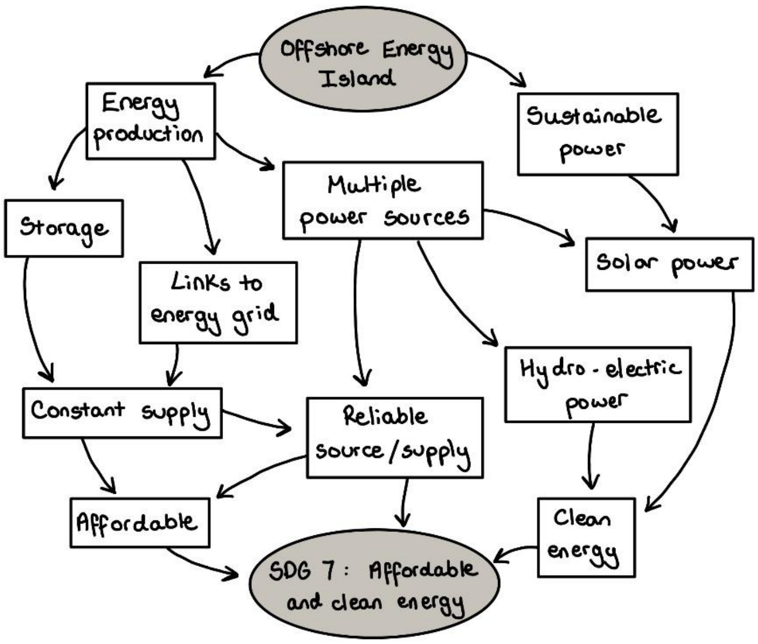



*Figure 37: Causal map for SDG11*

*Table 13: Tackling Sustainable Development Goals*

| Sustainable Development Goals | How can this offshore energy island help tackle SDGs? |
|---|---|
| GOAL 1: No Poverty | Improves access to affordable and sustainable energy.<br>Provides jobs in construction and maintenance. |
| GOAL 2: Zero Hunger | Provides jobs so people can provide for themselves and their families. |
| GOAL 3: Good Health and Well-being | More accessible energy for all homes and hospitals to shelter and look after people. |
| GOAL 4: Quality Education | Schools will have access to sustainable energy to provide power for the best education technology. |
| GOAL 5: Gender Equality | Equal job opportunities for all genders. |
| GOAL 6: Clean Water and Sanitation | Provides energy to sanitation works. |
| GOAL 7: Affordable and Clean Energy | Concept is easy to reproduce and as more islands are built like it, the energy produced should become more affordable. |
| GOAL 8: Decent Work and Economic Growth | Creates jobs in construction and operation.<br>Reduces energy costs. |
| GOAL 9: Industry, Innovation, and Infrastructure | Reduces need for inland energy production and frees up space for other uses. |
| GOAL 10: Reduced Inequality | Makes energy more accessible for everybody, particularly low-income households. |
| GOAL 11: Sustainable Cities and Communities | Will provide energy to cities in a sustainable manner. |
| GOAL 12: Responsible Consumption and Production | Reduces consumption of energy from fossil fuels.<br>Industries and supply chains can run on sustainable and responsible practices. |
| GOAL 13: Climate Action | Provides a source of renewable energy to replace fossil fuels. |
| GOAL 14: Life Below Water | The island will have minimal impact on life below water. |
| GOAL 15: Life on Land | Offshore so does not impact ecosystems on land directly. Reduces air and water pollution which benefits humans and animals on land.<br>Construction could have a negative impact to life on land. |
| GOAL 16: Peace and Justice Strong Institutions | Provides a renewable energy source that is not associated with geopolitical tensions connected to the use of fossil fuels. |
| GOAL 17: Partnerships to achieve the Goal | Partnerships with TNCs will be formed to complete the construction and installation. Furthermore, partnerships with regional government and local council will be established to ensure clean energy for the surrounding area. |

*Table 14: Environmental Impacts on our Project*

| Environment Impacts | Impact |
|---|---|
| Land | Positive:<br>Takes up less space on land to allow for ecosystems to thrive.<br>Negative:<br>Construction will take place on land which could be noisy and disruptive. |
| Water Demand | Positive:<br>No water is used in the renewable energy generating methods.<br>Negative:<br>Some materials used in the construction will require water. |
| Water Supply | Positive:<br>An influx of renewable energy encourages investment and opportunity in water sanitation and infrastructure. |
| Emissions and Waste | Positive:<br>Once in operation, the island will produce zero greenhouse gases.<br>Negative:<br>Construction could produce some greenhouse gases. |
| Biodiversity | Positive:<br>Decreases fossil fuel use which reduces air and water pollution.<br>Negative:<br>Could disturb marine life. |
| Material Consumption | Positive:<br>Renewable and waste materials will be used in the construction of the island where possible.<br>Negative:<br>The project uses a large amount of steel and concrete which are reliable building materials. |
| Electricity Generation | Positive:<br>All electricity generation will be from a renewable source. |
| Energy Consumption | Positive:<br>The project will be Carbon neutral/positive after a duration of time. The energy consumed in material construction and transport will be offset by renewable energy.<br>Negative:<br>Manufacturing processes and initial installation require large amounts of energy. |

Table 15: Societal Impacts on our Project

| Societal Impacts | Impact |
|---|---|
| Fertility | The project will have no bearing on fertility societal impact |
| Population | The project will have no bearing on population societal impact |
| Mortality | The project will have no bearing on mortality societal impact |
| Health | Positive:<br>Renewable energy reduces the use of unconventional energy generation methods which can often negatively impact the air quality in the surrounding area |
| Education | Positive:<br>Education relating to renewable energy and sustainability is encouraged through the project and media surrounding it |
| Vehicles | Positive:<br>Reliability of renewable energy will encourage the use and policy of electric vehicles in the local and regional area<br>Negative:<br>May restrict area for shipping routes |
| Employment | Positive:<br>The project is large scale and supports local businesses in construction, materials and management. Longer term employment opportunities in maintenance and monitoring are created |
| Income Distribution | Positive:<br>Large scale projects provide a positive multiplier effect to the local and regional economy by providing employment, inviting opportunity for further industry and reducing the cost of energy |
| Poverty | Positive:<br>Energy poverty is reduced due to the surplus of renewable energy. This will reduce strain on conventional energy supply and lessen the average cost of energy for the public<br>Employment opportunities and secondary investment will contribute to the development of the surrounding area.<br>Negative:<br>The only poverty metric affected is energy poverty |

## Eco Audit

In the design stage and material selection process, a conscious effort was made to pick appropriate materials to reduce the energy consumption and $CO_2$ footprint of the offshore energy island as much as possible. It was important that each component part should be made from a large proportion of recycled material, and at the end of the islands life all materials should be recycled or reused to avoid landfill.
CES Edupack has been used to evaluate and analyse the environmental impact of the project.

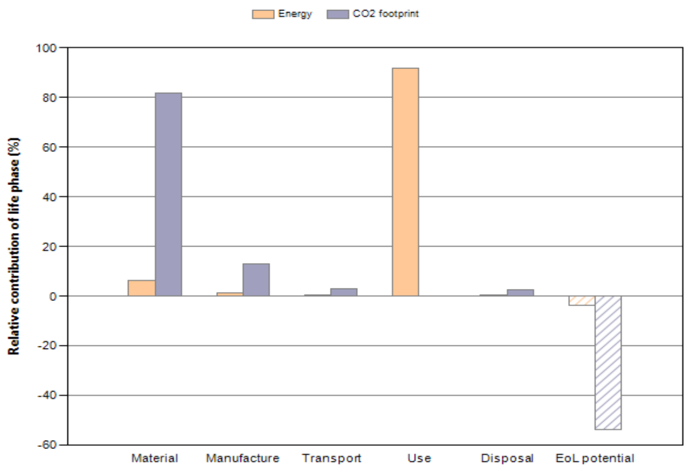



*Figure 38– Eco Audit Graph, energy consumption and CO2 footprint of one pontoon (CES Edupack)*

*Table 16– Numerical Summary of Figure X (CES Edupack)*

| Phase | Energy (MJ) | Energy (%) | CO2 footprint (kg) | CO2 footprint (%) |
|---|---|---|---|---|
| Material | 2.15e+08 | 6.3 | 2.19e+07 | 81.6 |
| Manufacture | 4.63e+07 | 1.3 | 3.47e+06 | 13.0 |
| Transport | 1.06e+07 | 0.3 | 7.6e+05 | 2.8 |
| Use | 3.15e+09 | 91.8 | 0 | 0.0 |
| Disposal | 9.87e+06 | 0.3 | 6.91e+05 | 2.6 |
| Total (for first life) | 3.44e+09 | 100 | 2.68e+07 | 100 |
| End of life potential | -1.2e+08 | | -1.44e+07 | |

Energy is consumed mostly during the 'use' phase of the island's life (Figure 35). While this seems like a bad thing, the energy consumed by the island to run itself will all be from the renewable energy that is being generated. On top of this, the energy consumed by the island is only a very small fraction of the energy that is hoped to be produced by the island in total.

The total $CO_2$ footprint for the first life of one pontoon is $2.68 \times 10^7$ kg (Table 16). The end-of-life potential offsets this by $-1.44 \times 10^7$ kg giving a total of $1.24 \times 10^7$ kg $CO_2$. Although this is still contributing to the levels of greenhouse gases in the atmosphere, the aim is for the island to be carbon neutral. Table X shows that ideally the island will not produce any $CO_2$ at all during the 'use' phase of life, which is far less than any fossil fuel production. In the long run, the island should become neutral as production of fossil fuels die down.

# Cost and Business Plan

## PEST Analysis

This PEST analysis will investigate the political, economic, social, and technological factors a business would experience. This analysis will apply these factors to the offshore energy island designed and developed throughout the report above.

*Table 17 - PEST explanation*

| Factor Type | Explanation |
|---|---|
| Political | Political factors are influenced mainly by the governments and governing bodies of the country the business is situated, in this case that is Australia. The field the business is in, in this case the energy sector, can also have an influence on the business in a political manner. The Australian government however has overall control on the standards and financial constraints the business will face. |
| Economic | Governments and the wealth of the state have the largest influence on the economic factors of the business. Factors include, investment levels, impact of globalization, state of the business cycle and the cost of technology. |
| Social | Social factors directly affect the spending patterns of the public along with affecting the public themselves. Some of the factors affecting them are lifestyle choices and attitudes, age distribution, rate of population growth, major events and intrinsic cultural barriers and branding and technology image. |
| Technological | Technological factors refer to how new practices and equipment can affect businesses. In this case, the offshore energy island contains multiple technological innovations, and this positively affects business. Factors could include technological awareness, incentives for innovation, cost of the technological advancements, levels of additional research, application outside of the laboratory and levels of innovation. |

*Table 18– PEST Analysis*

| Factor Type | Factor |
|---|---|
| Political | As per the Paris agreement, Australia must submit their reduction in emissions after committing to the agreement. They have committed to reducing their emission levels to 30% below their 2005 levels by 2030. With companies dedicated to offshore power in Australia and globally alongside the Australian government, this shows the commitment to reaching their goal.<br><br>Despite how new technology or ideas are surrounding offshore energy islands, no one objects to them due to the benefits they bring. Funding will come from private partners combined with the government due to the goals they are required to meet.<br><br>All employees in Australia are protected by their laws, mainly their employee standards legislation. With employees necessary for the maintenance and oversight of the platform, these laws will need to be followed closely. |
| Economic | There is money available for further research into offshore energy harnessing facilities, with a national GDP growth of 2.2% in recent years. This further research could advance or expand the current design of the offshore energy island.<br><br>This project will likely be partly funded by taxpayers' money, due to the government having a strong positive stance on the outcome of the productivity of the energy island. Energy prices could be seen to fall dependent on the overall power harnessed.<br><br>Global production of greenhouse gases has increased due to globalization so an economically beneficial solution must be found. The energy island will provide power so that it does not need to be generated by the burning of an excessive amount of fossil fuels.<br><br>There is a slight unknown when it comes to the overall cost of an offshore energy island as there are not many produced and working. There is potential for damage during storms or unforeseen damaged that costs more than first expected, perhaps making the whole project not economically viable and requiring the government to step in in order to continue to aid sustainability at extra cost. Other sustainable options may end up being of a cheaper cost. |

| | |
|---|---|
| Social | Australia has a small population growth of only 0.1%. This population growth means the overall CO2 production should not increase drastically due to this. As a result, offshore energy production will be benefitting Australia's carbon footprint rather than just mitigated any steady increases due to a rising population level.<br><br>Attitudes and lifestyle choices can impact energy usage greatly, and consequently affect the usefulness of the energy island. With high production occurring in summer due to the increased sunlight, the overflow of energy must be stored outside of the power grid as it is needed more during the winter months when production is at a low.<br><br>Globally, environmental sciences is a fast growing field, with more learnt and applied to projects like this every year. Employment rates are increasing with this sector and this project will contribute to this.<br><br>Australia is ranked 6th in the world on the Renewable Energy Country Attractiveness Index for renewable energy investment and deployment opportunities. |
| Technological | Australia is ranked 25th on the global innovation ranking with a high score of 47 points, placing it above Italy, Spain and the United Arab Emirates. This level of innovation is essential to the location choice system of a project such as this. With new technology in the energy island and the fact it is located offshore<br><br>With sustainable practices in general being very expensive due to the cost of the technology involved, the overall cost of the project is not too significant with large scale alternatives still requiring private partners and the Australian government to help fund operations and construction. |

The business type is a partnership, where the offshore energy island has more than one owner and those owners are known as partners. The partners have a responsibility to ensure the business runs smoothly and that energy production is kept at optimal efficiency with all energy produced being either used or stored. There is an obvious advantage to this as there is a higher availability of skills and experience within the partners alongside an increase in capital for the business. For an energy island that is not located on land but rather a floating pontoon, the increased capital will pay dividends ensuring the construction is done properly and energy can be sourced at full availability.

The partnership will act to run a manufacturing business, due to the primary aim of energy production. The business will own or finance a large amount of physical assets such as the platform, underwater piping, or machinery. Despite the floating nature of the offshore energy island, it will remain in a fixed location due to the mooring. The platform will have a very large initial outlay, due to the 325 solar panels located on each platform.

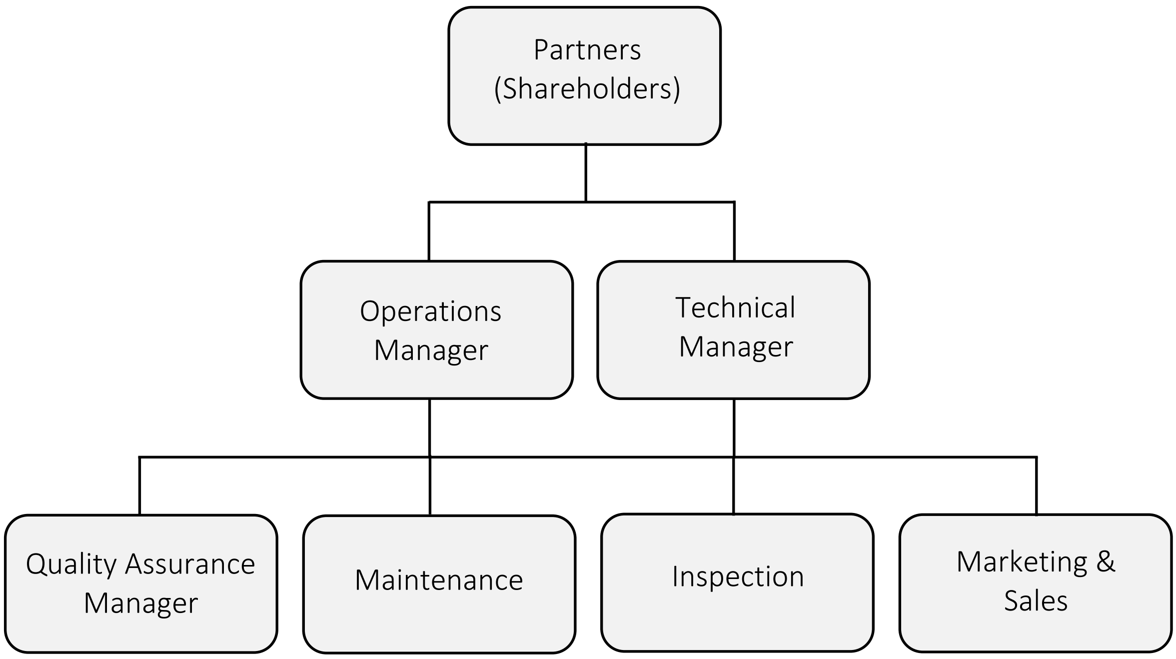



*Figure 39 - Functional organizational structure*

A functional organizational structure, as depicted in Figure 39, is a great tool for laying an insight into the working of the business at hand. The energy island will need at least 2 tiers beneath that of the partners, with an operations and technical manager essentially running the platform. There will need to be quality assurance along with an inspection team to ensure all machinery meets the appropriate standards along with health and safety regulations. All machinery, including the solar panels and piping along with the pontoon itself, will need regular maintenance, replacing parts if it is deemed necessary. The final team shown in this functional organizational structure is the marketing and sales team, this team will focus solely on the end customer of the produced energy working closely with the Australian national grid.

*Table 19 – Material details*

| No. | Material Name | Size Description | Member Length / Area |
|---|---|---|---|
| 1 | S355 Steel Longitudinal Support UB | 152 x 89 x 16 | 848.4 m |
| 2 | S355 Steel Truss UB | 203 x 133 x 30 | 3430.8 m |
| 3 | S355 Steel UC | 203 x 203 x 127 | 428.3 m |
| 4 | S355 Square Hollow Deck Support | 60 x 60 x 8 | 7918.4 m |
| 5 | S355 Square Hollow Section 2 | 100 x 100 x 6.3 | 45.0 m |
| 6 | S355 Square Hollow Section 3 | 90 x 90 x 8 | 18.0 m |
| 7 | S355 Square Hollow Section 4 | 50 x 50 x 5 | 56.56 m |
| 8 | S355 Square Hollow Section 5 | 50 x50 x 3.2 | 72.72 m |
| 9 | S355 Square Hollow Section 6 | 40 x 40 x 4 | 113.12 m |
| 10 | S355 Square Hollow Section 7 | 120 x 120 x 12.5 | 2553.35 m |
| 11 | S355 Steel Grip Plate | 5mm thickness | ~ 3199 $m^2$ |
| 12 | S355 Steel Plate | 10mm thickness | ~ 3199 $m^2$ |
| 13 | S355 Steel Plate | 25mm thickness | 836 $m^2$ |
| 14 | S355 Steel Plate | 30mm thickness | 253.33 $m^2$ |
| 15 | Concrete Deck Panel | 200mm thickness | ~ 3199 $m^2$ |
| 16 | Steel Hull Plate | 60mm thickness | ~ 3440 $m^2$ |
| 17 | Steel Side panels | 10mm thickness | ~ 396 $m^2$ |
| 18 | ANSI 316 Steel Fender Cables | 22mm 1x19 cable | 12 m |
| 19 | Pneumatic Fenders | P80 | 8 Fenders |
| 20 | Concrete Pile Foundations | 1.4m diameter | 60 m |
| 21 | AISI 1045 Steel 390QT Cable | 0.05m diameter | 2520 m |

The 5mm thick steel grip plate along with the 10mm steel plate and concrete deck panels are placed over a substantial area, the entire deck, and consequently are likely to be very costly to the platform's overall cost. The same can be seen with the steel truss universal beams and the hot finished square hollow deck support beams, positioned over distances of 3.4km and 7.9km respectively.

Many of the square hollow sections, along with the fender system, are small, light and the design does not include a large distance of them. Section 3 has only 18m of it used, this will therefore not contribute a lot to either the offshore energy island's weight or its overall cost.

*Table 20 – Estimated material cost*

| No. | Mass per Length ($kgm^{-1}$) | Density ($kgm^{-3}$) | Mass (kg) | Cost per kg (£$kg^{-1}$) | Cost (£) |
|---|---|---|---|---|---|
| 1 | 16.0 | - | 13574.40 | 0.50 | 6787.20 |
| 2 | 30.0 | - | 102924.00 | 0.50 | 51462.00 |
| 3 | 127.5 | - | 54608.25 | 0.50 | 27304.13 |
| 4 | 12.5 | - | 98980.00 | 0.50 | 49490.00 |
| 5 | 18.2 | - | 819.00 | 0.5 | 409.50 |
| 6 | 20.1 | - | 361.80 | 0.5 | 180.90 |
| 7 | 6.85 | - | 387.44 | 0.5 | 193.72 |
| 8 | 4.62 | - | 335.97 | 0.5 | 167.98 |
| 9 | 4.39 | - | 496.60 | 0.5 | 248.30 |
| 10 | 40.9 | - | 104432.02 | 0.5 | 52216.01 |
| 11 | - | 7850 | 125560.75 | 0.50 | 62780.38 |
| 12 | - | 7850 | 251121.50 | 0.50 | 125560.75 |
| 13 | - | 7850 | 164065.00 | 0.50 | 82032.50 |
| 14 | - | 7850 | 59659.22 | 0.50 | 29829.61 |
| 15 | - | 2300 | 1471540.00 | 0.05 | 73577.00 |
| 16 | - | 7850 | 1620221.16 | 0.50 | 810110.58 |
| 17 | - | 7850 | 31079.72 | 0.50 | 15539.86 |
| 18 | 2.36 | - | 28.32 | 0.50 | 14.16 |
| 19 | - | 92 each | 736.00 | 1.35 | 993.60 |
| 20 | - | 2300 | 212434.50 | 0.05 | 10621.72 |
| 21 | - | 7850 | 38841.87 | 0.50 | 19420.94 |
| Total | | | **4352207.49** | | **1418940.82** |

The total cost of all the materials used in order to produce the offshore energy island is approximately £1.42 million. The largest contributor to the cost of the materials is the S355 steel plate used for the platforms hull with a thickness of 60mm, mainly due to the fact that this material is used over a large surface area in excess of 3400$m^2$. A large proportion of the material weight is attributed to the concrete deck panels. These panels contribute 35.5% of the total platform weight, however, they only contribute 5.2% of the total platform material cost. Concrete is only 10% of the price to source when compared to steel, only £0.05 as opposed to £0.50 [] , clearly showing why this is the case.

# Management

## Identifying Challenges and Tasks

To ensure a design which satisfied all criteria set out by the project goals and team limitations, the project was broken down into tasks and a list of challenges were identified. This allowed for a more manageable workload where interfaces were easily recognised.
Three major areas of workload were identified at the beginning of the project; ‘structural considerations and design’, ‘tethering and connections’ and ‘other’ which consisted of further considerations such as sustainability, construction methods and eco-auditing.

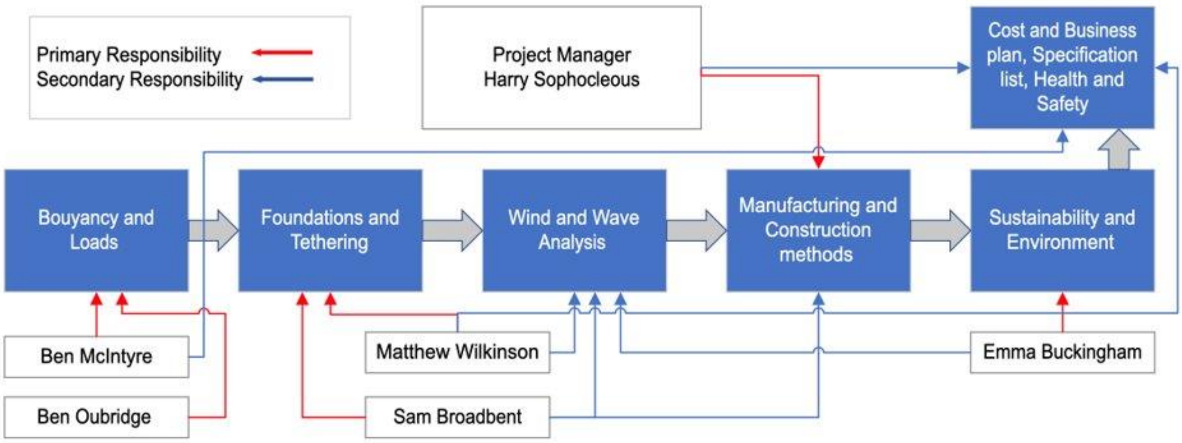



*Figure 40: Group management structure showing Primary and Secondary responsibilities*

Figure 40 above represents the management structure and distribution of tasks within the team. Using a primary and secondary responsibility system, tasks are easily divided and can be overlooked by at least two members of the group to avoid errors.

## File and information management

Microsoft teams was used as the main framework for sharing and storing important files. Shared documents can be accessed by all members of the group and edited with timestamps showing recent alterations to documents. Using a system such as teams mitigates the risk of losing files and allows all members to work on a shared file simultaneously, reducing the need to manage a large influx of files.

## Meeting and time scheduling

Meetings between the team took place at least once a week at a regular time as this allowed for clear deadlines to be set. Further meetings were organised when parts of the process required further discussion. A record of meeting minutes can be found in the Appendix.

A Gantt chart was created once the main tasks had been delegated and identified as a group. A Gantt chart is a useful tool as it allowed early forecasting of the entire project with specific deadlines and time overlaps which can all be visually identified.

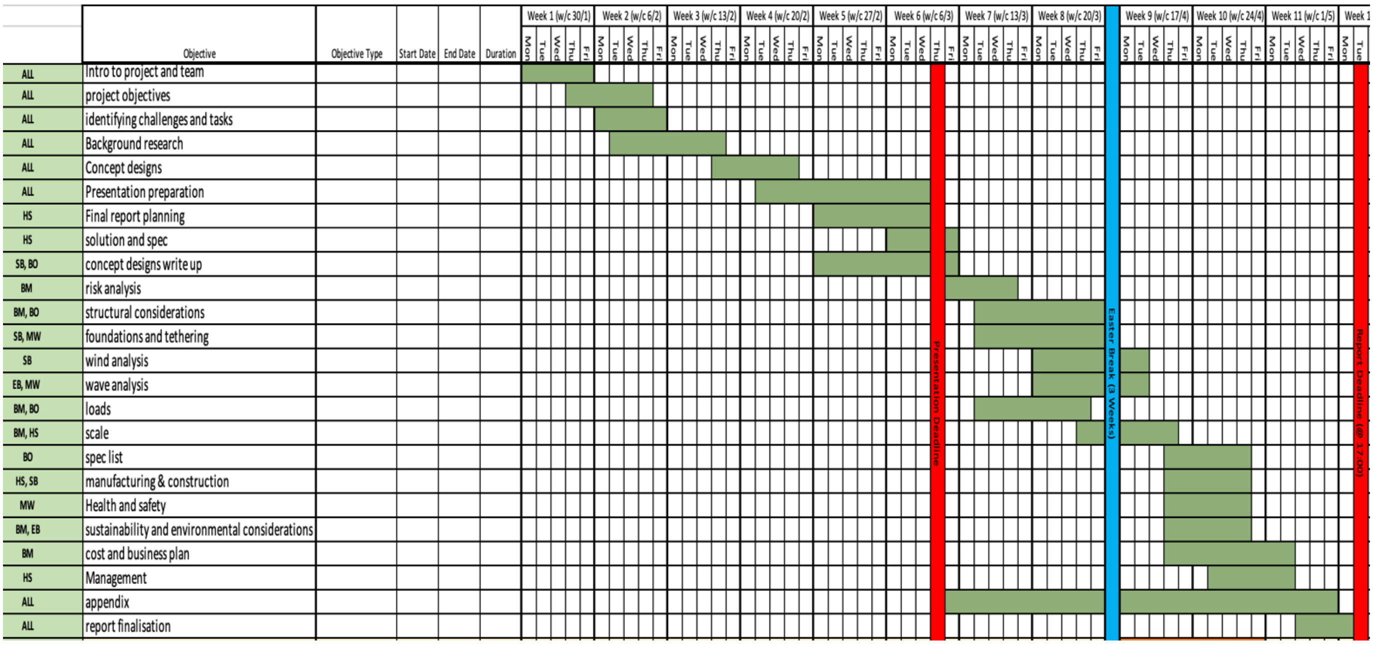



*Figure 41: Gantt chart for the Civil Group showing primary tasks with time duration and deadlines*

# Appendix

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## Sample Calculations

### Wave analysis

Wavelength:

$$\lambda = \frac{gT^2}{2\pi} tanh(\frac{2\pi d}{\lambda})$$

$$299.97 = \frac{9.81 * 14.62^2}{2\pi} tanh(\frac{2\pi * 70}{299.97})$$

Trial and error – lambda should be changed on right and left side until they are equal.

Wave particle velocity (for intermediate waves):

$$u = \frac{\pi H}{T} \frac{coshk(z+d)}{sinhkd} \cos{(kx - \sigma t)}$$

$$\frac{\pi * 6.1}{14.62} \frac{\cosh{(0.021(6.1+70))}}{\sinh{(0.021 * 70)}} \cos(\pi) = -1.64\, m/s$$

Wave particle acceleration (for intermediate waves):

$$\dot{u} = \frac{2\pi^2 H}{T^2} \frac{coshk(z+d)}{sinhkd} \sin{(kx - \sigma t)}$$

$$\frac{2\pi^2 6.1}{14.62^2} \frac{\cosh{(0.021(6.1+70))}}{\sinh{(0.021 * 70)}} \sin(\pi) = 0\, m/s^2$$

Where $(kx - \sigma t)$ takes on the maximum values at key wave points i.e., $\pi$

H – significant wave height, T – time period, z – distance from significant wave level, d - depth of water, k - $\frac{2\pi}{\lambda}$, $\sigma - \frac{2\pi}{T}$

Wave load on small volume structure (cable):

$$F(t) = \rho V(1 + C_A)\dot{u} + \frac{1}{2}\rho C_D S u|u|$$

$$1025 * 0.05(1+1)0 + \frac{1}{2} 1025 * 1.2 * 2.1 * -1.64|-1.64| = -3.47\, kN$$

u - fluid particle velocity, $\dot{u}$ – fluid particle acceleration, V – displaced volume, S – projected area normal to force direction, $\rho$ – mass density of fluid, $C_A$ – added mass coefficient, $C_D$ – drag coefficient

### Simulation

Drag force:

$$F_d = \frac{1}{2}\rho u^2 A C_D$$

$\rho$ – Liquid density, u – relative velocity, A – reference area, $C_D$ – drag coefficient

## Meeting Records

| Meeting: | Date: | Absentees: | Actions Completed: | Actions to be Taken: |
|---|---|---|---|---|
| 1 | 09-Feb | SB, EB | brainstorming of initial ideas for project route | delegation of initial research to the rest of the team |
| | | | main areas of concern for each discipline identified | answers to main 'considerations' before next meeting |
| | | | | |
| 2 | 14-Feb | SB | Presented the ideas and comments from the team leader meeting | research to be carried out by all group members before next team leader meeting |
| | | | Research areas have been identified and split throughout teh group | |
| | | | | |
| 3 | 16-Feb | | Workshop tasks were carried out and global warming impacts considered | planning of new project idea |
| | | | original project idea was discussed and tweaked based on factors of uncertainty | research to be carried out which is more relevant to new project idea |
| | | | | |
| 4 | 21-Feb | SB, BM | Ideas were fed to the group from the group leaders meeting | slides and information to be made for the presentation based on delegations |
| | | | the plan for the week 6 presentation was discussed | concept ideas agreed upon by the group |
| | | | Other work including planning the main report were also discussed | |
| 5 | 23-Feb | BO,BM | Industry experts were consulted and gave advice on concept designs | tasks delegated and presentation slides with speech to be completed by the group |
| | | | technical elements were discussed and evaluated | design decisions should be finalised |
| | | | presentation was further discussed | |
| 6 | 28-Feb | EB, MW | Slides for presentation discussed and compiled | Slides and speech to be completed for Thursday |
| | | | report gantt chart created | |
| | | | | |
| 7 | 01-Mar | BO | Work on presentation | Slides to be finalised |
| | | | workshop of risks and security | practice speech for presentation |
| | | | | |
| 8 | 07-Mar | | Slides were discussed and tweaked | presentation to be practiced under timed conditions |

| | | | | |
|---|---|---|---|---|
| 9 | 14-Mr | SB EB | Remainder of project tasks and report discussed | report template to be made with allocated tasks |
| | | | | |
| 10 | 24-Mar | BO | report template and task list presented | tasks to be completed by next meeting date |
| | | | discussions of technical details | |
| | | | | |
| 11 | 27-Mar | | Discussion of technical elements | CAD and simulation responsibilities allocated and planned |
| | | | Discussion regarding testing methods | |
| | | | | |
| 12 | 12-Apr | | Material discussion | ensure list of materials is made pre eco-audit |
| | | | | wind and wave analysis pages presented and finalised |
| | | | | |
| 13 | 20-Apr | SB | health and safety planned | health ans safety pages to be completed |
| | | | business plan planned | business plan to be completed |
| | | | risk pages checked over | eco audit to be completed |
| 14 | 25-Apr | | eco audit discussed with CAD and materials personnel | eco audit to be completed |
| | | | sections specified and confirmed | |
| | | | | |
| 15 | 04-May | | Planning further aspects of eco audit | calculations to be finalised |
| | | | Finalisation of CAD model | |
| | | | | |
| 16 | 05-May | | adding final technical aspects to report (piling data) | ensuring all text flows well and is in the same tense |
| | | | adding figures and tables where necessary | |
| | | | | |
| 17 | 06-May | | adding write ups and explanations for necessary aspects | discussing final tasks to be completed in the report |
| | | | page numbers, title page etc | |
| | | | calculations finalised and presented | |
| 18 | 08-May | MW | finalising report | finalisation of report |
| | | | grammar check | references and organisation |
| | | | references checking | |

Table of Figures

**University of Birmingham**

School of Engineering

# Integrated Design Project 3

## FINAL GROUP REPORT

## Mechanical Engineering

## MEng

## Rotary Mass Wave Energy Conversion

| | |
|---|---|
| **Team Number** | 3 |
| **Group Number** | 3 |


| Student Names | ID Numbers |
|---|---|
| Adam Cheshire | 2126006 |
| Ewan Dunnett | 2037795 |
| Charles King | 2170235 |
| Adam Lokkerbol | 2141143 |
| Joseph Roberts-Nuttall | 2007146 |
| David Shepherd | 2140888 |
| James Smith | 2174663 |

| Feedback (Compulsory Section) | | |
|---|---|---|
| Reflecting on the feedback that we have received on previous assessments, the following issues/topics have been identified as areas for improvement: | 1 | Calculations should be easy to follow and not ambiguous within the text of the report. |
| | 2 | Limited detail provided regarding the design decisions made. |
| | 3 | Explicit references could be better made to the UN sustainable development goals. |
| In this assignment, we have attempted to act on previous feedback in the following ways: | 1 | Calculations have been formatted into tables to aid the flow and understanding of the report. |
| | 2 | Demonstrated concept development via workflow from sketches, static & dynamic calculations, CAD models and FEA simulations. |
| | 3 | Section 7 of the report makes clear reference to the UN SDGs and places them within the context of the report. |
| Feedback on the following aspects of this assignment (i.e. content/style/approach) would be particularly helpful to us: | 1 | How effective the layout and formatting of the report has been in enabling a comprehensive but succinct review of the proposed system. |
| | 2 | Feedback regarding the level of detail included in the report. |
| | 3 | Technical feedback regarding the selection of materials and manufacturing processes. |

Final Word Count: 4931

## Contents

# i. Group Management

## i.a. Group Structure and Task Delegation

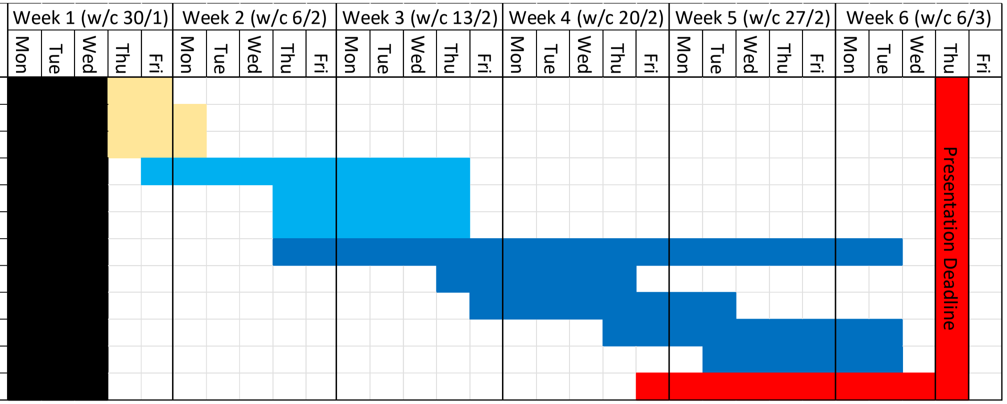
Other than Group Leader, there were no other specific roles assigned within the group; rather, responsibility was shared between tasks and sub-systems. The role of group leader was to liaise between team and group level, plan and monitor group progress, as well as to co-ordinate meetings and the delegation of tasks. Most task delegation was determined through volunteers, beginning with a template and deliverables being developed by the Group Leader, before the group specify particular tasks (either individually or as work packages) and a general order for completion, often based on the project GANTT chart. Members would choose their preferred tasks, and if the distribution of personnel was appropriate (based on workload required, nature of the tasks, or personal schedule/workload), then the group would proceed to their relevant tasks; otherwise, further discussion would be held and personnel reassigned temporarily, with the opportunity to adjust later, if necessary – if an agreement could not be met, then tasks could be assigned at the Group Leader's discretion, although this was not required. The distribution of tasks is represented in Table 1 below; the table shows areas in which members led or were primarily responsible for, so group members often contributed, in part, to tasks outside of what they were assigned, but this is not shown.

| Group Member | Roles/Tasks/Contributions |
|---|---|
| Adam Cheshire | Team Leader, Group Leader, Internal Frame, Risk Management |
| Ewan Dunnett | Mass System, Design for Materials and Manufacturing |
| Charles King | Powertrain, Business Plan |
| Adam Lokkerbol | Shell, Business Plan |
| Joseph Roberts-Nuttall | Mass System, Prototype Development, Design for Materials and Manufacturing |
| David Shepherd | Powertrain, Wider Engineering Impact |
| James Smith | Mass System, Design for Materials and Manufacturing |

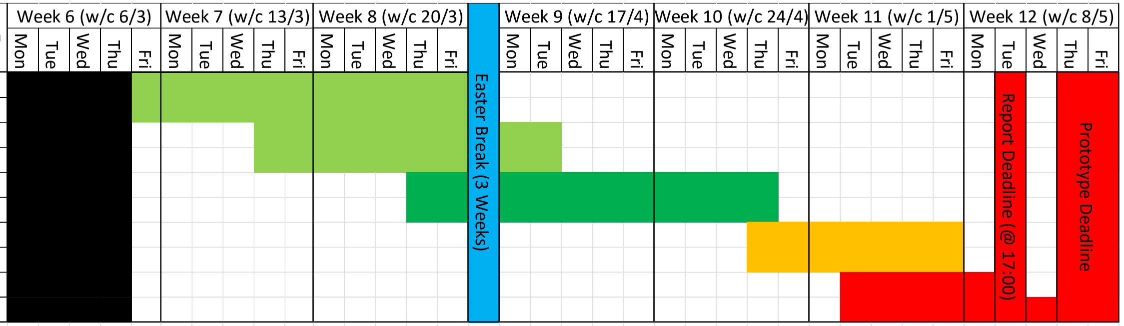
*Table 1 - Group roles, tasks and contributions*

*Figure 1 - Group Project GANTT Chart*

| Objective | Objective Type | Start Date | End Date | Duration (days) |
|---|---|---|---|---|
| Establish comms with group/team | Group Admin | 02-Feb | 03-Feb | 2 |
| Determine group lead (+ roles?) | Group Admin | 02-Feb | 06-Feb | 5 |
| Challenge Allocation | Group Admin | 02-Feb | 06-Feb | 5 |
| Research challenge area/idea generation | Research | 03-Feb | 16-Feb | 14 |
| Environmental Factors/Climate Change Adaptability | Research | 09-Feb | 16-Feb | 7 |
| Stakeholder Analysis | Research | 09-Feb | 16-Feb | 7 |
| Business Case | Requirements | 09-Feb | 07-Mar | 26 |
| Initial Requirements | Requirements | 16-Feb | 23-Feb | 7 |
| Aim, Solution and Brief Definition | Requirements | 17-Feb | 28-Feb | 11 |
| PDS | Requirements | 23-Feb | 07-Mar | 12 |
| Concept Development + System Breakdown | Requirements | 28-Feb | 07-Mar | 7 |
| Presentation Preparation | Assignment | 24-Feb | 09-Mar | 13 |




| Objective | Objective Type | Start Date | End Date | Duration (days) |
|---|---|---|---|---|
| Design Calculations | Design | 10-Mar | 24-Mar | 14 |
| Material Research | Design | 10-Mar | 24-Mar | 14 |
| CAD Development | Design | 16-Mar | 18-Apr | 33* |
| Initial Component/Sub-system Identification | Design | 16-Mar | 18-Apr | 33* |
| Design Analysis (CFD/FEA) | Design Validation | 23-Mar | 27-Apr | 35* |
| Design Iteration | Design Validation | 23-Mar | 27-Apr | 35* |
| Manufacture Analysis | Manufacturing | 27-Apr | 05-May | 8 |
| Costing | Manufacturing | 27-Apr | 05-May | 8 |
| Report Preparation | Assignment | 02-May | 09-May | 7 |
| Prototype Developmnet/Generation | Assignment | 02-May | 12-May | 10? |




* - Duration includes Easter Break, but is not all considered to be active time

### i.b. File/Asset Management and Communication

Microsoft Teams was used as the primary method of communication and organisation within the group, with a WhatsApp group being used as an auxiliary means of communication. MS Teams allowed the use of shared storage as well as live-access documents, so that all members of the group can be kept up to date on the latest versions of files as easily as possible and accessibility and efficiency of workflow can be optimised in this regard. MS Teams does provide some surety in terms of file safety, but external backups were made to ensure security where necessary. For CAD modelling, Autodesk Fusion 360 was used in a similar manner to Teams, allowing shared storage and access to models for the whole group.

The whole group met weekly to discuss, but was not limited to: actions from/for Group Leader meetings, delegation of tasks, progress and evaluation, and design ideas/considerations/critical decisions. A summary of the meeting minutes can be seen in Appendix A.4. Smaller numbers of group members also met frequently as work parties, or to discuss task-specific or sub-system specific matters. As such, face-to-face communication was preferred, but the use of MS Teams and WhatsApp meant that all members could be present and involved, albeit not in-person, if needed. MS Teams communication centred around communication between groups, task related discussions, updates and key organisational notifications, whereas WhatsApp was used for more immediate communication, informal discussion and updates, and information that was not likely to need repeating or accessing at a later date (this could still be done, but was vastly inefficient and so avoided).

### i.c. Integration

Although a specific channel within MS Teams permitted inter-group communication for non-Group Leaders, and hence a more direct exchange of information regarding specific tasks or integration, most communication between our group and others was conducted by the Group Leader, either discussed as matters within Group Leader meetings, or using the Group Leader meeting as an opportunity for direct communication. Figure 2 summarises the information exchanged between groups.

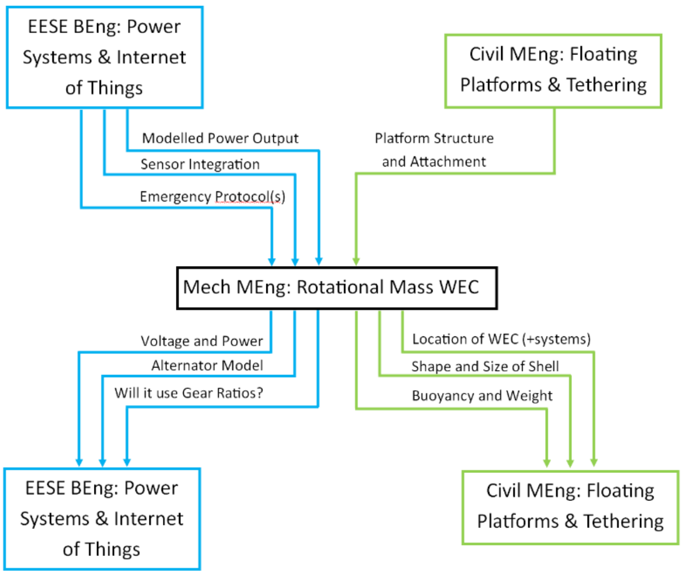



*Figure 2 - Information flow between groups*

# 1. System Overview

*Figure 3. Overall design*

## 1.1 Task

Our group decided, within the offshore energy island project, that wave energy production would be a viable task to produce sustainable energy offshore. It was then decided, based off extensive research, that a rotating mass method would be an appropriate approach. Due to the brief requiring sustainability, the United Nations Sustainability Development Goals (SDGs) [1] were used to develop the design and were followed closely throughout the whole project.

## 1.2 Final Design

Our design was inspired by the Wello Oy Penguin Wave Energy Converter [2]. Our design uses a 60-tonne rotating mass, attached to a 3.25 tonne shaft, supported by two roller bearings and one thrust bearing. The mass has an inertia of 307,500 kg/m$^2$ which at the expected operating speeds can produce a power output up to 300 kW. These are attached to a frame made from universal I-beams, housed within a Glass Fibre Reinforced Plastic (GFRP) hemi-ellipsoid shell. The main shaft feeds into an Ortlinghaus Series 123 Hydraulic Clutch-Brake [3] which allows for the system to be disengaged if weather conditions become extreme. A second shaft joins at the clutch brake and feeds out into a ZF Redulus GP 615 two-stage planetary to bevel gearbox [4] for increasing the speed to the generators input. This is then followed by another shaft which feeds into CVTCORP's mCVT (mechanical continual variable transmission) gearbox [5] which provides a constant output into a 340 kW Stamford S4L1M-F42 Class-H generator [6].

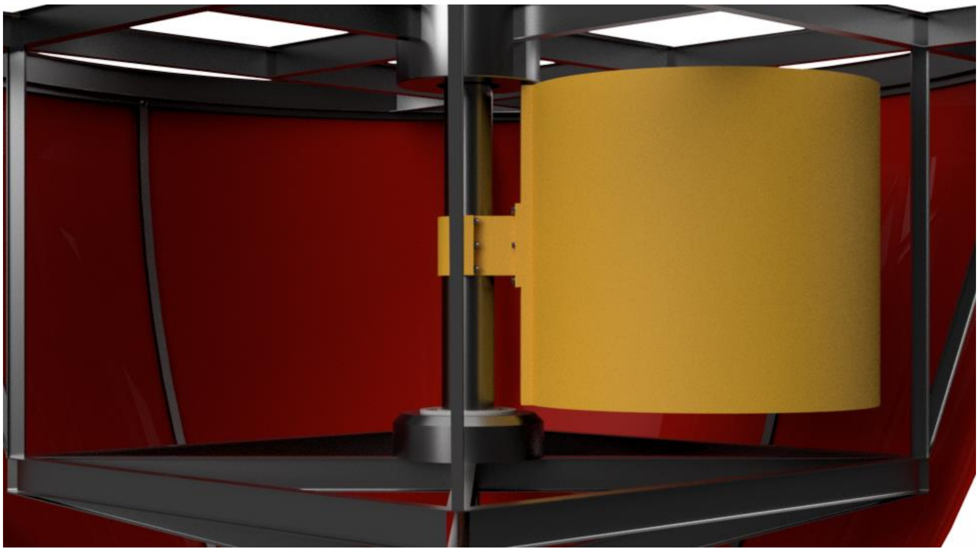


*Figure 4. Internal view*

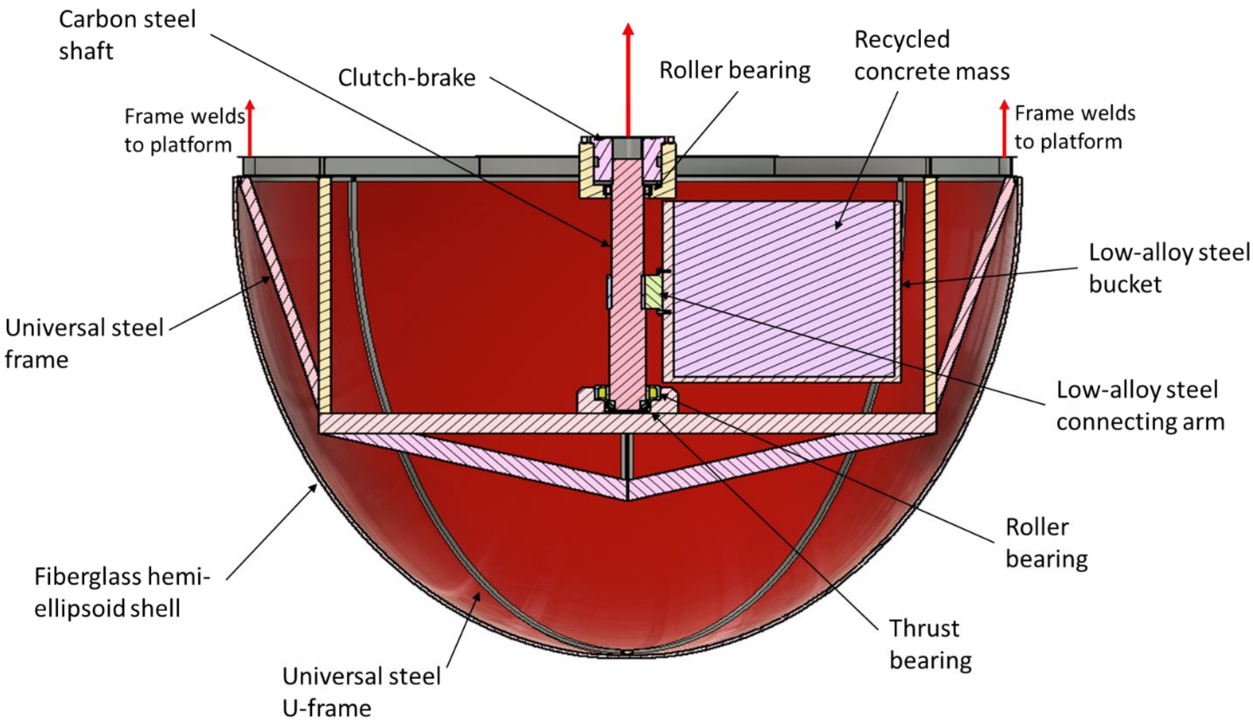



*Figure 5. Section view through the mass*

# 2. PDS

*Table 2. PDS*

| **PDS** | | |
|---|---|---|
| **Aspect** | **Objective** | **Criteria** |
| Performance | Power output | ≈300kW |
| | Efficiency | Maximised not at the expense of sustainability |
| | Frictional factor of rotating mass | Must minimise friction – use of roller and thrust bearings |
| | Carbon neutral | Net zero carbon emissions during function |
| | Cost | Minimised not at the expense of sustainability or efficiency (£) |
| | Gearbox load | Must be able to handle torque output from rotating mass |
| Quantity | Initial number of connected platforms | 130 |
| | Capacity to expand | Modular formation for ease in expansion |
| Life Span | Service time | Expected in-service life comparable to that of the wind turbines (20 years) |
| | Effects of fatigue (Mass-system) | Factor of safety of 4 due to unpredictable working conditions, designed with materials with sufficient endurance strength for this FOS |
| Rotating Mass | Mass | 60 tonnes (20 Cast Iron, 40 Recycled Concrete) |
| | Density | 3164 kg/$m^3$ |
| | Radius | 1.5 metres |
| | Eccentricity Shift | 2 metres |
| | Height | 2.68 metres |
| Environment | Range of wave sizes expected [7] [8] | Range: 0.05 – 6.2 metres<br>Average: 1.62 metres<br>Rising by 4 cm per decade in Aus. |
| | Wave Period [7] [8] | Mean: 5.95 s<br>Standard deviation 1.12 s<br>$90^{th}$ percentile: 4.51 s<br>$10^{th}$ percentile: 7.38 s |
| | Sea depth [9] | 50 - 70 metres |
| | Sea temperature [10] | Max. – Min.: 11.6 – 21.4 degrees Celsius<br>Yearly Average: 15.7 degrees Celsius<br>Estimated sea temperature rise: 0.5$^{o}$C in next 20 yrs. for Aus. |
| | Wildlife considerations [11] | Can't disrupt wildlife or ecosystems in or surrounding the windfarm [1] |
| Maintenance | Must be accessible from the surface of the platform | Access from the platform must be easy and safe to perform repairs, checks, and improvements. |
| Materials | Recycling/Reclamation | We shall prioritise recycled or reclaimed materials where possible/non-critical |
| | Reuse of materials after life | Materials should be able to be reused, recycled, or downcycled at the end of the lifetime. |

| | | |
|---|---|---|
| | Environment | Sea-based, high corrosion, should be non-polluting, high strength against waves, hard to resist abrasion |
| | Availability | Can be sourced and manufactured in Australia |
| | Built to adapt for climate change | Must be suitable for climate conditions by end of life (20 yrs.) (stronger waves, storms, acidity, sea levels rising) |
| | Low emissions in manufacture | Materials chosen should have low enough emissions during manufacture that it will be offset during the lifetime |
| | Corrosion resistance | Materials should be able to withstand corrosion due to the acidity of the sea and should accommodate further acidification due to climate change. |
| Sustainable Development Goals | 7) Clean and Affordable Energy | Will provide a source of low emission energy |
| | 9) Industry, Innovation, and Infrastructure | Will provide jobs to locals, money into the local economy and showcase innovative new technology to the rest of the world |
| | 13) Climate Action | Providing clean energy will mean less dependence on high-emitting sources of energy |
| | 14) Life Below Water | Won't disrupt ocean-based wildlife and ecosystems |

# 3. Mass System

## 3.1 Technical Evaluation

### *3.1.1 Mass*

#### *3.1.1.1 Calculations*

The distribution of the wave data can be assumed to follow a normal curve from Figure 6. The following data was the calculated for the wave data.

| | |
|---|---|
| Mean Wave period | 5.95 s |
| Standard deviation of wave period | 1.12 s |
| 90th percentile (to account for 80% run time) | 7.38 s |
| 10th percentile (to account for 80% run time) | 4.51 s |

Wave Data:

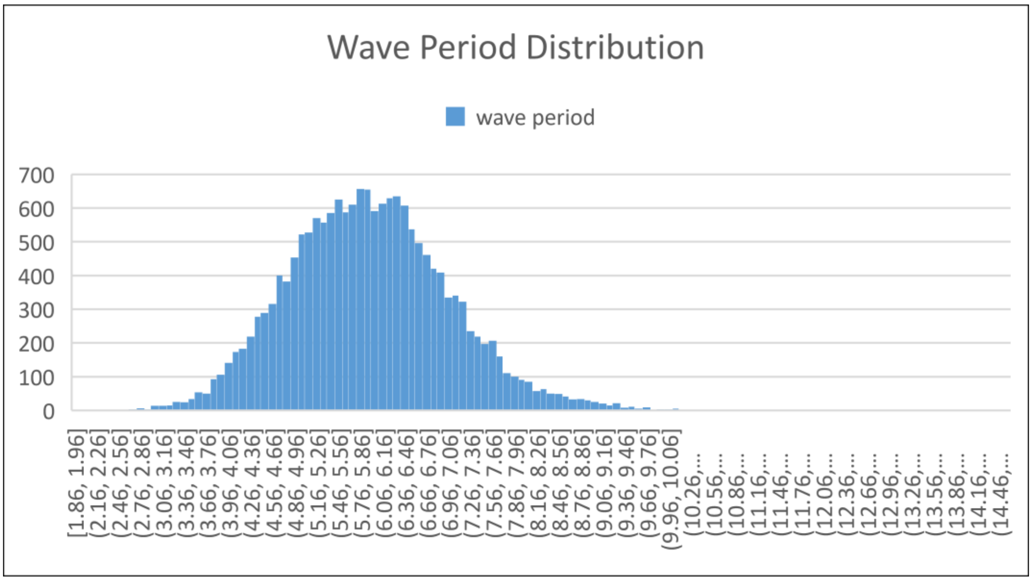



*Figure 6. Wave Period Distribution*

The wave period correlates to the speed the WEC will rotate at as it is assumed that the mass will complete a full rotation each wave period. This allows a max, min and mean value for the rotational speed to be calculated.

The calculations of the mass relied on selecting a size to create the desired output, since there were several variables to consider in this design, the main factors had to be decided. These were the inertia of the rotating mass, the minimum acceleration required for the mass to maintain the direction of rotation and the output in the form of kinetic energy to be transferred to the alternator. With the equation for the kinetic energy of a rotating object a higher inertia is preferable for a higher output. Yet, to allow for a larger acceleration a reduced inertia is preferable. The balance between the two of these to find an inertia with an allowable acceleration is the ideal outcome. Due to a lack of data arising in the steepness of the tilt in a boat on the sea a range of tilt angles were included for resolving the force and hence getting the angular acceleration of the rotating mass.

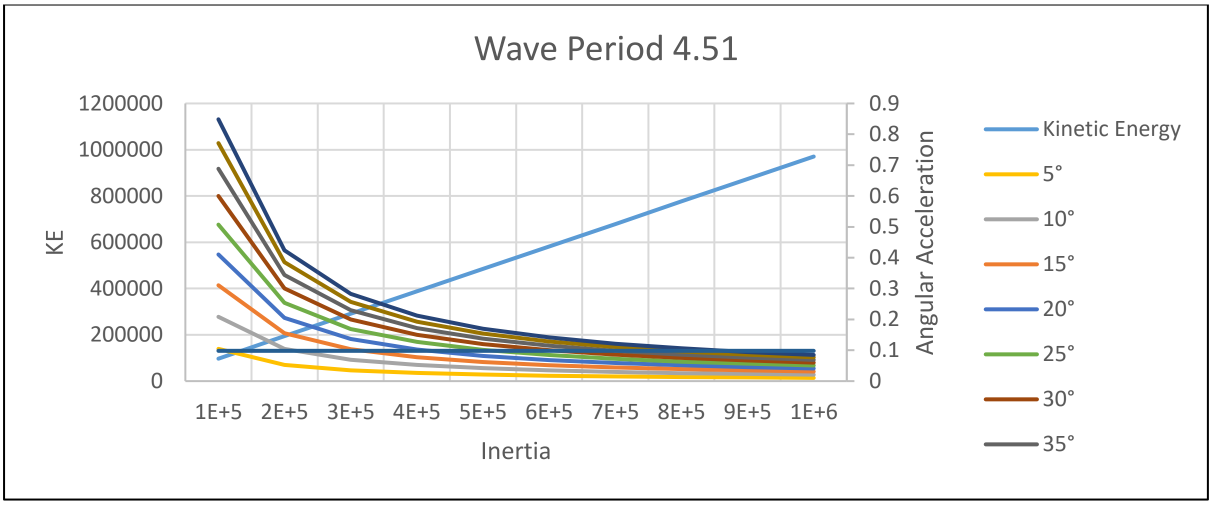



*Figure 7. Graph showing power output against different induced accelerations for minimum wave period 4.51 s.*

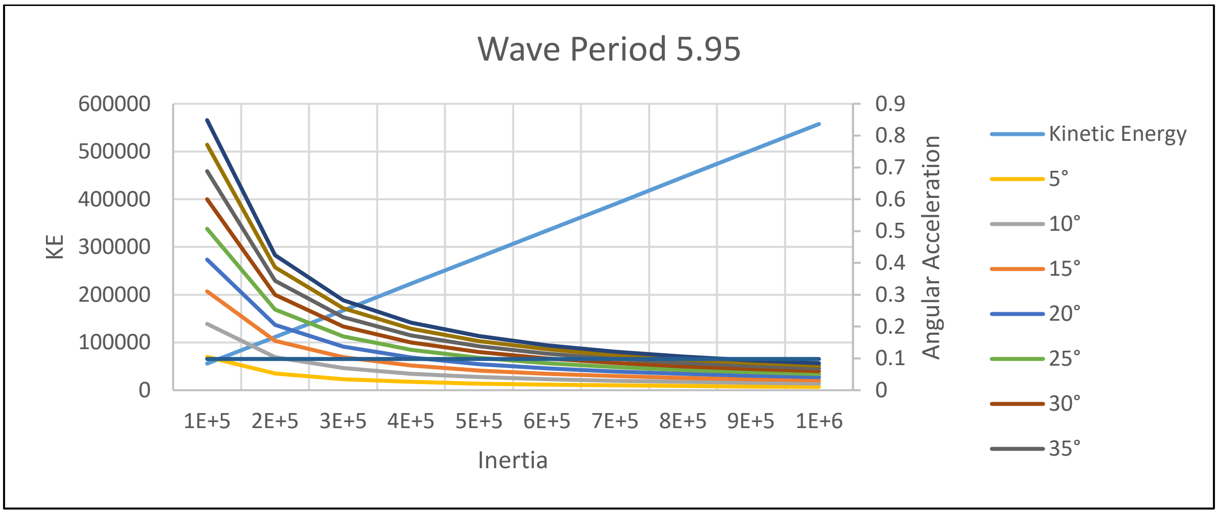



*Figure 8. Graph showing power output against different induced accelerations for mean wave period 5.95 s*

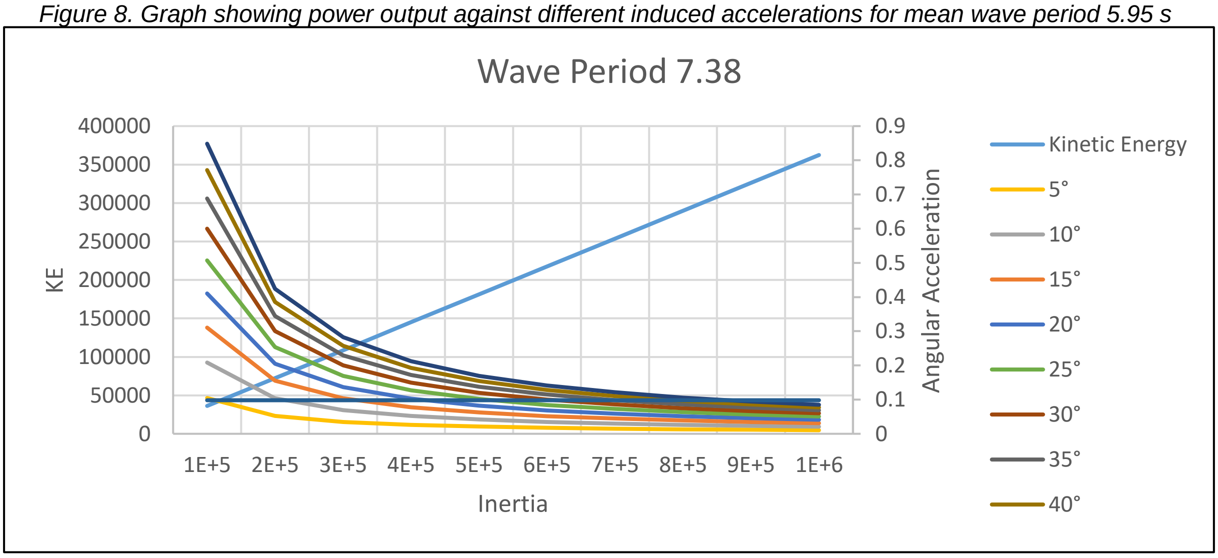



*Figure 9. Graph showing power output against different induced accelerations for maximum wave period 7.38s*

The minimum acceleration (represented by the horizontal blue line) comes from investigating the difference in the wave period, the data for waves was in 30 min intervals, so an approximation had to be made between this difference. This data can be seen in the graph below. Most of these results fall in a small difference in the wave period. The acceleration solely needs to be able to allow for a change in speed from wave to wave. The data for the difference in wave period and hence change of speed, a minimum value could be approximated at 0.1 $rad/s^{-1}$ on Figure 77 to Figure 9.

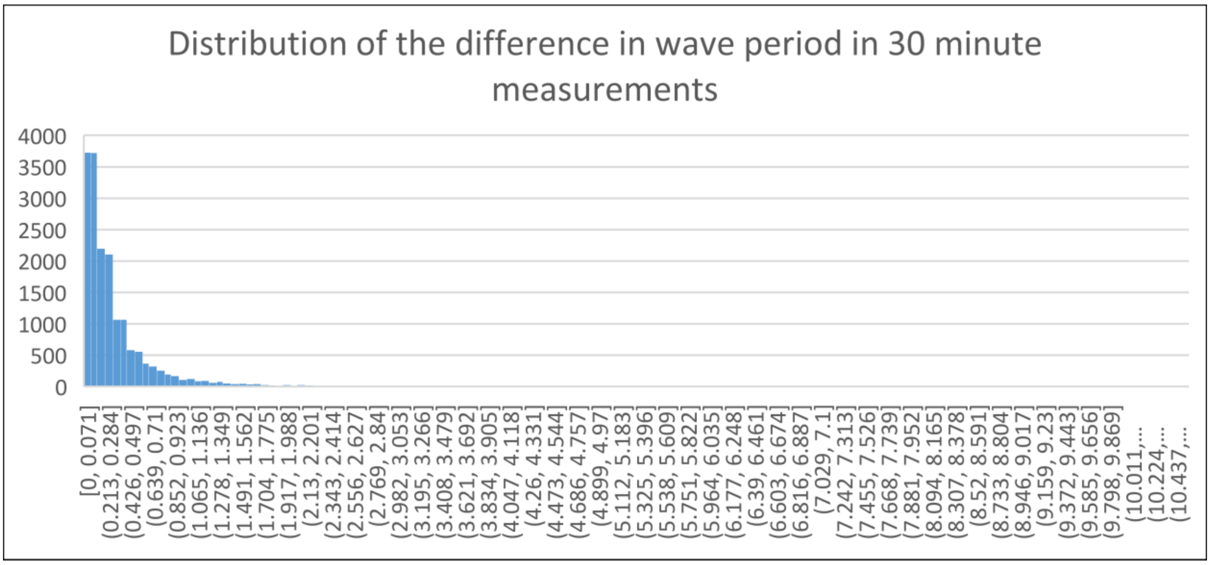



*Figure 10. Graph showing the distribution of the difference in wave period*

## Mass sizing:

The mass was required to be a specific size to create a viable power output. A rotating mass has kinetic energy when rotating relating to its speed and inertia. This kinetic energy can be converted to electrical energy via an alternator. The mass therefore needed to provide a significant kinetic energy to provide the required output when rotating. It was decided most of the mass would consist of recycled concrete to increase the sustainability of the project. The following values were found for the mass.

*Table 3. Mass Parameters and Calculations*

| | | |
|---|---|---|
| Inertia | | $I = \frac{1}{2} \cdot M \cdot r^2 + M \cdot R^2 = 307500\ kg.m^2$ |
| Max Kinetic Energy Output (expected) | | $Ke = \frac{1}{2} \cdot I \cdot {\omega_{max}}^2 = 298\ Kw$ |
| Mass | Total | 60 Tonnes |
| | Recycled Concrete | 40 tonnes |
| | Low Alloy Steel | 20 Tonnes |
| Density | Recycled Concrete | 2437 $kg/m^3$ |
| | Low Alloy Steel | 7850 $kg/m^3$ |

| | | |
|---|---|---|
| | Mass Average Density | 3164 kg/m³ |
| Volume | Recycled Concrete | $V = \frac{M}{\rho} = 16.41 \text{ m}^3$ |
| | Low Alloy Steel | $V = \frac{M}{\rho} = 2.55 \text{ m}^3$ |
| | Mass Total Volume | $18.96 \text{ m}^3$ |
| Mass Dimensions | Radius | $\text{r} = 1.5 \text{ m}$ |
| | Eccentricity shift | $\text{R} = 2 \text{ m}$ |
| | Height | $h = \frac{V}{\pi \cdot r^2} = 2.68\, m$ |

In the event of a storm surge the maximum angular acceleration has been calculated to reach 1 rad.s$^{-2}$ and the minimum appreciable angular acceleration 0.2 rad.s$^{-2}$. The resulting max and min torque at any one point in time would be calculated as shown in Table 4.

*Table 4. Torque outputs*

| | | |
|---|---|---|
| Torque | Max | $T = Ia = 307500 \cdot 1 = 307500 \approx 300kNm$ |
| | Min | $T = Ia = 307500 \cdot 0.2 = 61500 \approx 60kNm$ |

## Steel Bucket:

The steel bucket was made to have uniform thickness to limit the warping effects from irregular cooling during the casting process.

shows a representation of the shape of the component. The red shaded section represents the area where the recycled concrete will be.

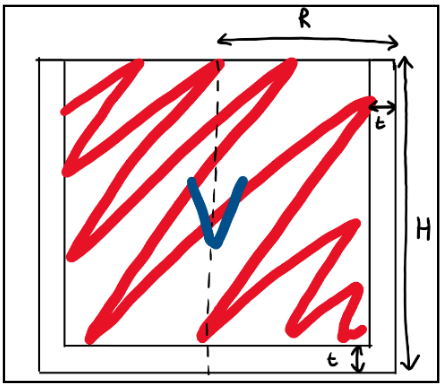


*Figure 11. Steel Bucket Diagram*

*Table 5. Steel Bucket Calculations*

| | | |
|---|---|---|
| Concrete Volume | | $16.41 \text{ m}^3$ |
| Thickness | Equation | $V = \pi \cdot r^2 \cdot h = \pi(R-t)^2(H-t)$ <br> $\left(\frac{V}{\pi} - R^2 \cdot H\right) + (R^2 + 2 \cdot R \cdot H)t - (2R + H)t^2 + t^3 = 0$ |
| | Thickness | $\text{t} = 82 \text{ mm}$ |

*Table 6 Bucket Material Selections*

| Bucket Materials | Castability | Yield Strength (MPa) | | Density (we need ≈7850 kg/m$^3$) | Price Per Unit Volume (£/m$^3$) | Approx. Price of Raw Material Per Bucket |
|---|---|---|---|---|---|---|
| | | Min | Max | | | |
| Cast iron, white, low alloy, EN GJN HV350 (former BS 1A) | Acceptable | 230 | 460 | 7800 | 1.57E+03 | £4,025.64 |
| Carbon steel, SA216 (Type WCC), cast, normalized & tempered | Acceptable | 262 | 290 | 7840 | 4.93E+03 | £12,576.53 |
| Low alloy steel, SAE 4130, cast, normalized & tempered | Excellent | 475 | 525 | 7840 | 5.13E+03 | £13,086.73 |
| Low alloy steel, SAE 4335M, cast, quenched & tempered | Excellent | 1150 | 1270 | 7840 | 6.95E+03 | £17,729.59 |

To maintain a mass of 60 tonnes, a density of approximately 7850kg/m$^3$ was required. Low alloy steel, SAE 4130, cast, normalized & tempered was selected since it demonstrated excellent castability, a suitable density and strength, and was cheaper than SAE 4335M steel.

### *3.1.2 Arms*

#### *3.1.2.1 Calculations*

#### Arm Sizing:

The length of the arm was predetermined to be 0.45 m to ensure the eccentric shift of the mass was as required. The following parameters were then investigated to reduce deflection in the arm:

- Number of connecting arms between the shaft and the bucket
- Height of the connecting arm
- Width of the connecting arm

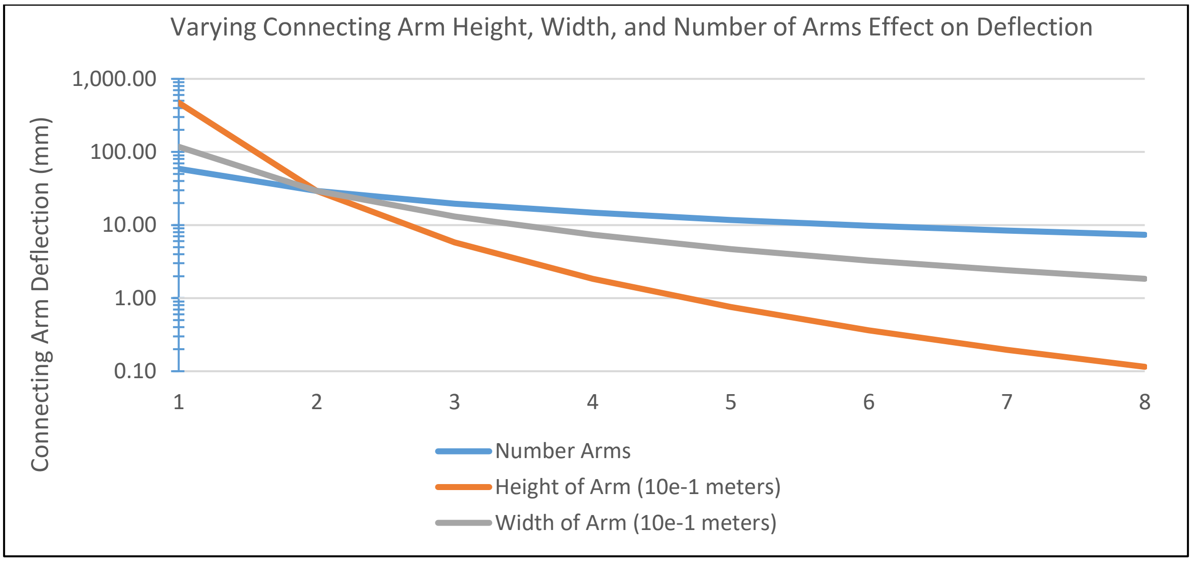



*Figure 12. Graph showing the effect of varying the number of the connecting arms (blue), the height of the arm (orange), and the width of the arm (grey) on the deflection of the arm.*

Increasing the number of connecting arms showed the least effect on the deflection in the arm compared to the height and width. Where the height and width parameters were varied, the counter parameter was assumed to be 0.2 m (e.g. when varying height at 0.1 m, the corresponding width was kept to 0.2 m). The height of the arm showed the greatest difference since this parameter was cubed in the second moment of area. Consequently, only one arm was to be employed since this would greatly reduce cost and complexity. A height and width of 0.5m was chosen since this provided a recognisable reduction in deflection that was justifiable for any additional cost of material and manufacturing.

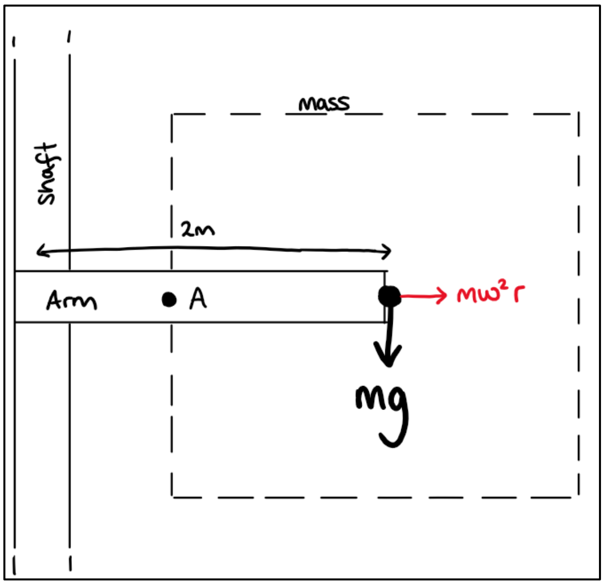



*Figure 13. Representation of Forces Acting Upon the Arm*

*Table 7. Arm Stress Calculations*

| | | |
|---|---|---|
| Second Moment of Area | | $I = \dfrac{B \cdot H^3}{12} = 0.0052\ m^4$ |
| Maximum Bending Moment | | $M = F \cdot d = 1177200\ Nm$ |
| Length of Arm | | $y = 0.45\ m$ |
| Maximum Deflection | | $\delta_{max} = \dfrac{F \cdot y^3}{3E \cdot I} = 1.51\ mm$ |
| Normal Stress | | $\sigma_x = y \cdot \dfrac{M}{I} = 102\ MPa$ |
| Tensile forces in arm | Centripetal force | $F = m \cdot \omega^2 \cdot r = 233\ kN$ |
| | Weight force from tilt | $F = m \cdot g \cdot \sin\theta = 383\ kN$ |
| | Total | $616\ kN$ |
| Tensile stress | | $\sigma_T = \dfrac{F}{A} = 2.46\ MPa$ |
| Combined stress | | $\sigma = \sigma_x + \sigma_T = 104\ MPa$ |

The arm was to be cast since this would greatly reduce manufacturing costs and material wastage, and consequently excellent castability was a critical condition since porosity defects would be serious to the strength of the arm acting as a cantilever beam. Figure 14 and Table 8 helped to determine that low alloy steel, SAE 4335M, cast, quenched & tempered would be used for the small and large arm sections.

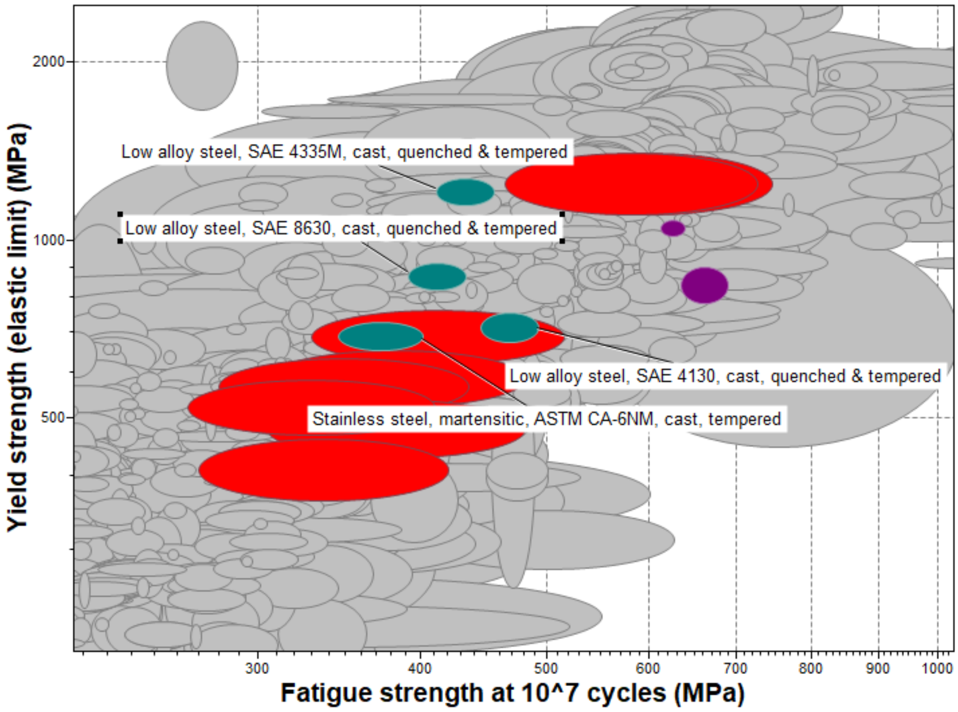



*Figure 14. Arm material selection from Granta EduPack Level 3*

*Table 8. Arm Material Selections*

| **Arm Materials** | **Castability** | **Yield Strength** (MPa) | | **Endurance Strength at $10^7$ Cycles** | | **Price Per Unit Volume** (£/m$^3$) | **Approx. Price of Raw Material Per Bucket** |
|---|---|---|---|---|---|---|---|
| | | Min | Max | Min | Max | | |
| Stainless steel, martensitic, ASTM CA-6NM, cast, tempered | Excellent | 655 | 725 | 346 | 401 | 1.12E+04 | £1,098.83 |
| Low alloy steel, SAE 8630, cast, quenched & tempered | Excellent | 827 | 914 | 392 | 433 | 7.81E+03 | £766.24 |
| Low alloy steel, SAE 4130, cast, quenched & tempered | Excellent | 676 | 752 | 445 | 492 | 6.95E+03 | £681.86 |
| Low alloy steel, SAE 4335M, cast, quenched & tempered | Excellent | 1150 | 1270 | 412 | 455 | 5.13E+03 | £503.30 |

### *3.1.3 Shaft*

#### *3.1.3.1 Calculations*

Shaft Sizing:

The bending moments and shear force on the shaft were evaluated using the free body diagrams in Figures 15 and 18 to produce the graphs shown in Figures 16, 17, 19, and 20.

The system had to be understood in both equilibrium (0° tilt) and at a highly occurring maximum tilt of 15° determined from the wave data analysis.

‘No tilt’ diagrams and graphs:

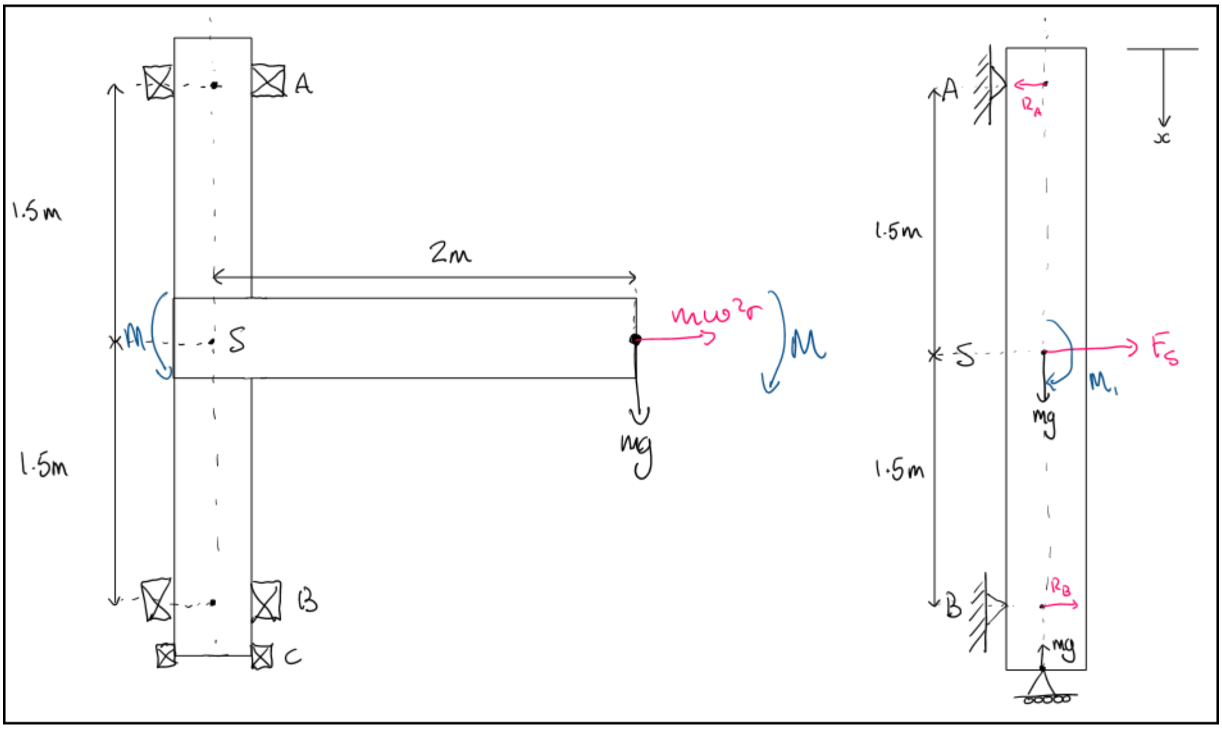



*Figure 15. Shaft at 0° tilt free body diagram indicating forces and components .*

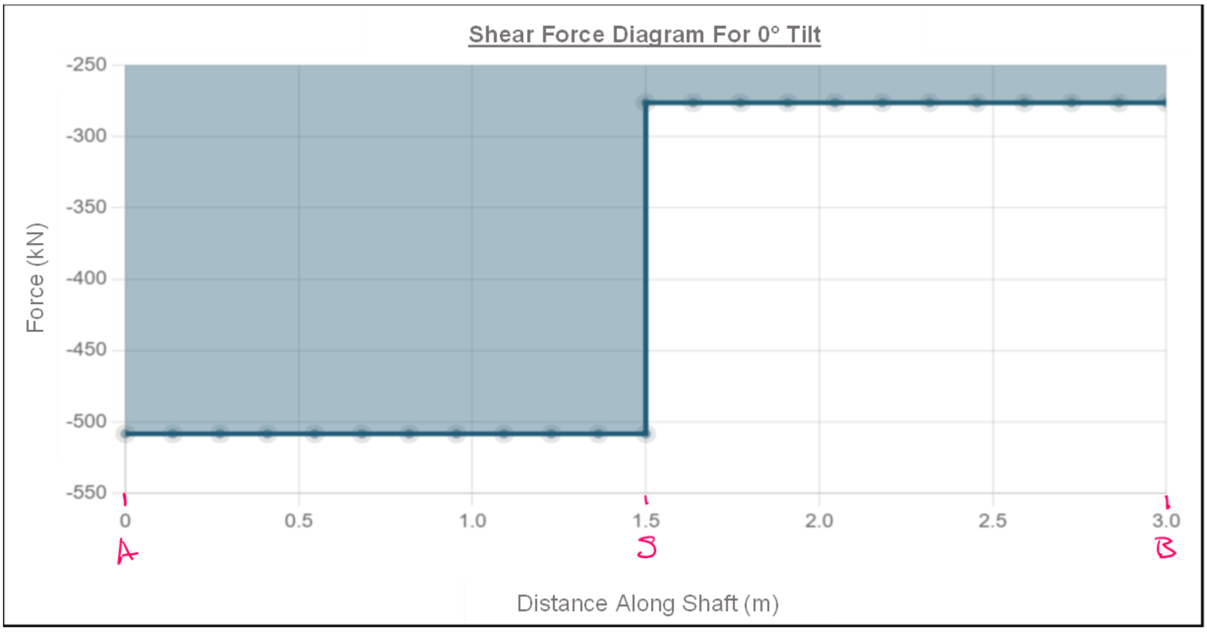



*Figure 16. Shear force diagram for 0° tilt .*

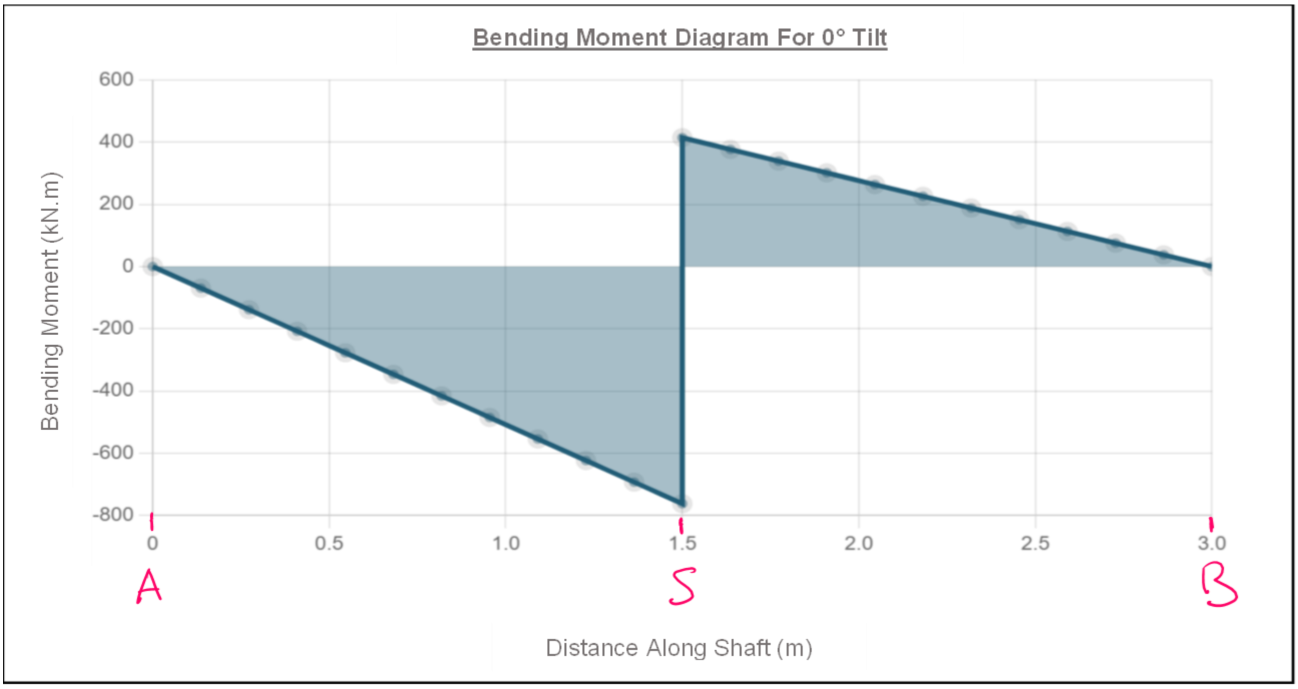



*Figure 17. Bending moment diagram for 0° tilt .*

'Maximum average tilt' diagrams and graphs:

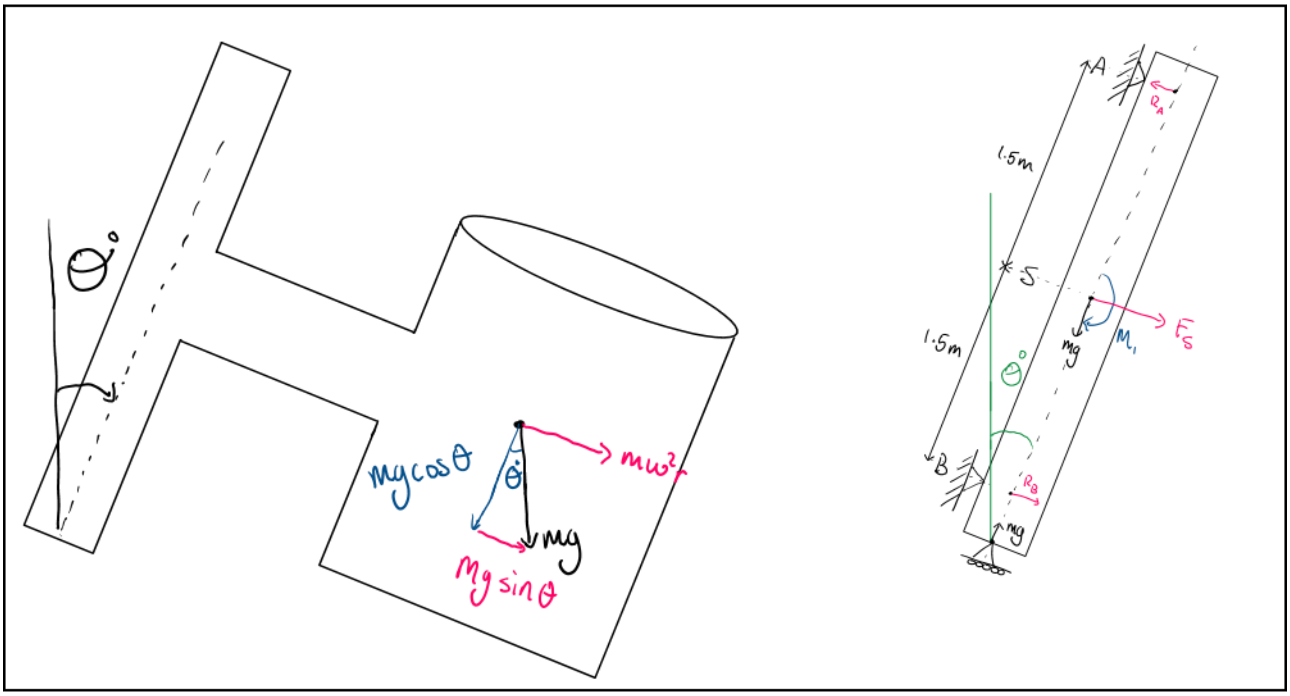



*Figure 18. Shaft at 15° tilt free body diagram indicating forces and components.*

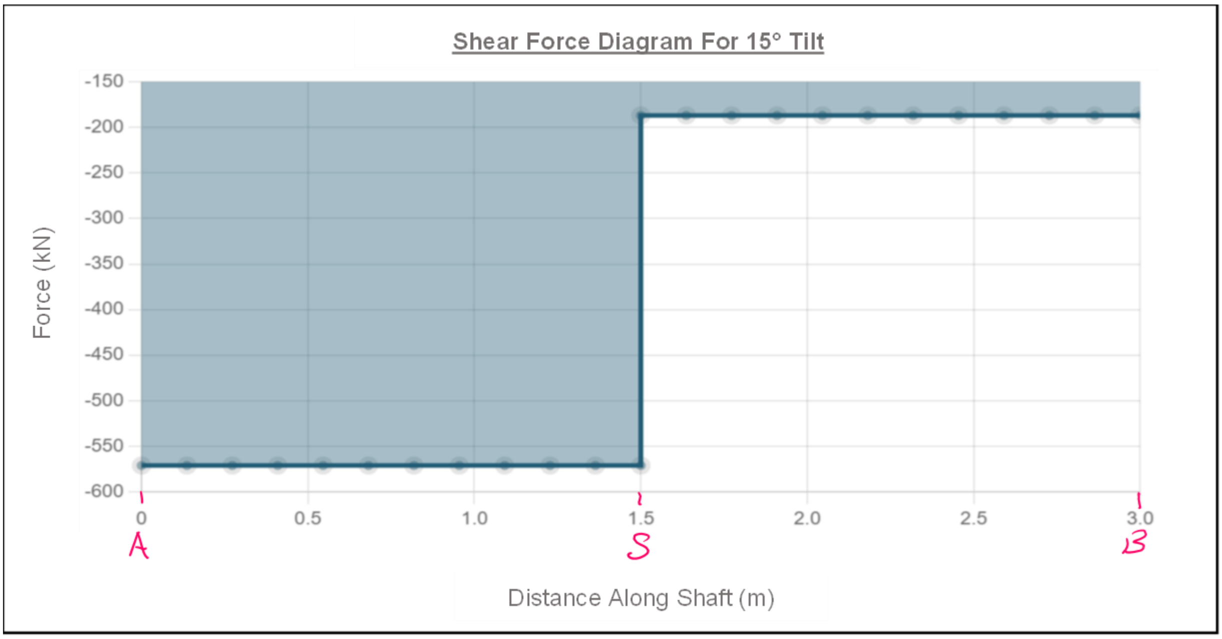



*Figure 19. Shear force diagram for 15° tilt .*

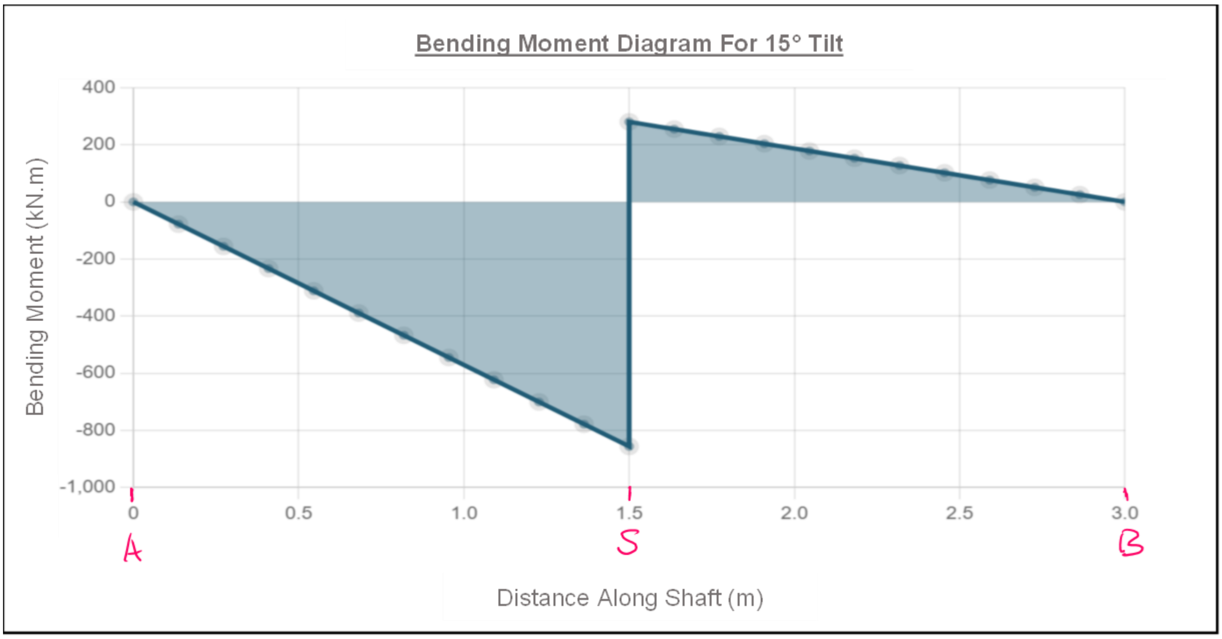



*Figure 20. Bending moment diagram for 15° tilt .*

*Table 9. Bending Moment and Shear Force Analysis*

| | | | |
|---|---|---|---|
| Central bending moment $M_1$ (kNm) | 0° | $2mg = 1177\ \mathrm{kN \cdot m}$ | |
| | 15° | $2mg \cdot \cos 15 = 1137\ kN \cdot m$ | |
| Central force $F_s$ (kN) | 0° | $m\omega^2 r = 232\ kN$ | |
| | 15° | $m\omega^2 r + mg \cdot sin15 = 384\ kN$ | |
| Reaction force at A $F_a$ (kN) | 0° | $\frac{M_1 + 1.5F_s}{3} = 508\ kN$ | |
| | 15° | $\frac{M_1 + 1.5F_s}{3} = 571\ kN$ | |
| Reaction force at B $F_a$ (kN) | 0° | $F_a - F_s = 276\ kN$ | |
| | 15° | $F_a - F_s = 187\ kN$ | |
| Bending moment $M$ (kNm) | 0° | 0 ≤ x < 1.5 $M = F_a x$ | $M_{0°max} = -762\ kNm$ |
| | | 1.5 < x ≤ 3 $M = F_b(3 - x)$ | $M_{0°min} = 414\ kNm$ |
| | 15° | 0 ≤ x < 1.5 $M = F_a x$ | $M_{15°max} = -857\ kNm$ |
| | | 1.5 < x ≤ 3 $M = F_b(3 - x)$ | $M_{15°min} = 281\ kNm$ |
| Shear Force $V$ (kN) | 0° | 0 ≤ x < 1.5 $V = -F_a$ | |
| | | 1.5 < x ≤ 3 $V = F_s - F_a$ | |
| | 15° | 0 ≤ x < 1.5 $V = -F_a$ | |
| | | 1.5 < x ≤ 3 $V = F_s - F_a$ | |

## Distortion Energy Theory

A minimum yield stress of 1000 MPa was decided upon to ensure an overly large shaft diameter would not be required, reducing the overall weight and size of the system. A static loading factor of safety of 4 was chosen. Utilising distortion energy theory, a minimum shaft diameter was calculated.

*Table 10. Minimum shaft diameter specification*

| | |
|---|---|
| Maximum Bending Moment | $M_{max} = 857000\ Nm$ |
| Maximum Torque | $T_{max} = 300000\ Nm$ |
| Minimum Shaft Diameter | $d = \sqrt[\frac{1}{3}]{\left(\frac{32 \cdot f_s}{\pi \cdot S_y}\right) \cdot \sqrt{{M_{max}}^2 + \frac{3}{4}{T_{max}}^2}} > 0.33\ m$ |

To account for standard bearing bores, a shaft diameter of 0.4 m was selected.

Shaft Design Against Fatigue:
The shaft experiences a combined fluctuating loading of torque and bending moments as the rotating mass changes speed. Soderberg criteria was employed since it offers a more conservative model of fatigue (and therefore safer) than the Goodman or Gerber criteria. The fluctuations are not completely reversed. Granta EduPack database indicated materials with the highest yield and fatigue strengths were steels and titanium.

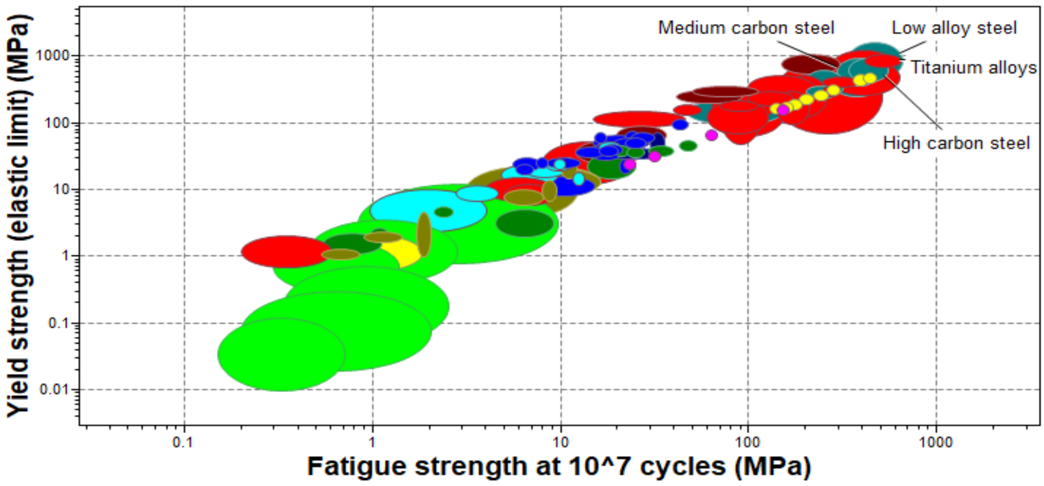



*Figure 21 Graph of yield strength against fatigue strength for families of materials in the Granta EduPack level 2 database*

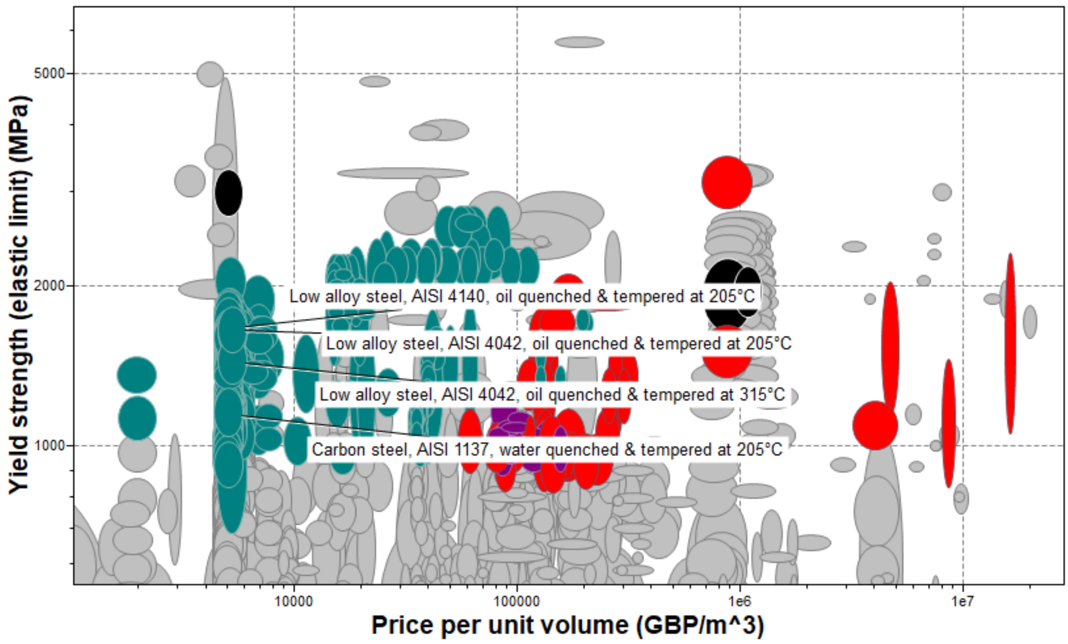



*Figure 22 Four grades of heat-treated steels were then selected based upon their common use for heavy duty shafts*

*Table 11. Shaft Material Selections*

| Materials | Applications | Yield Strength (req. 1000MPa) | | Endurance Strength at $10^7$ Cycles | | Price Per Unit Volume (£/m$^3$) | Approx. Price of Bar Metal Per Shaft |
|---|---|---|---|---|---|---|---|
| | | Min | Max | Min | Max | | |
| Low alloy steel, AISI 4140, oil quenched & tempered at 205°C | Heavy duty shafts, connecting rods, high tensile bolts, propeller shaft joints, track pins | 1480 | 1810 | 593 | 684 | 4.52E+03 | £2,466.56 |
| Low alloy steel, AISI 4042, oil quenched & tempered at 205°C | Heavy duty shafts, connecting rods, high tensile bolts | 1500 | 1820 | 599 | 691 | 4.53E+03 | £2,472.02 |
| Low alloy steel, AISI 4042, oil quenched & tempered at 315°C | Heavy duty shafts, connecting rods, high tensile bolts | 1310 | 1600 | 555 | 640 | 4.53E+03 | £2,472.02 |
| Carbon steel, AISI 1137, water quenched & tempered at 205°C | Heavy duty shafts, axles, crankshafts, couplings, used particularly where ENHANCED MACHINABILITY is important | 1005 | 1290 | 526 | 608 | 4.35E+03 | £2,373.80 |

Carbon steel, AISI 1137, water quenched & tempered at 205°C was selected since it met the minimum required yield strength and had a suitable endurance strength against fatigue. In addition, it is used where enhanced machinability is required, allowing for high precision spline manufacture and surface roughness control.

The min and max bending and shear stress calculated previously in Tables 4 and 9 has been used in the fatigue analysis.

*Table 12 Shaft design against fatigue calculations using Carbon steel, AISI 1137 wq&t @ 205°C*

| | | |
|---|---|---|
| Maximum bending moment on shaft | | $M_{max} = 850000\ Nm$ |
| Minimum bending moment on shaft | | $M_{min} = -300000\ Nm$ |
| Maximum shear stress experience by the shaft | | $T_{max} = 300000\ Nm$ |
| Minimum shear stress experience by the shaft | | $T_{min} = 60000\ Nm$ |
| Minimum shaft diameter | | $d = 0.4\ m$ |
| Stress | Max | $\sigma_{max} = \frac{32 \cdot M_{max}}{\pi \cdot d^3} = 327.5\ MPa$ |
| | Min | $\sigma_{min} = \frac{32 \cdot M_{min}}{\pi \cdot d^3} = 207.9\ MPa$ |
| | Mean | $\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} = 267.7\ MPa$ |

| | | |
|---|---|---|
| | Amplitude | $\sigma_r = \frac{\sigma_{max} - \sigma_{min}}{2} = 59.8\ MPa$ |
| Shear Stress (Torsional) | Max | $\tau_{max} = \frac{16 \cdot T_{max}}{\pi \cdot d^3} = 23.9\ MPa$ |
| | Min | $\tau_{min} = \frac{16 \cdot T_{min}}{\pi \cdot d^3} = 4.8\ MPa$ |
| | Mean | $\tau_m = \frac{\tau_{max} + \tau_{min}}{2} = 14.4\ MPa$ |
| | Amplitude | $\tau_r = \frac{\tau_{max} - \tau_{min}}{2} = 9.6\ MPa$ |
| Material Yield Stress | | $1000\ MPa$ |
| Material Yield Strength in Shear | | $S_{sy} = 0.5S_y = 500\ MPa$ |
| Material Endurance Strength | | $S_e = 526\ MPa$ |
| Working Endurance Strength | | $S'_e = K_a K_b K_c K_d K_e S_e =$ 195.5 MPa |
| Factors Affecting the Fatigue Strength | Surface Finish ($K_a$) | $K_a = 0.7$ |
| | Size Effects ($K_b$) | $K_b = 0.8$ |
| | Reliability ($K_c$) | $K_c = 0.753$ |
| | Temperature ($K_d$) | $K_d = 1$ |
| | Stress Concentration and Notch Sensitivity ($K_e$) | $K_e = \frac{1}{K_f}$ = 0.88 |
| | Fatigue Strength Concentration Factor ($K_f$) | $K_f = 1 + q[K_t - 1]$ = 1.13 |
| | Stress Concentration Factor ($K_t$) | $K_t = \frac{\sigma_{max}}{\sigma_m} = 1.13$ |
| | Notch Sensitivity ($q$) | $q = 1$ |
| Material Torsional Endurance Strength | | $S_{es} = 0.5S'_e = 84.8\ MPa$ |
| Factor of Safety | | $f_s = \frac{S_{sy}}{\sqrt{\frac{1}{4}\left(\sigma_m + \frac{S_y}{S'_e}\sigma_r\right)^2 + \left(\tau_m + \frac{S_{sy}}{S_{es}}\tau_r\right)^2}} = 1.6$ |

The factor of safety calculated is greater than unity, consequently the shaft has been designed for ‘infinite’ life. [12]

## Spline

A spline was required to transfer the torque from the rotating mass to the shaft and it was decided for ease in manufacturing that this would be done with one key. The size of the key was calculated to account for the stresses through this section. To ensure the key was as per industry standards, ISO/R773, 'Metric Key Keyway Dimensions' were adhered to, and stress calculations were referenced via RoyMech. [13]

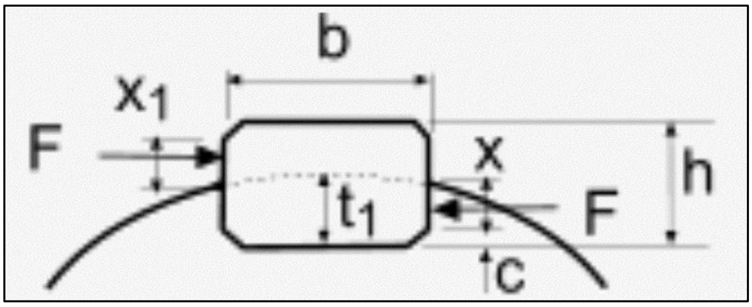



*Figure 23 Spline Key Dimensions*

*Table 13 Spline Calculations*

| | | |
|---|---|---|
| Mean Radius of Spline | | $r = 210\ mm$ |
| Effective Length of Spline | | $Le = 500\ mm$ |
| Key Width | | $b = 90\ mm$ |
| Depth of key | | $d = 45\ mm$ |
| Chamfer Size | | $c = 2\ mm$ |
| Depth of Key Face Key/Shaft | | $x = 26\ mm$ |
| Depth of Key Face Key/Arm | | $x_1 = 15\ mm$ |
| Max Angular Acceleration | | $\alpha = 0.5\ rad/s$ |
| Force | | $F = I \cdot \alpha = 150\ kN$ |
| Maximum Torque | | $\tau = F \cdot d$ |
| Spline Factors | Design factor ($K_{ds}$ , fixed Close fit) | 1 |
| | Application Factor ($K_{as}$, wave power source, no shock and generator uniform) | 1 |
| | Fatigue Life Factor ($K_{fs}$ , approx. 10,000 torque cycles unidirectional) | 1 |
| | Service Factor ($K_{ss}$) | $K_{ss} = \frac{K_{as} \cdot K_{ds}}{K_{fs}} = 1$ |
| Resulting Shear Stress | | $\tau_s = \frac{\tau \cdot K_{ss}}{b.Le.r} = 31.7\ MPa$ |
| Max Stress Key/Shaft | | $\sigma_{max} = \frac{\tau \cdot K_{ss}}{x.Le.r} = 109.9\ MPa$ |
| Max Stress Key/Arm | | $\sigma_{max} = \frac{\tau \cdot K_{ss}}{x_1.Le.r} = 185.5\ MPa$ |

### 3.1.4 Bearings

#### 3.1.4.1 Calculations

Bearing sizing:
From Figure 24, bearing B was included to omit the requirement of bearing C to accommodate radial in addition to axial loads. Cylindrical roller bearings were chosen due to their high radial load carrying capacity, low friction, and ability to accommodate axial displacement in both directions.

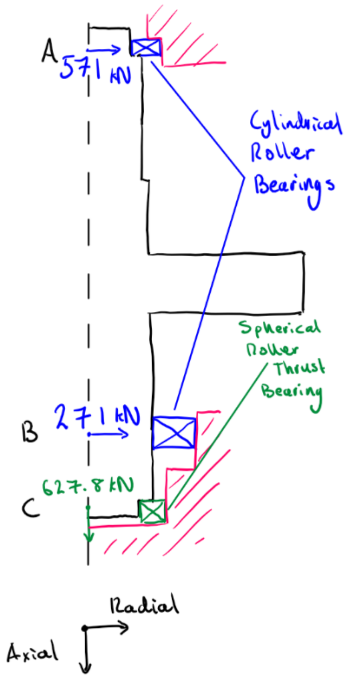



*Figure 24. Bearing positioning*

Bore diameters were determined by combining the minimum shaft diameter and shoulder requirements for assembly with standard bores advertised by SKF selector [14].

*Table 14. Bearing bores and loads*

| Bearing | Bore (mm) | Radial Load (kN) | Axial Load (kN) |
|---|---|---|---|
| A | 400 | 571 | 0 |
| B | 460 | 276 | 0 |
| C | 320 | 0 | 627.8 |

SKF defined bearings under a radial to axial load ratio greater than 1:0.55 ($F_r > 0.55F_a$). Additional bearings should be introduced to withstand the radial load. Therefore, bearing B was introduced to omit the load on bearing C providing a wider range of choices. Equivalent bearing load ($P$) was equal to radial load for bearings A and B and axial load for bearings C [15]. Minimum basic dynamic load ratings ($C$) were calculated, assuming 85 % operation time over 20 years.

*Table 15. Bearing equivalent loads, life rating, and dynamic load ratings criteria*

| Variable | Formula | Bearing A | Bearing B | Bearing C |
|---|---|---|---|---|
| Equivalent bearing load $P$ (kN) | $P = XF_r + YF_a$ | 571 | 276 | 627.8 |
| Minimum basic life rating $L_{10Min}$ (millions of revolutions) | $L_{10Min} = \frac{365 \cdot 24 \cdot Operation_{\%} \cdot Life_{years}}{10^6}$ | 89.6 | 89.6 | 89.6 |
| Minimum basic dynamic load rating $C$ (kN) | $C = P \cdot L_{10}^{\frac{1}{n}}$ | 2199 | 1063 | 2418 |

## Bearing A choices:

*Table 16. SKF Bearing A selection*

| Designation | Principal dimensions | | | Basic load ratings | | Speed ratings | |
|---|---|---|---|---|---|---|---|
| | | | | dynamic | static | Reference speed | Limiting speed |
| | d [mm] | D [mm] | B [mm] | C [kN] | $C_0$ [kN] | [r/min] | [r/min] |
| NJ 1080 MA | 400 | 600 | 90 | 1 380 | 2 320 | 1 100 | 1 500 |
| NJ 2980 ECMA | 400 | 540 | 82 | 1 380 | 2 800 | 1 200 | 1 600 |
| ☆ NU 1080 MA | 400 | 600 | 90 | 1 380 | 2 320 | 1 100 | 1 500 |
| NU 1080 N2MA | 400 | 600 | 90 | 1 380 | 2 320 | 1 100 | 1 500 |
| NU 2980 ECMA | 400 | 540 | 82 | 1 400 | 2 800 | 1 200 | 1 600 |
| NU 3980 ECMA | 400 | 540 | 106 | 1 760 | 3 750 | 1 000 | 1 500 |
| NU 2080 ECMA | 400 | 600 | 118 | 2 420 | 4 550 | 950 | 1 400 |
| NU 3080 MA | 400 | 600 | 148 | 2 700 | 5 300 | 950 | 1 400 |

## Bearing B choices:

*Table 17. SKF Bearing B selection*

| Designation | Principal dimensions | | | Basic load ratings | | Speed ratings | |
|---|---|---|---|---|---|---|---|
| | | | | dynamic | static | Reference speed | Limiting speed |
| | d [mm] | D [mm] | B [mm] | C [kN] | $C_0$ [kN] | [r/min] | [r/min] |
| NJ 2992 ECMA | 460 | 620 | 95 | 1 720 | 3 600 | 1 000 | 1 300 |
| NUP 3992 ECMA | 460 | 620 | 118 | 2 050 | 4 550 | 850 | 1 300 |
| NU 2092 ECMA | 460 | 680 | 128 | 2 810 | 5 400 | 800 | 1 200 |
| NU 1292 MA | 460 | 830 | 165 | 4 180 | 6 800 | 750 | 1 100 |
| ☆ NU 2292 MA | 460 | 830 | 212 | 5 120 | 8 650 | 700 | 1 100 |
| NU 3192 ECMA/HB1 | 460 | 760 | 240 | 5 280 | 9 650 | 670 | 1 100 |

Bearing C choices:

*Table 18. SKF Bearing C selection*

| Designation | Principal dimensions | | | Basic load ratings | | Speed ratings | |
|---|---|---|---|---|---|---|---|
| | | | | dynamic | static | Reference speed | Limiting speed |
| | d [mm] | D [mm] | H [mm] | C [kN] | $C_0$ [kN] | [r/min] | [r/min] |
| 29264 | 320 | 440 | 73 | 1 110 | 5 100 | 850 | 1 400 |
| 29364 E | 320 | 500 | 109 | 3 350 | 11 200 | 750 | 1 200 |
| 29464 E | 320 | 580 | 155 | 5 700 | 19 000 | 600 | 1 100 |

*Table 19. SKF Bearing selected and specification A [16], B [17], C [18]*

| **Bearing** | **Selection** | **$C_{req}$ (kN)** | **C (kN)** | **$L_{10req}$ ($10^6$ revs)** | **$L_{10}$ ($10^6$ revs)** |
|---|---|---|---|---|---|
| A | NU 3080 MA | 2199 | 2700 | 89.6 | 117 |
| B | NU 2292 MA | 1063 | 5120 | 89.6 | 16900 |
| C | 29464 E | 2418 | 5700 | 89.6 | 1561 |

Selections prioritised safety factors for basic load ratings, reducing the chance of failure due to wear; increasing total life and negating the need to replace bearings. Bearings will be located by the shell housing in conjunction with the shaft shoulders. For bearing fits see assembly routing.

### *3.1.5 Outsourced Components*

#### *3.1.5.1 Calculations*

Bolt Specification:

Bolts will experience the same tensile and shear stress as in the arm, however, the area acting is reduced. Figure 2525 represents the flange section that will attach the arm to the bucket and the forces going through the bolts. Figure 266 represents the flange section between arm sections and the forces going through the bolts.

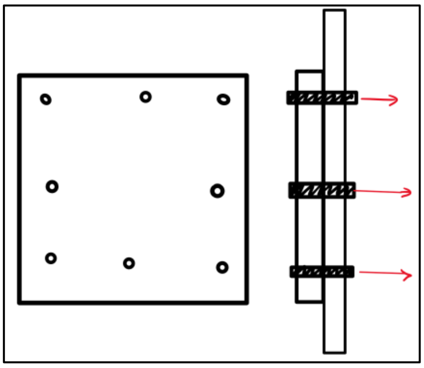


*Figure 25. Arm to Bucket Bolting Arrangement*

*Table 20 Arm to Bucket Bolt Calculations*

| | | |
|---|---|---|
| No. of Bolts to connect to bucket | | 9 |
| Factor of Safety | | 4 |
| Shear stress | Stress in Arm | 113.2 MPa |

| | | |
|---|---|---|
| | Stress Per Bolt | 12.6 MPa |
| | M30 Bolt Force | 11.3 kN |
| Tensile Forces in Bolts | Centripetal Force | $F = m \cdot \omega^2 \cdot r = 233\ kN$ |
| | Weight Force from Tilt | $F = m \cdot g \cdot \sin\theta = 383\ kN$ |
| | Total | $616\ kN$ |
| Tensile force per Bolt | | $F = \frac{616}{9} = 68.4\ kN$ |

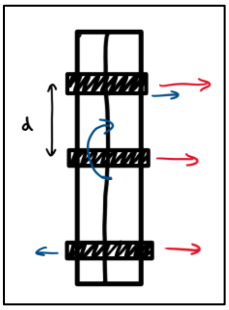



*Figure 26. Arm to Arm Bolting Arrangement*

*Table 21 Arm to Arm Bolt Calculations*

| | |
|---|---|
| Number of bolts with max bending moment force | $4$ |
| Distance of bolts from effective pivot | $d = 0.2\ m$ |
| Bending moment through bolts | $M = F \cdot d = 227\ kN$ |
| Max force through bolts | $F_{max} = \frac{616}{6} + \frac{227}{4} = 159.4\ kN$ |
| Grade required | $10.9\ M36\ Bolts$ |

The table below shows the bolt sizing and grades that are acceptable for all bolts in green, the yellow shows the bolts acceptable for the arm to bucket section and the red shows the bolts which are unacceptable for the use in the system when a FOS of 4 is used. The data for the bolts has been referenced in accordance with EN 1993-1-8, ‘Eurocode 3: Design of steel structures - Part 1-8: Design of joints’ to determine the stress grade of each bolt.

*Table 22 Acceptable Bolt Choice Forces*

| Size | Bolt Grade | | | | | | | Bolt Grade | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 4.6 | 4.8 | 5.6 | 5.8 | 6.8 | 8.8 | 10.9 | 4.6 | 4.8 | 5.6 | 5.8 | 6.8 | 8.8 | 10.9 |
| | Tensile Resistance (kN) | | | | | | | Shear Resistance (kN) | | | | | | |
| M30 | 50.5 | 50.5 | 63.1 | 63.1 | 75.7 | 101 | 126.2 | 33.7 | 28.1 | 42.1 | 35.1 | 42.1 | 67.3 | 70.1 |
| M33 | 62.5 | 62.5 | 78.1 | 78.1 | 93.7 | 124.9 | 156.2 | 41.6 | 34.7 | 52 | 43.4 | 52 | 83.3 | 86.8 |
| M36 | 73.5 | 73.5 | 91.9 | 91.9 | 110.3 | 147.1 | 183.8 | 49 | 40.9 | 61.3 | 51.1 | 61.3 | 98 | 102.1 |

To simplify the assembly process, 150 mm M36 bolts were selected to be used throughout the mass subassembly.

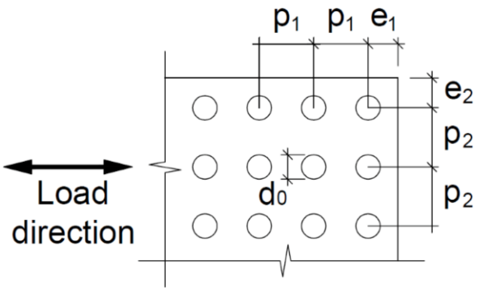



*Table 23 Bolt Design Parameters as per EN 1993-1-8*

| Size | $E_1$ (mm) | $E_2$ (mm) | $P_1$ (mm) | $P_2$ (mm) |
|---|---|---|---|---|
| M36 | 47 | 47 | 86 | 94 |

## 3.2 Validation

To validate the design FEA was used. A static study was conducted to review the stresses and validate the design against the chosen factor of safety 4. Simplifications were made in the FEA design to reduce computing power, yet, not limit the results of the study. The results were based on the maximum force results likely to occur.

The study was conducted with the materials and design choices chosen in the technical evaluation. Figure 27. FEA Factor of safety below 4 sectionsrepresents the locations where the factor of safety in the design fall below the value of 4. It is clear that the designed areas all comply with this specification. The spline key is the only component with a factor of safety lower than 4, this is acceptable for the application due to it being under compression

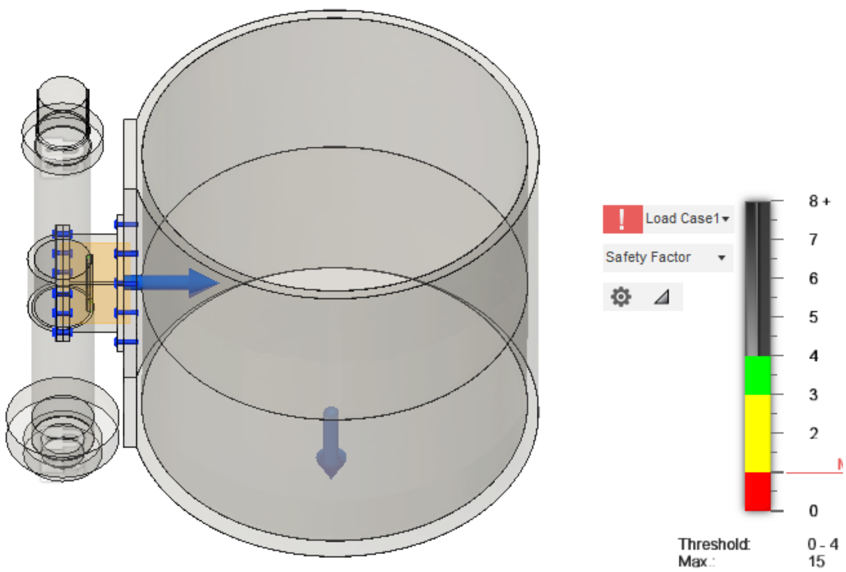



*Figure 27. FEA Factor of safety below 4 sections*

Figure 28. FEA Stress Analysis represents the stress on the system, the figure shows the stresses from a range of 10 MPa to 150 MPa to ease visualisation of the stress concentrations. The range 0 MPa – 10 MPa was redacted as insignificant. The key locations for stress concentrations are on the shaft, where the arm encounters the shaft, where the bearings contact the shaft and the arm itself. The maximum value of stress is 371 MPa

which features on the spline key. This value as explained in the section above is acceptable here. These images validate the design to be capable in the environment.

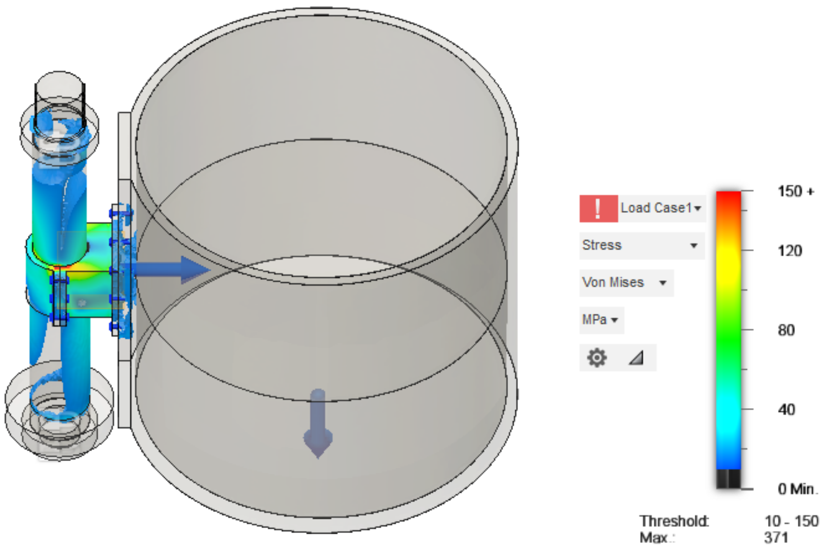



*Figure 28. FEA Stress Analysis*

Figure  is the final FEA representation on the mass showing the displacement of the mass. The legend shows the maximum expected displacement to be 5.6 mm on the furthest point from the axis and the shaft experiences values of displacement no greater than 0.5 mm.

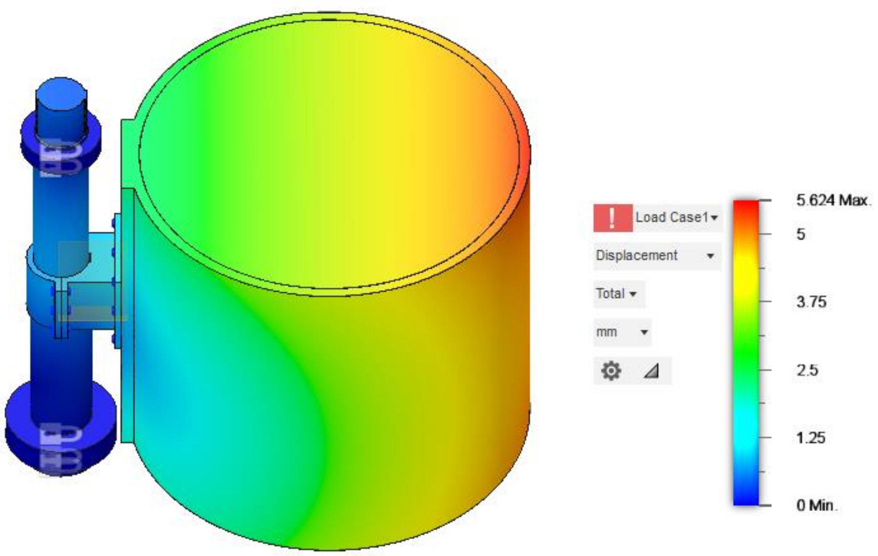



*Figure 29 FEA displacement results*

# 4. Powertrain

## 4.1 Bevel and CVT Gearboxes

### *4.1.1 Calculations*

*Table 24. Gear ratio and torque requirements*

| | |
|---|---|
| Gear Ratio [19] | $G = \frac{\omega_B}{\omega_A} = \frac{1{,}500}{10} = 150$ |
| Maximum Torque | 300 000 Nm (From Mass System) |

### *4.1.2 Validation*

Two transmissions are employed in the gear train: a two-stage planetary to bevel transmission for increasing the output speed to 1,500 rpm and altering its direction by 90 degrees to align it parallel to the platform surface. This is succeeded by a mechanical continuously variable transmission (mCVT) which ensures a steady generator output by compensating for fluctuations caused by varying wave sizes.

The gear ratio for the first transmission was determined based on the average speed of the rotating mass (10 rpm) and the desired output speed into the mCVT (1,500 rpm), resulting in a ratio of 1:150. To handle the mass's output torque of 300 kNm, the ZF Redulus GP 615 gearbox was selected, capable of withstanding torques up to 321 kNm. The chosen gearbox will be paired with CVTCORP's mCVT , which has a ratio span of 6:1 and is customized according to specific requirements for outputting into the generator.

### *4.1.3 Simulink Model*

A Simulink model [20] can be produced to show how this setup would work.

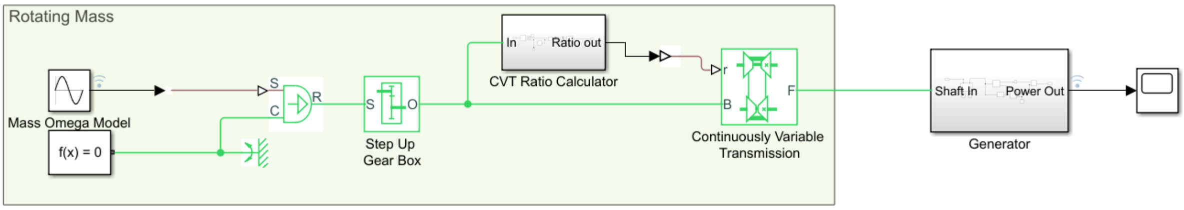



*Figure 30: Entire Simulink Model Showing the Rotating Mass System*

The model (Figure 30) consists of a Sinusoidal wave that represents the varying angular velocity of the rotating mass between 7 and 22 revolutions per minute, this feeds into an ideal angular velocity source. The source then goes into the step-up gearbox. After the step-up gearbox is the mCVT with a branch that calculates the required gear ratio for the mCVT to be calculated. Figure 31 shows the logic of the calculator:

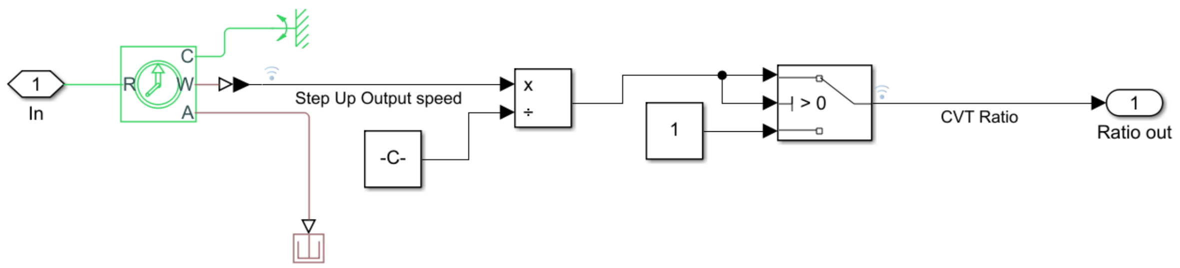



*Figure 31: CVT Gear Ratio Logic*

Figure 30 & 32: mCVT gear ratio logic shows a rotation sensor that measures the angular velocity. The outputted value is then divided by a constant of 1500 as this is the desired output velocity. This gives the ratio that then goes through a switch which prevents an output of 0.

The mCVT output velocity then goes into a generator modelled after the one being used (see section 4.3 for details). The power produced by the generator can then be measured. Figure 32 shows the input of the sin wave, power measured and mCVT ratio over 90 seconds:

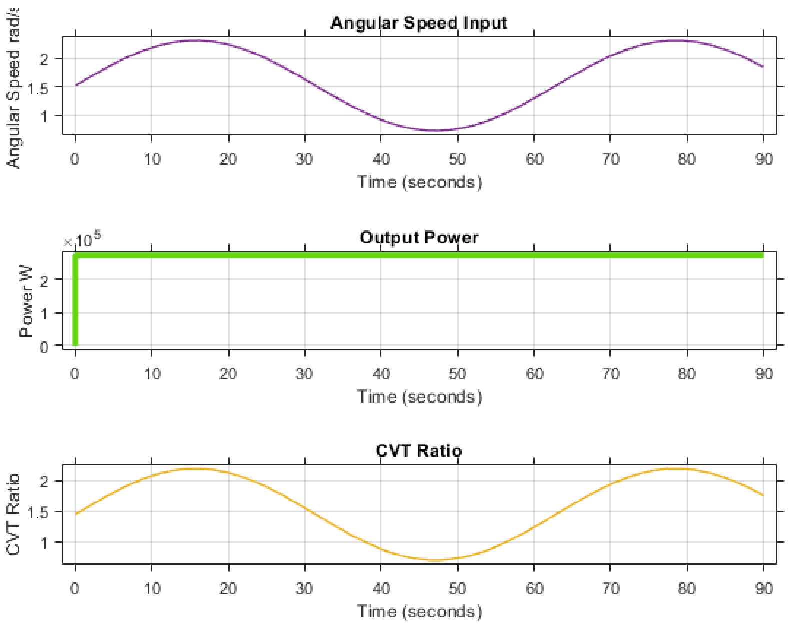



*Figure 32: Angular Speed Input, Output Power And CVT Ratio against Time*

## 4.2 Clutch Brake

A clutch-brake has been chosen as it can be used for two safety purposes. It can be used to slow the rotating mass down and can also be used to completely disconnect the mass and allow it to rotate freely, from the gearbox and generator to prevent damage to them in the case of severe weather.

The Ortlinghaus Series 123 Hydraulic Clutch-Brake [3] is chosen for its torque handling capability of 3,000-600,000 Nm, which matches the mass' operating torque of 300,000 Nm. It utilizes wet-running, oil-cooled plates with steel/sinter friction pairing and operates with hydraulic actuation pressure oil at 60 Bar. This compact clutch-brake boasts high operating efficiency, low maintenance requirements, and features such as high torque, low moment of inertia, and fast switching speeds. Enclosed in its own casing, it prevents leakage and minimizes noise.

*Figure 33. Ortlinghaus Series 123 Hydraulic Clutch-Brake*

## 4.3 Generator

The generator chosen is a Stamford S4L1M-F42 Class-H [6] it has the following specs

| | |
|---|---|
| Output Frequency | 50 Hz |
| Output Voltage | 415 V |
| Generator Base rating | 340 kVA |
| Power output | 272 kW |
| Rated for marine applications | Yes |
| Compatible with other project systems | Yes (50 Hz) |

# 5. Shell and Structure

## 5.1 Internal Frame

### *5.1.1 Shape, Size and Buoyancy*

Before the frame or shell could be designed, the profile first needed to be determined. 3 main factors affected the profile: volume required by the rotating mass, volume necessary for buoyancy, and hydrostatic pressure due to the WEC being submerged. With regard to hydrostatic pressure, to prevent stress concentrations, the profile features gradual transitions in geometry and avoids sharp corners [21]; alongside the fact that the rotating mass sweeps a cylindrical profile while in operation, suggested that a profile with a circular section is the simplest way to satisfy these considerations and improve rigidity of the shell. The buoyant force affecting a cylindrical volume that encapsulates the swept profile of the mass, with allowance for clearance between the mass and the frame, was calculated to identify if additional buoyancy was required. Buoyancy of the WEC was sufficient (Table 25), especially as the actual profile will be larger than that of the nominal cylinder; therefore, determining the actual profile became a matter of finding the most efficient profile in terms of volume.

| | |
|---|---|
| Mass of Rotating Mass, m (kg) | $60 \times 10^3$ |
| Weight (N) | $W = mg = 60 \times 10^3 \times 9.81 = 0.5886 \times 10^6\ N$ |

| | |
|---|---|
| Swept Radius of Mass (m) | 3.5 |
| Nominal Radius of Cylinder, R (m) | 3.8 |
| Height of Mass (m) | 2.68 |
| Nominal Height of Cylinder, H (m) | 4 |
| Density of Water, ρ ($kgm^{-3}$) | 995 |
| Buoyant Force (N) | $B = V\rho g$ <br> $= \pi R^2 H\rho g = 1.77 \times 10^6\ N$ |

*Table 25 - Dimensions and Buoyant Force of Nominal Cylinder*

Different profiles were tested using Desmos Graphing Calculator (Figure 34), illustrating 2D sections of paraboloids and ellipsoids and comparing areas to that of the nominal cylinder; the smallest difference in areas being the most efficient use of volume, minimising excess materials and loads applied to the platform (Table 26). Area calculation only concerned the lower halves of the areas; X is half the width of the profile along the x-axis (widest point), and Y is the distance below the y-axis (deepest point).

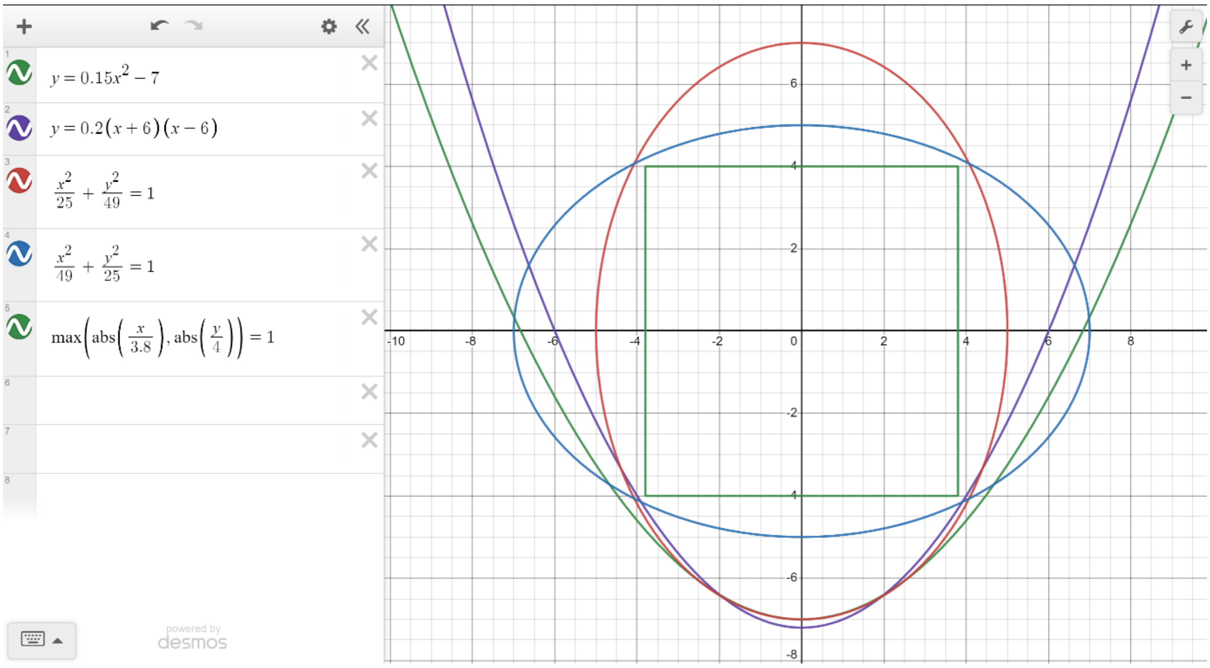



*Figure 34 - Observing different possible profile sections using Desmos Graphing Calculator*

| Profile | Shape | Section Area ($m^2$) | Difference in Area ($m^2$) |
|---|---|---|---|
| | Nominal Cylinder | $A = 2XY = 2 \times 3.8 \times 4 = 30.4$ | |
| 1 | Paraboloid | $A = \int_{-X}^{X} 0.15x^2 - 7\ dx$ <br> $= \left[0.15\frac{x^3}{3} - 7x\right]_{-6.831}^{6.831} = 63.76$ | 33.36 |
| 2 | Paraboloid | $A = \int_{-X}^{X} 0.2(x+6)(x-6)\ dx$ <br> $= \left[0.2\frac{x^3}{3} - 7.2x\right]_{-6}^{6} = 57.6$ | 27.2 |

| | | | |
|---|---|---|---|
| 3 | Ellipsoid | $A = \frac{1}{2}\pi XY = \frac{1}{2} \times \pi \times 5 \times 7 = 54.98$ | 24.58 |
| 4 | Ellipsoid | $A = \frac{1}{2}\pi XY = \frac{1}{2} \times \pi \times 5 \times 7 = 54.98$ | 24.58 |

*Table 26 - Areas of different possible profile sections*

From Table 26, profile 3 was selected; a hemi-ellipsoid with a depth of 7 m and a maximum radius of 5 m interfacing with the platform. Buoyancy was checked (Table 27).

| | |
|---|---|
| X (m) | 5 |
| Y (m) | 7 |
| Volume ($m^3$) | $V = \frac{1}{2}\frac{4}{3}\pi X^2 Y$ <br> $= \frac{1}{2} \times \frac{4}{3} \times \pi \times 5^2 \times 7 = 366.52$ |
| Buoyant Force (N) | $B = V\rho g$ <br> $= 366.52 \times 995 \times 9.81 = 3.578 \times 10^6\ N$ |

*Table 27 - Checking buoyant force of selected profile*

### *5.1.2 Material Selection and Manufacture*

To simplify manufacturing the frame, it will be a welded structure of standard structural components; reducing production costs and environmental impacts, as beams and columns feature recycled steel [22]. As manufacturing will take place in Australia, Australian standards of steel will be used; AS/NZS 4100 3679.2 and 3678 Grade 300 steel [23] for universal beams of designation 310UB32 and 150UB14 [24]. The properties of the beams used in the design of the frame are summarised (Table 28).

| Property | 150UB14 | 310UB32 |
|---|---|---|
| Yield Strength, $f_y$ (MPa) | 320 | |
| Tensile Strength, $f_u$ (MPa) | 430 | |
| Elastic Modulus, E (GPa) | 200 | |
| Shear Modulus, G (GPa) | 80 | |
| Density, ρ ($kgm^{-3}$) | 7750 | |
| Cross-Sectional Area, A ($m^2$) | 1.78 $\times 10^{-3}$ | 4.08 $\times 10^{-3}$ |
| 2nd Moment of Area, $I_X$ ($m^4$) | 6.66 $\times 10^{-6}$ | 63.2 $\times 10^{-6}$ |

*Table 28 - Properties of selected universal beams*

The structure will be welded using flux-cored arc welding (common for this type of application) [25] and the structure will not require disassembly until end of life, at which point the method of disassembly is not critical as the universal beams are intended to be reused or recycled. Use of a bolted structure introduces additional production costs through extra hardware required and additional processes, and potential failure modes through stress concentrations and assembly requirements.

### 5.1.3 Frame Design

The internal frame was designed iteratively, firstly through theoretical calculations, then reinforced and validated through use of CAD and FEA software. The frame began as four columns and a series cross-members (Figure 35) to determine the vertical stresses and deflections in the beams (Tables 29 and 30).

*Figure 35 - Initial draft of internal frame structure*

| | |
|---|---|
| Weight of Mass, mg (N) | 0.5886 x$10^6$ |
| No. of Columns, n | 4 |
| Factor of Safety, $f$ | 2 |
| Minimum Cross-sectional Area, A ($m^2$) | $A \geq \frac{\mathrm{f}mg}{nf_y}$ <br> $\geq \frac{2 \times 0.5886 \times 10^6}{4 \times 320 \times 10^6}$ <br> $\geq 0.919 \times 10^{-3}$ |

*Table 29 - Vertical stress calculations for internal frame*

When comparing Tables 28 and 29, even the smallest designation of universal beam has a more than sufficient cross-sectional area with four columns to bear the load of the mass and the weight of the frame itself. For deflection, it was assumed that 310UB32 beam would be used. The nominal length equating to the diameter of the nominal cylinder mentioned previously, including the depth of two columns; with two intersecting cross-members taking the load, the deflection is taken as half of that of a single cross-member.

| | |
|---|---|
| Nominal Length, L (m) | $L = (2 \times 3.8) + (2 \times 0.15) = 7.9$ |
| Deflection, δ (m) | $\delta = \frac{1}{2}\frac{mgL^3}{48EI_x}$ <br> $= \frac{1}{2}\frac{0.5886 \times 10^6 \times 7.9^3}{48 \times 200 \times 10^9 \times 63.2 \times 10^{-6}}$ <br> $= 0.239m$ |

*Table 30 - Initial deflection calculations for internal frame*

A deflection of 0.239 m is unacceptably large, and so a truss was added to improve rigidity (Figure 36). FEA was used to assess stresses and displacements within the structure; a static study was performed with the relevant material properties applied. A point load equivalent to the weight of the mass was situated at the centre of the structure, and the top faces of the columns were constrained as fixed supports, as they will be fixed to the underside of the platform via an intermediary section. Results of the study are shown (Figure 37), with the legend showing deflection in millimetres.

*Figure 36 - Second iteration of internal frame structure*

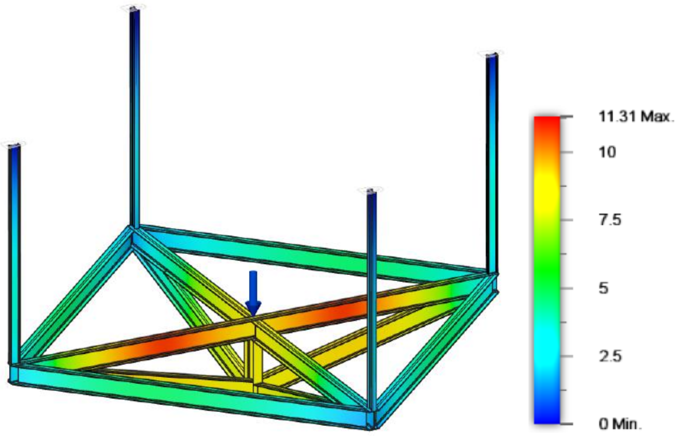



*Figure 37 - FEA results for 2nd iteration of internal frame structure*

A maximum deflection of 11.31 mm was deemed more acceptable, and so the frame was completed with braces to support any potential transverse loading to the columns and further improve the vertical support of the structure, and a top section that allows the attachment of the shell to the frame and the frame to the platform (Figure 38). Another simulation was performed with the same load conditions, except this time with the top face of the structure constrained as fixed supports instead of the columns, producing Figure 39, with the legend showing displacement in millimetres.

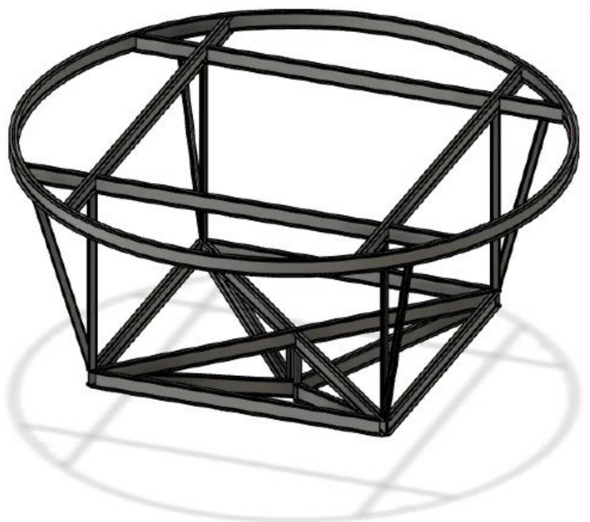


*Figure 38 - Third iteration of internal frame structure*

The final result shows a maximum displacement of 10.63 mm, which for the scale of the structure, the loads involved, and this application, is sufficient. The result also shows an uneven distribution of load between the two intersecting trusses, which is likely due to contact conditions and as such, the load will be more evenly distributed, resulting in a smaller maximum deflection.

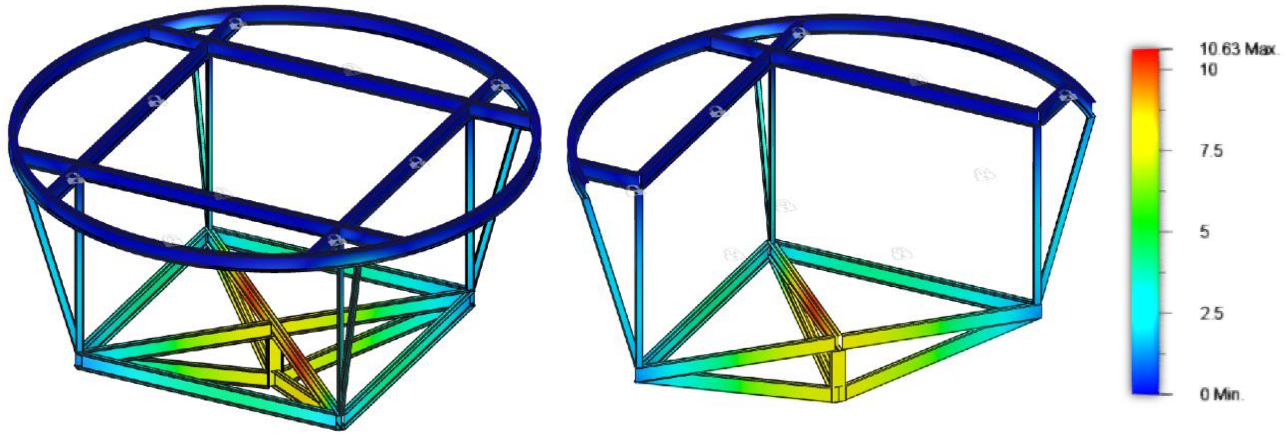



*Figure 39 - FEA results for 3rd iteration of internal frame structure*

Only two components were left, as a matter of assembly, and these were a top and bottom housing to situate the mass system and house the bearings and brake/clutch (shown in Figure 40). These will be cast in recycled steel before being machined to the necessary dimensions and surface finishes.

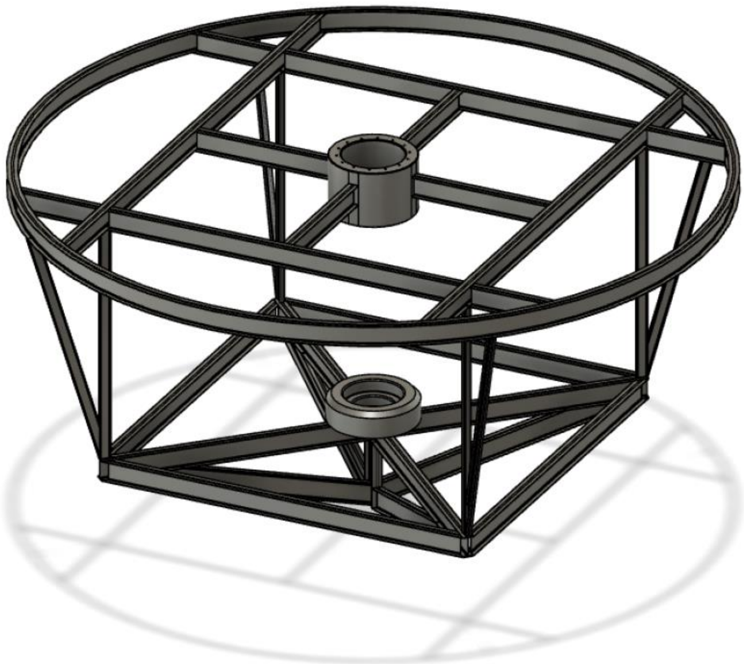


*Figure 40 - Final iteration of internal frame structure*

## 5.2 Shell

### *5.2.1 Shell Design*

The shell was designed to match the ellipsoid shape that the frame was designed for. Consequently, it has a maximum internal radius of 5 m where it meets the platform and a height of 7 m. On top of this is a 75 mm tall vertical section for holes is to be drilled into the shell so that it can be attached to the frame. The optimal thickness was found to be 5 cm. A frame was designed to attach to the shell, made of two ‘U-frames’ linked by a circular beam around the top of the shell. This will provide additional strength to the shell. The U-beams have a 100x50 mm cross-section and the circular beam has a cross-section of 50x70 mm. The frame will attach to the shell through four M36 bolts placed around the circumference of the top of the shell/frame. Indents will be made into the shell and frame for these bolts to be placed. These have a cross-section of a 70 mm square and are 25 mm deep.

### *5.2.2 Material Selection and Manufacturing*

The material of the shell will be glass-fibre reinforced plastic (GFRP), due to a low carbon footprint, a high yield strength and low cost. Table 31 shows the different materials that were considered. The specific material chosen was 30% glass polypropylene.

*Table 31. Material selection for the shell [26]*

| **Material** | **Yield Strength** (MPa) | **Tensile Strength** (MPa) | **Cost** (£/kg) | **Carbon Emissions in Manufacture** (kg/kg) | **Durability in Sea Water** | **Recyclability** |
|---|---|---|---|---|---|---|
| Steel | 475 - 525 | 652 - 720 | 0.66 – 0.85 | 2.16 – 2.38 | Limited | Recyclable |
| Aluminium | 28.5 – 31.5 | 76 - 84 | 1.32 – 1.52 | 13.1 – 14.4 | Acceptable | Recyclable |
| GFRP | 489 - 521 | 489 - 521 | 2.21-2.49 | 1.97-2.17 | Excellent | Downcycle |
| Carbon-fibre | 3,750 – 4,000 | 4,400 – 4,800 | 18.30 – 24.50 | 19.3 – 21.3 | Excellent | Downcycle |
| Polyethylene | 16 – 20 | 27.5 - 33 | 1.01 – 1.06 | 2.76 – 3.04 | Excellent | Recyclable |

The shell will be manufactured through polymer casting as this is the process suitable for large plastic parts. The shell will be coated with a copper oxide powder to increase its durability in sea water and stop marine organisms attaching to the shell. The frame will be sand cast.

### *5.2.4 Validation*

FEA was used to investigate the strength of the shell. Gravity was applied to the centre of mass and hydrostatic pressure was applied to the outside of the shell. The model was constrained at the top where the shell would be fixed to the platform. Several simplifications were applied to form a simpler mesh and reduce computing time.

The first study shows the factor of safety throughout the model and is shown in Figure 41. The factor of safety rarely falls below 4 to follow the project specification. The only areas where the factor of safety falls below this threshold is around the bolt holes, where the factor of safety is 2.475. This factor of safety was still deemed high enough to accept this model, especially considering how small these areas are.

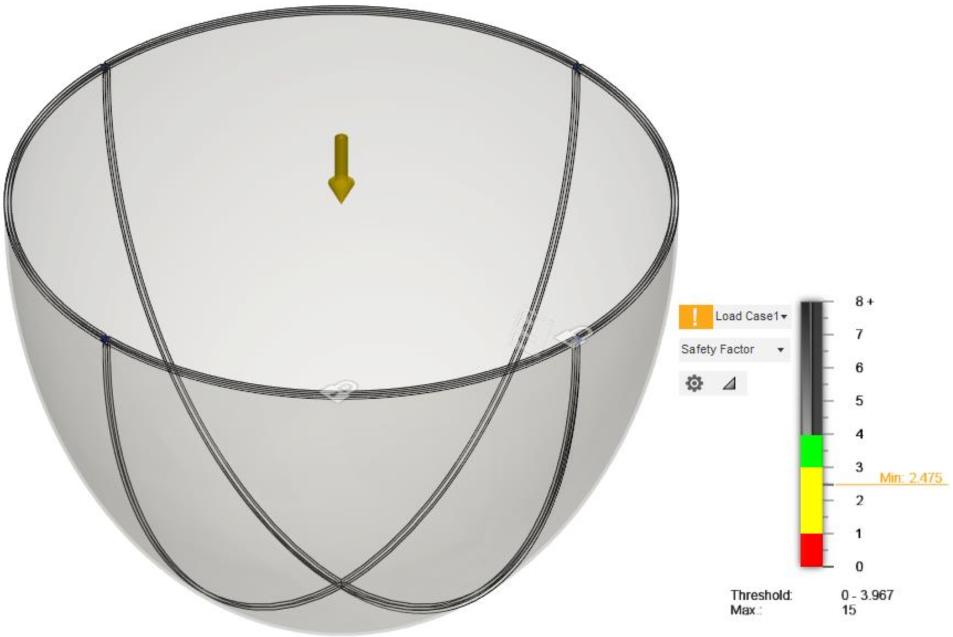



*Figure 41 - Factor of safety throughout shell*

Figure 42 shows Von Mises stress throughout the shell. Maximum stress in the shell is 5.23 MPa, below the 500 MPa tensile stress for GFRP. Maximum stress in the steel U-frames was 83.63 MPa, too small to cause damage. Thus, the structure was strong enough to validate the design.

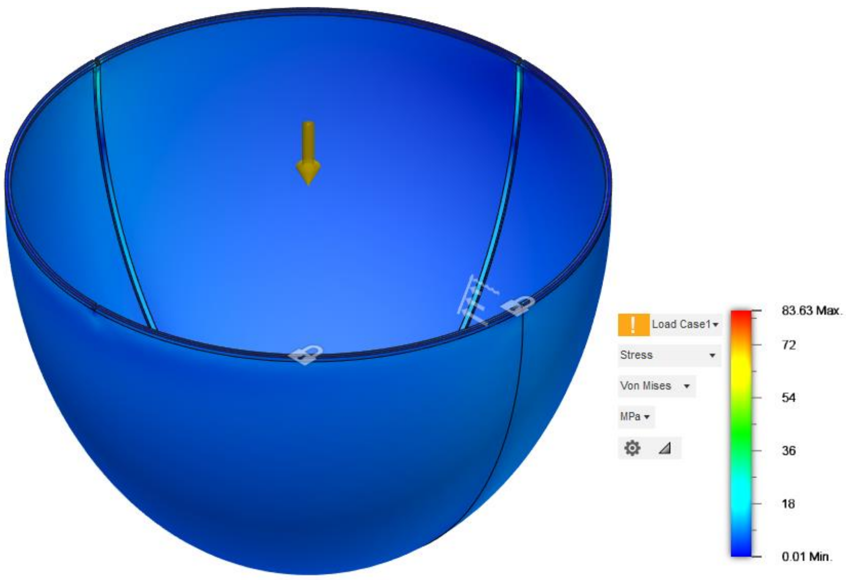



*Figure 42 - Von Mises stress throughout the shell*

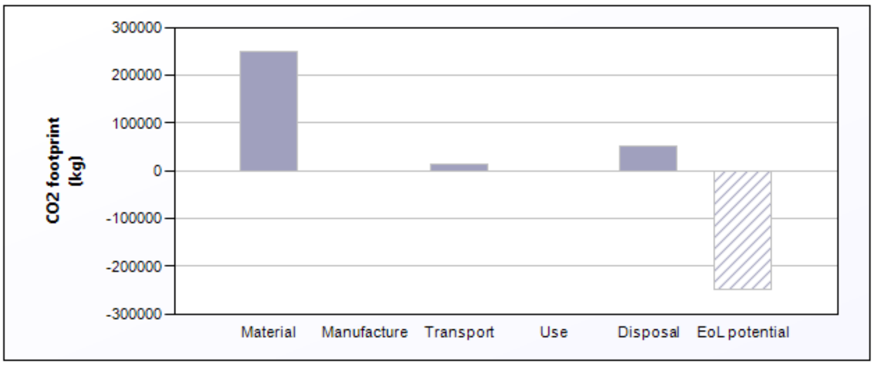
# 6. Design for Materials and Manufacturing

## 6.1 Materials Eco Audit

Since the system is designed to generate power sustainably, the energy offset is unaccounted for within the eco audit and consequently the focus will be on the CO2 footprint of each material.

Recycled Concrete:

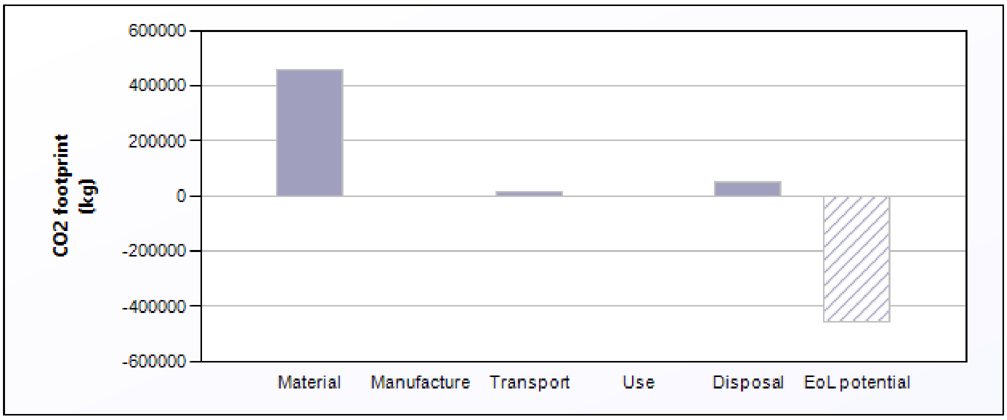
The use of expensive, $CO_2$ footprint heavy metals was minimised by filling a steel bucket with recycled concrete. Since the capacity of the project aimed to be expanded upon the success of the initial deployment in the bass strait, the concrete in end-of-life mass systems has been assumed to be reused for future systems.




| | CO2 (kg/year) |
|---|---|
| Equivalent annual environmental burden (averaged over 20 year product life): | 1.58e+04 |

*Figure 43. $CO_2$ Footprint analysis for recycled concrete*

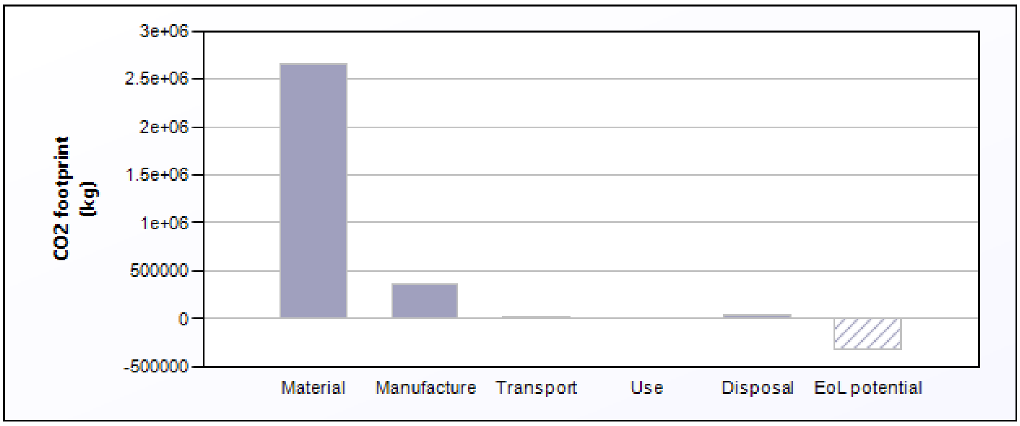
By using recycled concrete instead of virgin concrete (Figure 44), a reduction of 10400 kg/year of equivalent annual burden of $CO_2$ was achieved (average over 20-year product life period).




| | CO2 (kg/year) |
|---|---|
| Equivalent annual environmental burden (averaged over 20 year product life): | 2.62e+04 |

*Figure 44. $CO_2$ Footprint analysis for virgin concrete*

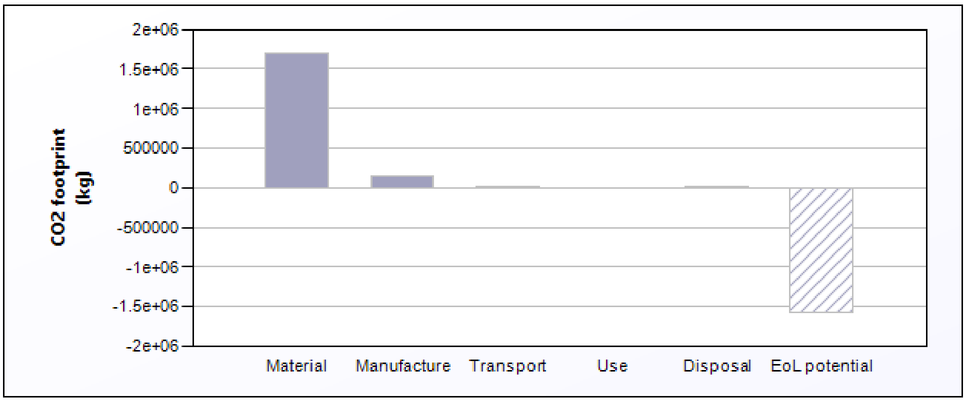
GFRP:
The glass-fibre reinforced polymer shell can be downcycled at the end of its life for insulation purposes rather than creating further landfill. Copper oxide coating will extend the 20-year life cycle. $CO_2$ footprint analysis is shown (Figure 45).




| | CO2 (kg/year) |
|---|---|
| Equivalent annual environmental burden (averaged over 20 year product life): | 1.55e+05 |

*Figure 45. $CO_2$ Footprint analysis for GFRP*

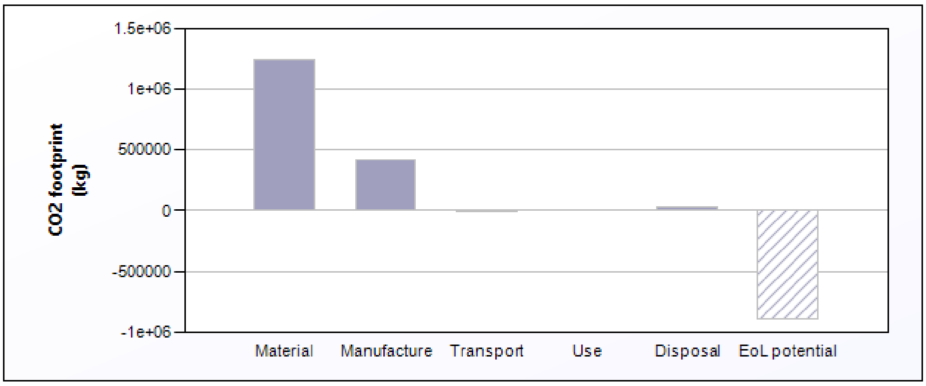
Grade 300 Steel – Universal I Beam (AS/NZS 4100 – 3679.2):
Ensuring Universal standards were adhered to, universal I beam was to be used for the internal shell frames. Consequently, at the end of life of the system, the I beams can be removed and remanufactured into replenished I beams. $CO_2$ footprint analysis is shown (Figure 46).




| | CO2 (kg/year) |
|---|---|
| Equivalent annual environmental burden (averaged over 20 year product life): | 9.35e+04 |

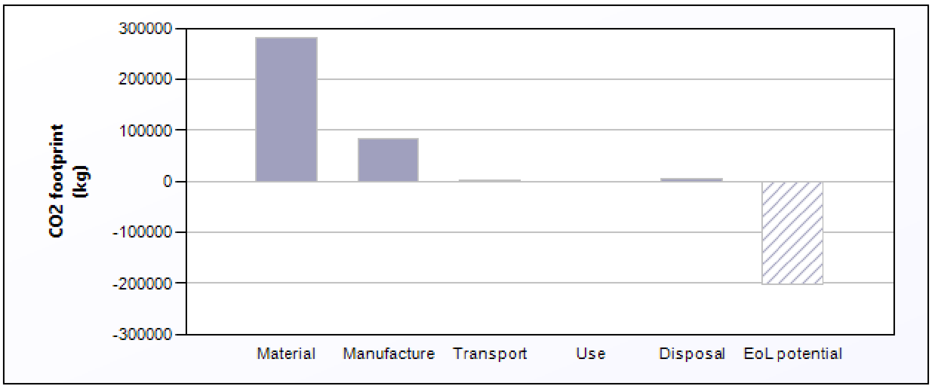
*Figure 46. $CO_2$ Footprint analysis for Grade 300 Steel*

Carbon Steel and Low Alloy Steel
Material selection for the shaft and arms was driven by the mechanical and manufacturability requirements. $CO_2$ footprint analyses for the shaft and arm material are shown (Figures 47 and 48).




| | CO2 (kg/year) |
|---|---|
| Equivalent annual environmental burden (averaged over 20 year product life): | 8.45e+04 |

*Figure 47. $CO_2$ Footprint analysis for carbon steel*




| | CO2 (kg/year) |
|---|---|
| Equivalent annual environmental burden (averaged over 20 year product life): | 1.87e+04 |

*Figure 48. $CO_2$ Footprint analysis for low alloy steel*

## 6.2 Drawings

See appendix A.1

## 6.3 Bill of Materials

See appendix A.2

## 6.4 Manufacturing Routing Sheets and Operations Lists

See appendix A.3

## 6.5 Assembly Routing

See appendix A.4

# 7. Wider Engineering Impact

The project used the United Nations sustainability development goals (SDG) [1] as guidelines to ensure sustainability is consistently considered.

## 7.1 Sustainability

*Table 32. Sustainability SDGs*

| SDG | Definition | Project Relation |
|---|---|---|
| 7 | Clean and Affordable energy | The rotating mass powers a generator via the motion of waves to produce clean electricity. The rotating mass system is designed to utilise sustainable materials where possible. |
| 9 | Industry, innovation, and infrastructure | Industry, innovation, and infrastructure – The rotating mass uses an innovative design utilising wave motion to generate power, this coupled with the infrastructure from the electrical group will feed the electricity produced into the Australian national grid. |
| 13 | Climate Action | With the ongoing current crisis of climate change the project seeks to limit the damage caused by the implementation, which includes the aim to be net carbon zero. This will aim to be achieved with utilising sustainable manufacturing, local suppliers where possible, and ensuring there is no unnecessary transportation. |
| 14 | Life below water | The rotating mass has been designed so that there is minimal impact to marine life. The shell's shape is non-invasive and has no parts where marine life could become stuck. Noise pollution is aimed to be kept at a minimum, with the clutch-brake being sealed in a casing. If after a period, the noise levels are deemed to be too high, insulation can be added to the shell to dampen this. |
| 15 | Life on land | The rotating mass shouldn't directly affect life on land; however, research has taken place for the Star of the South windfarm looking at birds migrating routes for example so this has been looked at. The manufacturing and assembly process used also aim to be non-intrusive to the wildlife |

| | | |
|---|---|---|
| | | both in terms of physically and environmentally when it comes to pollution. |

*Table 33. Sustainability impacts*

| Impact | Project Examples |
|---|---|
| Wildlife and Environmental Considerations | Many studies and investigations have been undertaken by the Star of the South windfarm to ensure the sea environment is not compromised by the windfarm and by extension the sustainable island. Fishing studies have also been undertaken by the Star of the South to understand the different type of fish present and how best to keep the environment suitable for them. On top of this the Star of the South has also followed many local regulations which have been assessed and made sure the rotating mass follows these as well. These studies have been looked at specifically to make sure that the rotating mass does not contribute to any damage to the local ocean ecosystems e.g., physical damage or noise pollution. |

## 7.2 Commercial

*Table 34. Commercial SDGs*

| SDG | Definition | Project Relation |
|---|---|---|
| 12 | Responsible consumption and production | Energy produced from the rotating mass could be directed towards the agricultural, manufacturing, and recycling industry to help these sectors become more sustainable. |

## 7.3 Social

*Table 35. Social SDGs*

| SDG | Definition | Project Relation |
|---|---|---|
| 8 | Decent work and economic growth | Due to the scale of the project, it will provide thousands of jobs in manufacture, construction, and maintenance. For |

| | | |
|---|---|---|
| | | example, in the manufacture of the mass and the shell, as well as the overall assembly of the platform. |
| 11 | Sustainable cities and communities | The sustainable energy produced from the rotating mass will be directed to local communities. This is likely to encourage more sustainable development, allowing for more focus on the integration of carbon capture and sustainable transport systems. |

## 7.4 International Factors

*Table 36. International factors SDGs*

| SDG | Definition | Project Relation |
|---|---|---|
| 16 | Peace, justice, and strong institutions | The island allows unions between countries, by aiding in the further development of those countries in the sharing of information in relation to the rotating mass and its applications in sustainable power generation. |
| 17 | Partnerships for the goals | The island aims to furthers unions and partnerships between countries as they strive towards a goal of environmental sustainability as the rotating mass is a form of sustainable energy production on the island. The ideas and principles behind the rotating mass and other forms of sustainable power generation could be taken on by other countries for them to develop more sustainability infrastructure. |

## 7.5 Ethical

*Table 37. Ethical engineering principles*

| Ethical Principal | Definition | Project Examples |
|---|---|---|
| Honesty & Integrity | "Professional engineers and technicians should adopt the highest standards of professional conduct, openness, fairness and honesty." | Considering how the project will affect local communities and the ecosystem. |
| | | Keeping reliable honest communication open with stakeholders so people are aware of the details, impacts, and progress of the project. |

| | | |
|---|---|---|
| Respect for Life, Law, & the Public Good | "Professional engineers and technicians should give due weight to all relevant law, facts and published guidance, and the wider public interest." | Ensuring appropriate research has taken place to ensure patent infringement does not occur, as well as adhering to other laws regarding the environment. |
| | | Ensuring the project reliably sticks to the aims defined in the United Nations SDGs (Sustainable Development Goals). |
| | | Where possible having parts made and manufactured as close to the site as possible to remove unnecessary transport and costs. |
| | | Ensuring all necessary safety precautions are in place based off the law and risks identified in the risk assessment. |
| | | Ensuring that all waste is disposed of responsibly, being recycled where possible. |
| Accuracy & Rigor | "Professional engineers and technicians have a duty to ensure that they acquire and use wisely and faithfully the knowledge that is relevant to the engineering skills needed in their work in the service of others." | Appropriate calculations are used to determine technical parameters based off data gained through thorough research. |
| | | Using appropriate methods of technical validation including calculations, FEA, DFMEA, material analysis, & environmental analysis. |
| Leadership and Communication | "Professional engineers and technicians should aspire to high standards of leadership in the exploitation and management of technology. They hold a privileged and trusted position in society and are expected to demonstrate that they are seeking to serve wider society and to be sensitive to public concerns." | Ensuring effective communication within the group as well as the wider team to ensure the project goals are accomplished in an integrated manner. |
| | | Ensuring effective honest communication with stakeholders |

## 7.5 Industry

*Table 38. Industry impacts*

| Impact | Project Examples |
|---|---|
| Electricity production | The star of the South windfarm would produce up to 2.2 GW of renewable electricity, enough |

| | |
|---|---|
| | to power 1.2 million homes across the state of Victoria which is around 20% of the state's demand . This would be supported by the power generated by the rotating mass. |
| Jobs | The windfarm itself would create up to 2,000 new jobs over its lifetime in Victoria, including 760 jobs during construction in Gippsland and 200 local jobs once up and running. More jobs would result from sustainable island too as people would be required to supply, manufacture, assemble, and maintain the islands. The windfarm itself would result in wider economic benefits worth more than $10.4 billion for Victoria (gross value added) which would also be compounded with by the additional value added from the sustainable islands. |

## 7.6 Legal

*Table 39. Legal impacts*

| Impact | Project Examples |
|---|---|
| Patents | An extensive patent search has been undertaken to ensure that the design for the rotating mass has not infringed on any intellectual property protected legally by a patent in Australia. The patent search found that many patents had been granted in relation to energy generation from waves however, there had only been one patent granted in relation to a rotating mass , but this version of a rotating mass design differs greatly to the design in this project. |
| Legal Protocols | Various methods have been used to follow legal protocol, for example, using Australian standards for design and material selection. Sustainability laws have also been followed, as well as the UN SDGs, to make sure the project is as sustainable as possible. |

## 7.7 Human Factors

*Table 40. Human impacts*

| Impact | Project Examples |
| --- | --- |
| Jobs and the Local Community | The jobs created by the windfarm and the islands would improve the quality of life for the employees as well as the local are due to an improved economy. The addition of new jobs would likely attract more people to the local area meaning there is likely to be an increase in local businesses e.g., cafes, restaurants, and shops. An increased population would likely increase the number of schools in the local area giving local children a wider better opportunity to learn. |

## 7.8 Health and Safety

*Table 41. Health and safety impacts*

| Impact | Project Examples |
| --- | --- |
| Health and Safety | Health and safety regulations would be set out and followed, including those set out by the Australian government. A risk assessment has also been undertaken to ensure that all plausible risks have been accounted for and have mitigations in place. |
| Personal and Wildlife Safety | The personal safety of all the employees would be of utmost importance. However, the safety of local wildlife is also very important and risks to its safety are addressed too and aim to be avoided. |

# 8. Risk Management

## 8.1 FMEA

*Table 42. Failure Modes Element Analysis*

| Process Step/Input | Potential Failure Mode | Potential Failure Effects | Severity (1 – 10) | Potential Causes | Occurrence (1 – 10) | Current Controls | Detection (1 – 10) | RPN | Action Recommended |
|---|---|---|---|---|---|---|---|---|---|
| What is the process step, change or feature under investigation? | In what ways could the step, change or feature go wrong? | What is the impact on the customer if this failure is not prevented or corrected? | | What causes the step, change or feature to go wrong? (How could it occur?) | | What controls exist that either prevent or detect the failure? | | | What are the recommended actions for reducing the occurrence of the cause or improving detection? |
| Shell | Cracked Shell | Shell may become compromised. | 5 | - Unexpected external loads/impacts<br>- Marine debris or wildlife<br>- Detached mass Logistical malpractices | 2 | - Platforms will be situated in a relatively inactive area, in terms of boats and wildlife<br><br>- Monitoring and control of power output/performance will indicate potential external impacts, non-mechanical failures or attention required | 7 | 70 | Scheduled inspections every 3 months to identify any damage, potential faults, and subsequent repairs/actions |
| | | Chamber may flood, limiting power output | 7 | | 3 | | 7 | 147 | |
| | | Sea water salinity/acidity can cause corrosion | 4 | | 3 | | 7 | 84 | |
| | Dented/Buckled Shell | Shell may obstruct movement of mass | 8 | - Unexpected external loads/impacts<br>- Marine debris or wildlife<br>- Detached mass<br>- Logistical malpractices | 3 | | 7 | 168 | |
| | | Change of chamber volume can affect buoyancy | 4 | | 4 | | 7 | 112 | |
| | | Shell may be compromised, leading to cracks and breaches | 5 | | 3 | | 7 | 105 | |
| | Detached Shell | Mass system will become flooded, limiting power output | 7 | - Unexpected external loads/impacts<br>- Detached mass<br>- Logistical malpractices<br>- Shear of overstressed fixings | 2 | | 1 | 14 | |
| | | Buoyancy is lost | 9 | | 2 | | 1 | 18 | |
| | | Sea water salinity/acidity can cause corrosion | 4 | | 2 | | 1 | 8 | |
| | Leaking Shell | Shell may become compromised. | 5 | - Under-torqued fixings<br>- Ruptured or insufficient seals<br>- Dented/Buckled/ Warped shell could weaken interfaces between shell halves and the frame | 4 | | 8 | 160 | |
| | | Chamber may flood, limiting power output | 7 | | 2 | | 8 | 112 | |
| | | Sea water salinity/acidity can cause corrosion | 4 | | 5 | | 8 | 160 | |
| Frame | Detached/ Collapsed Frame | Complete loss of power production | 8 | - Unexpected external loads/impacts<br>- Detached mass<br>- Compromised fixation to platform | 2 | - Monitoring and control of power output/performance will indicate potential non-mechanical failures or attention required | 1 | 16 | |
| | | Follow up damage to other sub-systems and components, | 7 | | 2 | | 1 | 14 | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | although may be recoverable | | - Excessive wave angle<br>- Large, sudden displacement of platform | | - Frame has been overrated with a requisite factor of safety in order to use universal beams | | | |
| | Deformation | Shell and frame may become compromised | 5 | - Detached mass<br>- Excessive wave angle<br>- Large, sudden displacement of platform | 3 | | 3 | 45 | |
| | | Potential damage to major components | 5 | | 3 | | 3 | 45 | |
| | | Loss in efficiency/power output | 4 | | 3 | | 2 | 24 | |
| | | Frame may obstruct movement of mass | 7 | | 3 | | 2 | 42 | |
| Rotating Mass | Detached | Loss of power output | 8 | - Shear of overstressed fixings<br>- Mispositioned mass<br>- Overspeed rotation of mass<br>- Large, sudden displacement of platform | 4 | - Monitoring and control of power output will detect loss of power<br>- Mass, shaft and fixings have been simulated and specified appropriately<br>- Fixings will be tensioned appropriately<br>- Brake/Clutch allows control of the speed of mass rotation | 1 | 32 | |
| | | Mass can cause follow up damage to shaft, frame and shell | 7 | | 4 | | 3 | 84 | |
| | | Change in momentum may disturb platform | 2 | | 4 | | 7 | 56 | |
| | Restricted/Failed Movement | Loss in efficiency/power output | 4 | - Deformed frame<br>- Excessive bearing wear/bearing failure<br>- Brake Malfunction | 4 | - Appropriate ratings for bearings<br>- Lubricant service every 2 years<br>- Control of braking will identify any malfunctions | 2 | 32 | Scheduled service of brake/clutch every year, and subsequent action, if required<br>Bearing relubrication every 2 years, and inspect condition |
| | | Additional stresses to frame | 3 | | 4 | | 9 | 108 | |
| | Bent/Deformed Shaft | Misalignment with brake, clutch and bearings | 4 | - Underrated shaft specification | 2 | Shaft has been modelled and specified appropriately | 8 | 64 | |
| | | Mispositioned mass | 2 | | 2 | | 9 | 36 | |
| | Overspeed rotation of mass | Impulse may cause rotation of platform | 2 | - Failed brake control<br>- Excessive wave angle | 5 | - Control of braking will identify any malfunctions<br>- Scheduled service of brake/clutch every year, and subsequent action, if required | 7 | 70 | |
| | | Excessive loads on shaft | 3 | | 5 | | 9 | 135 | |
| | | Power output surge | 3 | | 5 | | 2 | 30 | |
| | | Increased loads on mass arms | 3 | | 6 | | 9 | 162 | |
| | Excessive shaft deflection | Mass may foul frame | 6 | - Overspeed rotation of mass<br>- Excessive wave angle | 2 | - Shaft has been modelled and specified appropriately | 2 | 24 | |
| | | Permanent deformation of shaft | 5 | | 2 | | 5 | 50 | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Misalignment with brake, clutch and bearings | 4 | - Large, sudden displacement of platform | 3 | - Brake/Clutch allows control of the speed of mass rotation to limit deflection | 8 | 96 | |
| | Shaft misalignment | Irregular bearing, brake and clutch wear | 4 | - Incorrect assembly<br>- Deformation of shaft or frame | 3 | - Shaft has been modelled and specified appropriately<br>- Assembly features regular checks and repeatability | 6 | 72 | |
| | | Mispositioned mass | 2 | | 2 | | 9 | 36 | |
| | | Mass and shaft are not secure, so could detach | 5 | | 3 | | 4 | 60 | |
| Brake/Clutch | Failed Engagement/ Disengagement | Loss of power output | 8 | - Hydraulic malfunction<br>- Control malfunction<br>- Severe misalignment of shaft | 4 | - Control of brake/ clutch will identify any malfunctions<br>- Scheduled service of brake/clutch every year, and subsequent action, if required | 1 | 32 | |
| | | Surge in power output | 3 | | 3 | | 2 | 18 | |
| | | Overspeed rotation of mass | 3 | | 4 | | 3 | 36 | |
| | Incorrect Engagement/ Disengagement | Loss of power output | 8 | - Hydraulic malfunction<br>- Control malfunction | 4 | - Control of brake/ clutch will identify any malfunctions<br>- Scheduled service of brake/clutch every year, and subsequent action, if required | 1 | 32 | |
| | | Surge in power output | 3 | | 3 | | 2 | 18 | |
| | | Overspeed rotation of mass | 3 | | 4 | | 3 | 36 | |
| | Insufficient Braking | Surge in power output | 3 | - Excessive wear of brake pads<br>- Hydraulic malfunction<br>- Lack of hydraulic pressure | 3 | - Control of brake/ will identify any malfunctions<br>- Scheduled service of brake/clutch every year, and subsequent action, if required | 2 | 18 | |
| | | Overspeed rotation of mass | 3 | | 4 | | 3 | 36 | |
| | Slipping Clutch | Loss of power transmission/ efficiency | 4 | - Excessive wear of clutch<br>- Hydraulic malfunction<br>- Lack of hydraulic pressure | 3 | - Control of clutch will identify any malfunctions<br>- Scheduled service of brake/clutch every year, and subsequent action, if required | 2 | 24 | |
| CVT Gearbox | Incorrect speed selection | Underspeed or overspeed at alternator (loss in efficiency) | 4 | - Control malfunction<br>- Belt fatigue | 3 | Control of output will identify incorrect speed at alternator or fault during transmission | 1 | 12 | |
| | | Incorrect torque output (stress on powertrain) | 4 | | 3 | | 3 | 36 | |
| | No output | Loss of power output | 8 | - Ruptured belt<br>- Broken input/ output shaft | 1 | Control of output will identify critical loss of power | 1 | 8 | |
| | Belt fatigue | Loss in power transmission/ efficiency | 4 | - Erratic speed selection changes<br>- Extended high ratio use | 2 | Control of output will identify fault during transmission | 2 | 16 | Scheduled service of gearbox (determined by supplier/ manufacturer) |
| | | Reduced accuracy in speed selection | 4 | | 2 | | 4 | 32 | |
| Bevel Gearbox | No Output | Loss of power output | 8 | - Broken input/output shaft | 2 | Control of output will identify critical loss of power | 1 | 16 | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | - Stripped gears/ sheared gear teeth<br>- Seized or jammed gears | | | | | |
| | Oil Leak | Reduced durability of powertrain | 2 | - Damage to gearbox casing<br>- Perished seals/ gaskets due to age | 2 | Scheduled service of gearbox annually, and subsequent action, if required<br>Scheduled relubrication of gearbox every 2 years | 9 | 36 | |
| | | Loss in efficiency | 3 | | 2 | | 4 | 24 | |
| Alternator | No Output | Lack of power production | 8 | - Disconnected output<br>- Broken input shaft<br>- Alternator burnout | 2 | Control of output will identify critical loss of power | 1 | 16 | Scheduled service of alternator annually, and subsequent action, if required |
| | Loss in Output/ Efficiency | Reduced power production capability | 6 | - Excessive wear of magnets/ windings<br>- Overspeed or underspeed at input | 3 | Control of output will identify potential faults in power production | 2 | 36 | |

# 9. Business Plan

## 9.1 The Market

### *9.1.1 Customers*

Energy companies owning wind farms will be our customers. Our initial design focusses on the Star of the South wind farm, owned by Offshore Energy Pty Ltd. The marketing will aim at energy companies who specialise in renewable energies and operate in country, with the aim to boost the local economy. Energy companies integrating the energy islands into their wind farm will not only provide more power to their consumers, but also create a more consistent and predictable output from the whole system, as they lose soul dependency on wind variability. The main factors that they will be looking for in the WEC is its sustainability, power output and cost.

### *9.1.2 Market Research*

The market for the renewable wave energy sector grows rapidly as the world shifts to a net-zero economy and wave energy is viewed as a cheaper, more predictable alternative to other renewable energy sources. There are currently four known rotating mass WEC projects, but none based in Australia (our initial target market) whose government set a target for net-zero by 2050, but due to its history of relying on coal power, currently has a limited renewable energy sector. In 2020 only 8% of Australian energy consumption came from renewable energy sources, rising to 29% in 2021, showing growth of this sector and market.

## 9.2 Competitors

### 9.2.1 Table of Competitors

*Table 43 - Table of Competitors*

| Name, location, and business size | Products/services | Strengths | Weaknesses |
|---|---|---|---|
| Enorasy LLC, USA, Small | Robotic Juggler Offshore WEC | Has access to expertise from partners such as MIT and NREL. Receives grants from US Department of Energy. Focussed on WEC. | Very small company could lead to lack of expertise within project. Not based in Australia. |
| Wave for Energy s.r.l, Italy, Medium nationwide | Inertial Sea Wave Energy Converter (ISWEC), Water Energy Point Absorber (WEPA) | WEC is adaptable to different conditions, making their product highly scalable. Focussed on wave power. | Tested in Mediterranean Sea, where conditions are less harsh than the Ocean. Low power output. Not based in Australia. |
| Wello Oy, Finland, Large global | Penguin WEC | Various size of WEC makes it adaptable to other locations. Tested in harsh conditions. High power output. | Larger company more susceptible to public scrutiny and legal proceedings and must face more. Not focussed on using sustainable materials and manufacturing methods. |
| WITT Limited, UK, Medium | WITT Dragonfly, Personal WITT | Scalable. Works with six degrees of freedom. | Not focussed on WEC. Not based within Australia |

### 9.2.2 SWOT Analysis

| Strengths | Weaknesses |
|---|---|
| • Designed to integrate with an offshore island in a windfarm to make use of | • Lack of highly skilled workers within local area due to it being new |

| | |
|---|---|
| empty space and provide a more consistent output.<br>• Uses sustainable materials.<br>• Initially based in Australia with a growing market for renewable energy systems.<br>• Designed to be modular to increase scalability. | technology. Workers will be trained to work with the new technology.<br>• Due to the converter being in the ocean with harsh waves, access for maintenance will be restricted. Ways to make maintenance accessible have been incorporated into the design of where the converter attaches to the platform.<br>• Could disrupt local wildlife but since it will operate in a windfarm, the additional disruption will be minimal. It also won't be big enough to cause damage.<br>• Having a focus on sustainability could cause an increase in costs. |
| **Opportunities** | **Threats** |
| • Increased demand to reach a net-zero economy due to the climate crisis will increase a demand for renewable energy systems.<br>• Rising sea levels and bigger waves from climate change will allow the converter to harness more power.<br>• Due to a lack of development with rotating mass wave energy converters, there are few competitors, especially ones in full operation.<br>• Increasing gas prices around the world has increased the demand for cheaper, renewable energy sources such as wave power. | • Unpredictability of the effects of climate change could mean the product isn't tested in future conditions. The system has been designed with an increased size of waves, harsher storms, and more acidic water in mind.<br>• A change of politics within Australia and/or Victoria could lead to them being less willing to increase their renewable energy capacity.<br>• Changes to the local and global economy could make it more difficult to manufacture and maintain the components and increase costs. |
| **Unique Selling Points (USPs)** | |
| Our rotating mass wave energy converter will be designed to integrate with wind farms as well as the solar panels and point absorber that are also connected to the offshore island. This will mean the overall system will be able to provide a consistent output that other wind farms cannot provide. Our system will also be designed to be manufactured and to operate in the local area of the wind farm to help boost the local economy. The materials will be sustainable and sourced locally to minimise the carbon footprint. | |

*Figure 49 - SWOT Analysis*

## 9.3 Product to Market Strategy

*Table 44 - Product to market strategy*

| | |
|---|---|
| Marketing | Since the initial design was made specifically for the Star of the South wind farm, Offshore Energy Pty Ltd will be contacted directly. |

| | |
|---|---|
| | Benefits of the energy island will be demonstrated to create a partnership between the two companies. |
| Public Support | Marketing will also be aimed at the residents of Victoria to gain public support. Social media will advertise the benefits of the project and articles in appropriate magazines and journals will be published. Once operational, all necessary data will be published to the public. |
| Legal | The design will be presented to the Victoria state government as a project boosting the local manufacturing industry and help them reach their net-zero goals, to achieve support and funding. Permission to use the Bass Strait for offshore wave power should be granted by the Australian government since the Offshore Electricity Infrastructure Act 2021 (OEI Act) [46] declared the Bass Strait as a suitable area for offshore energy, meaning developers can easily apply for licenses. |
| Production | Production will begin on agreement. 130 modules will be produced for the Star of the South, and completion will aim to coincide with the completion of the wind farm by the end of the decade. Manufacturing for the system will be performed locally. |
| Payment | An initial payment will be made by Offshore Energy Pty Ltd for each unit, once each island is operating, a share of the profits from the entire wind farm/offshore island system will be earned, in accordance with the percentage of energy the offshore islands provide compared to the wind turbines. |
| Growth | Once operational, the islands will be advertised for other wind farms globally. Energy islands will be presented to energy companies constructing wind farms, using the project in the Star of the South as a case study. The benefits to the economy will be demonstrated to governments. Each time the islands are used |

| | |
|---|---|
| | in a different wind farm, production for those islands will be done in the local area. |

## 9.4 Finance

### *9.4.1 Cost*

#### *9.4.1.1 Mass System Sub-Assembly*

*Table 45 - Material cost for mass sub-assembly*

| **Material Cost** [26] | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Part** | **Material** | **Material Cost (£/kg)** | **Mass of Part (kg)** | **Quantity per assembly** | **Total Quantity** | **Cost / unit (£)** | **Total Cost (£)** |
| **Shaft** | Carbon steel, AISI 1137, water quenched & tempered at 205°C | 0.65 | 4481.28 | 1 | 130 | £2,899.39 | £376,920.34 |
| **Arm Large Side** | Low alloy steel, SAE 4335M, cast, quenched & tempered | 1.01 | 852.17 | 1 | 130 | £864.52 | £112,388.22 |
| **Arm Small Side** | | 1.01 | 202.60 | 1 | 130 | £205.54 | £26,720.34 |
| **Bucket** | Low alloy steel, SAE 4130, cast, normalized & tempered | 0.75 | 20783.2 | 1 | 130 | £15,618.57 | £2,030,414.72 |
| **Concrete** | Recycled Concrete | 0.02 | 40696.8 | 1 | 130 | £732.54 | £95,230.51 |
| **TOTAL** | | | | | | £20,320.57 | £2,641,674.14 |

*Table 46 - Costs for outsourced parts in mass sub-assembly*

| **Outsourced Costs** | | | | | |
|---|---|---|---|---|---|
| **Part** | **Supplier** | **Quantity per assembly** | **Total Quantity** | **Cost / unit (£)** | **Total Cost (£)** |

| | | | | | |
|---|---|---|---|---|---|
| **NU 3080 MA** | Zoro (Scheerer bearing corporation) | 1 | 130 | £18,766.00 | £2,439,580.00 |
| **NU 2292 MA** | Acorn industrial services limited (SKF authorised distributor) | 1 | 130 | £35,745.00 | £4,646,850.00 |
| **29464 E** | Acorn industrial services limited (SKF authorised distributor) | 1 | 130 | £17,614.00 | £2,289,820.00 |
| **M36 150 mm Bolt** | McMasterCarr | 14 | 1820 | £700.00 | £91,000.00 |
| **M36 Lock Washer** | McMasterCarr | 14 | 1820 | £27.00 | £3,510.00 |
| **M36 Nylon Insert Locknut** | McMasterCarr | 6 | 780 | £150.00 | £19,500.00 |
| **TOTAL** | | | | £73,002.00 | £ 9,490,260 |

*Table 47 - Manufacturing costs for mass sub-assembly*

| **Manufacture Cost** | | | | |
|---|---|---|---|---|
| **Part** | **Arm Short Side** | **Arm Long Side** | **Bucket** | **Shaft** |
| **Casting Process** | Sand casting - low surface quality | Sand casting - low surface quality | Sand casting - low surface quality | |
| **Casting Cost (£)** | £389.15 | £1,636.89 | £34,458.21 | |

| | | | | | |
|---|---|---|---|---|---|
| **Machining Description** | CNC 3 axis mill - 'complex' machining | CNC 3 axis mill - 'complex' machining | CNC 3 axis mill - 'complex' machining | See below | |
| **Machining Cost (£)** | 164.03 | 689.96 | 16,826.90 | Lathe CNC | 1,000.00 |
| | | | | Hobbing Machine | 1,600.00 |
| | | | | 3 axis mill | 800.00 |
| | | | | Curing oven | 100.00 |
| | | | | Total | 3,500.00 |
| **Painting Cost (£)** | 29.32 | 123.33 | 2,403.84 | 450.00 | |
| **Package Cost (£)** | 23.43 | 98.55 | 721.15 | 194.56 | |
| **Sea Freight Cost (£)** | 9.37 | 39.41 | 961.54 | 259.41 | |
| **Cost / Unit (£)** | 593.01 | 2,494.39 | 55,371.65 | 3,500.00 | |
| **Cost (£)** | £77,091.30 | £324,270.51 | £7,198,314.50 | £455,000.00 | |
| **TOTAL** | | | | £8,054,676.31<br>£61,959 per unit | |

*Table 48 - Mass sub-assembly summary of costs*

| **Summary** | |
|---|---|
| **Material** | £2,641,674.14 |
| **Outsourced** | £9,490,260 |
| **Manufacture** | £8,054,676.31 |
| **Total** | £20,186,610.45 |

### *9.4.1.2 Powertrain Sub-Assembly*

*Table 49 - Powertrain sub-assembly outsourced component costs*

| **Outsourced Cost** |
|---|

| Part | Supplier | Quantity Per Assembly | Total Quantity | Cost/Unit (£) | Total Cost (£) |
|---|---|---|---|---|---|
| **Ortlinghaus Series 123 Hydraulic Clutch-Brake** | Ortlinghaus | 1 | 130 | 7,500 | 975,000 |
| **ZF Redulus GP 615** | ZF | 1 | 130 | 15,000 | 1,950,000 |
| **CVTCORP's mCVT** | CVTCORP | 1 | 130 | 18,000 | 2,340,000 |
| **Stamford S4L1M-F42 Class-H** | Stamford | 1 | 130 | 20,000 | 2,600,000 |
| | | | Total: | 60,500 | 7,865,000 |

### *9.4.1.3 Shell and Structure Sub-Assembly*

*Table 490 - Material costs for structure sub-assembly*

| **Material Cost** [26] | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Part** | **Material** | **Material Cost (£/kg)** | **Mass of Part (kg)** | **Quantity per assembly** | **Total Quantity** | **Cost / unit (£)** | **Total Cost (£)** |
| **Shell** | Polypropylene, 30% random glass mat | 0.65 | 11,293.7 | 1 | 130 | 4,805.83 | 3,450,225.35 |
| **Shell Frame** | Carbon steel, ASME SA216, Annealed | 0.02 | 2,394.25 | 1 | 130 | 3,325.35 | 224,101.80 |
| **TOTAL** | | | | | | 8,131.18 | 3,674,327.15 |

*Table 501 - Costs for outsourced parts in structure sub-assembly*

| **Outsourced Costs** | | | | | |
|---|---|---|---|---|---|
| **Part** | **Supplier** | **Quantity or length (m) required per assembly** | **Total quantity or length (m)** | **Cost per part or metre (£)** | **Total cost (£)** |

| | | | | | |
|---|---|---|---|---|---|
| **150UB14 Steel Universal Beams** | Scott Metals | 28.62 | 3,720.6 | 38.72 | 144,061.63 |
| **310UB32 Steel Universal Beams** | Scott Metals | 126.02 | 16,382.6 | 79.85 | 1,308,150.61 |
| **M36 x 180 mm bolt** | McMaster-Carr | 4 | 520 | 23.69 | 12,318.80 |
| **M36 Hex Nut** | McMaster-Carr | 4 | 520 | 12.74 | 6,624.80 |
| **TOTAL** | | | | | 1,471,155.84 |

*Table 551 - Manufacturing costs for structure sub-assembly*

| **Manufacture Cost** | | | | |
|---|---|---|---|---|
| **Part** | **Shell** | **Shell Frame** | **Internal Frame** | |
| **Manufacture Process** | Polymer Casting | Sand cast | Cutting | Welding |
| **Process Cost (£)** | 11,293.70 | 7,182.75 | 2,690.00 | 6,870.00 |
| **Post-Process** | EU45 High Strength Copper Oxide Antifouling | | | |
| **Post-Process Cost (£)** | 811.32 | 0 | 0 | |
| **Transport Cost (£)** | 522.3 | 110.73 | 202.03 | |
| **Cost/unit (£)** | 12,627.32 | 7,293.48 | 9,762.03 | |
| **Cost (£)** | 1,641,551.60 | 948,152.40 | 1,269,063.90 | |
| **TOTAL** | | | | £3,858,767.90<br>£ 29,682.83 per unit |

*Table 53 - Summary of costs for structure sub-assembly*

| **Summary** | |
|---|---|
| **Material** | £3,674,327.15 |

| | |
|---|---|
| **Outsourced** | £1,471,155.84 |
| **Manufacture** | £8,054,676.31 |
| **Total** | £13,200,159.30 |

#### 9.4.1.4 Labour Costs

*Table 54 - Labour costs and production time for different units of labour*

| Units of labour | Production time per unit (hours) | Labour cost per unit (£) | Total labour cost for 130 units (£) |
|---|---|---|---|
| 1 | 986 | 19,720 | 2,563,600 |
| 10 | 98 | 19,600 | 2,548,000 |
| 20 | 48 | 19,200 | 2,496,000 |
| 30 | 30 | 18,000 | 2,340,000 |
| 40 | 23 | 18,400 | 2,392,000 |
| 50 | 22 | 22,000 | 2,860,000 |

### 9.4.2 Profitability and Rate of Return

$$Rate\ of\ Return = \frac{Final\ Value - Initial\ Value}{Initial\ Value} \times 100$$

*Table 525 - Profitability and Rate of Return*

| | |
|---|---|
| **Total Part/Material Cost per Unit** | £173,270.33 |
| **Total Manufacturing Cost per Unit** | £91,641.83 |
| **Total Labour Cost per Unit** | £18,000.00 |
| **Total Cost per Unit** | £282,912.16 |
| **Total Cost per 130 Units** | £36,778,581.24 |
| **% Mark-up** | 60 |
| **Sale Price per Unit** | £452,659.46 |
| **Sale Price per 130 Units** | £58,845,729.98 |
| **Public Funding from Government** | £16,000,000.00 |

| | |
|---|---|
| **Private Funding from Investors** | £24,000,000.00 |
| **Total Funding** | £40,000,000.00 |
| **Total Owed to Investors** | £24,960,000.00 |
| **Immediate Profit** | £22,067,148.74 |
| **% Profit to Investors** | 15 |
| **Money Returned to Investors** | £3,310,072.31 |
| **Actual Profit** | £18,757,076.43 |
| **Business Rate of Return** | 51 |
| **Investors Rate of Return** | 13.79 |

## 9.5 Investment Sources

The project will be funded 40% through government grants and 60% through private funding. Public funding will be provided by the Australian Renewable Energy Agency (ARENA) and their Advancing Renewables Programme (ARP) [52], which provides high-value grants through the Australian government to fund projects focussed on renewable energy. For private investment, Copenhagen Infrastructure Partners (CIP) will be contacted to gauge interest in providing an investment since they are the largest investors in the Star of the South wind farm. Then other investors will be contacted, particularly whom have previously funded renewable energy projects. Due to the high rate of return and the low risk of the project, it is attractive to investors. 15% of the profits will be returned to investors.

## 9.6 Commercial Risks

*Table 536. Commercial risks*

| Risk | Likelihood (1 = very unlikely, 5 = very likely) | Impact (1 = low disruption, 5 = large disruption) | Action |
|---|---|---|---|
| Reduction in funding and investment. | 3 | 4 | Request new sources of funding from the government, investors, or private limited companies. If this still fails, reduce the number of modules, or use cheaper methods of manufacturing. |
| Delays in supplied components/materials | 4 | 5 | Use trusted and reliable suppliers. Keep back-up stock as a precaution. |

| | | | |
|---|---|---|---|
| Since rotating mass wave energy converters are new technologies, there could be a lack of skilled labour in local area. | 5 | 4 | Train local workers to be able to use the new technology. Partner with local universities (such as the University of Melbourne). |
| Competitor’s products chosen over ours. | 2 | 5 | Ensure our product is the most appealing by using sustainable materials, commit to being based in the local area, keeping costs competitive and making it easily integrated with the wind farm. |
| Increased costs of materials, components and/or labour. | 3 | 3 | Have access to more sources of investment, bulk-buy materials, and components to keep costs low and find regular forecasts on costs and revenue. |

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# Appendix

## A.1 – Bill of Materials

Bill of Materials

| Part | Material | Supplier | Supplier Part Number | Quantity per Assembly | Cost (£) |
|---|---|---|---|---|---|
| Mass | Cast Iron and Recycled Concrete | N/A | N/A | 1 | £732.54 |
| Arm Large Side | Low Alloy Steel | N/A | N/A | 1 | £864.52 |
| Arm Small Side | Low Alloy Steel | N/A | N/A | 1 | £205.54 |
| Shaft | Low Alloy Steel | N/A | N/A | 1 | £2,899.39 |
| Bucket | Low Alloy Steel | N/A | N/A | 1 | £15,618.57 |
| Top Bearing | Steel | SKF | NU 3080 MA | 1 | £18,766.00 |
| Bottom Bearing | Steel | SKF | NU 2292 MA | 1 | £35,745.00 |
| Thrust Bearing | Steel | SKF | 29464 E | 1 | £17,614.00 |
| M36 150 mm Bolt | Class 10.9 Steel | McMaster-Carr | 1078N102 | 14 | £700 |
| M36 Lock Washer | Zinc-Plated Steel | McMaster-Carr | 91202A265 | 14 | £27 |
| M36 Nylon Insert Locknut | Class 10 Steel | McMaster-Carr | 94645A350 | 6 | £150 |
| Shell | 30% glass polypropylene GFRP | N/A | N/A | 1 | £4,805.83 |
| Shell Frame | Carbon steel | N/A | N/A | 1 | £3,325.35 |
| M36 180 mm Bolt | Alloy steel | McMaster-Carr | 91290A944 | 4 | £94.47 |

| | | | | | |
|---|---|---|---|---|---|
| M36 Hex Nut | Class 10 zinc-plated steel | McMaster-Carr | 90870A116 | 4 | £72.37 |
| Universal Steel Beams 150UB14 | Grade 300 AS 3678 Steel | Scott Metals | 150UB14 | 26.62 m | £1108.17 |
| Universal Steel Beams 310UB32 | Grade 300 AS 3678 Steel | Scott Metals | 310UB32 | 126.02 m | £10,062.70 |
| Base Housing | Low-Alloy Steel | N/A | N/A | 1 | |
| Top Housing | Low-Alloy Steel | N/A | N/A | 1 | |
| Clutch Brake | N/A | Ortlinghaus | Series 123 Hydraulic Clutch-Brake | 1 | £975,000 |
| Gearbox | N/A | ZF | Redulus GP 615 | 1 | £1,950,000 |
| Transmission | N/A | CVTCORP | CVTCORP's mCVT | 1 | £2,340,000 |
| Alternator | N/A | Stamford | S4L1M-F42 Class-H | 1 | £2,600,000 |

# A.2 – Routing Sheets

## Routing Sheets

| Routing Sheet | | |
|---|---|---|
| Part Name: Shaft | | Part No.: 1 |
| Quantity: 130 | Matl.: Carbon steel, AISI 1137, water quenched & tempered at 205°C | Planner: E. Dunnett |
| Revision No.: 1 | Date: 20/04/23 | Order No.: |
| Op. No. | Description | Machine Tool |
| 100 | Turn initial geometry | CNC lathe |
| 200 | Machine spline | Hobbing machine |
| 300 | Machine keyseat | 3 Axis CNC mill |
| 400 | Finishing | Shakedown and finishing |

| Routing Sheet | | |
|---|---|---|
| Part Name: Arm Large Side | | Part No.: 2 |
| Quantity: 130 | Matl.: Low alloy steel, SAE 4335M, cast, quenched & tempered | Planner: E. Dunnett |
| Revision No.: 1 | Date: 20/04/23 | Order No.: |
| Op. No. | Description | Machine Tool |
| 100 | Cast initial geometry | Sand casting line |
| 200 | Machine flange surfaces | 3 Axis CNC mill |
| 300 | Drill 14 x 39Ø holes | 3 Axis CNC mill |
| 400 | Finishing | Shakedown and finishing |
| 500 | Powder coat | Powder coating line |

| Routing Sheet | | |
|---|---|---|
| Part Name: Arm Short Side | | Part No.: 3 |
| Quantity: 130 | Matl.: Low alloy steel, SAE 4335M, cast, quenched & tempered | Planner: E. Dunnett |
| Revision No.: 1 | Date: 20/04/23 | Order No.: |
| Op. No. | Description | Machine Tool |
| 100 | Cast initial geometry | Sand casting line |
| 200 | Machine flange surface | 3 Axis CNC mill |
| 300 | Drill 6 x 39Ø holes | 3 Axis CNC mill |
| 400 | Finishing | Shakedown and finishing |
| 500 | Powder coat | Powder coating line |

| Routing Sheet | | |
|---|---|---|
| Part Name: Bucket | | Part No.: 4 |
| Quantity: 130 | Matl.: Low alloy steel, SAE 4130, cast, normalized & tempered | Planner: E. Dunnett |
| Revision No.: 1 | Date: 20/04/23 | Order No.: |
| Op. No. | Description | Machine Tool |
| 100 | Cast initial geometry | Sand casting line |
| 200 | Machine flange surface | 3 Axis CNC mill |
| 300 | Drill 8 x M36 x 4 mm holes | 3 Axis CNC mill |
| 400 | Finishing | 3 Axis CNC mill |
| 500 | Powder coat | Powder coating line |

| Routing Sheet | | |
| --- | --- | --- |
| Part Name: Base Housing | | Part No.: 5 |
| Quantity: 130 | Matl.: Low-alloy Steel, SAE 4340, cast, quenched & tempered | Planner: A. Cheshire |
| Revision No.: 1 | Date: 05/05/23 | Order No.: |
| Op. No. | Description | Machine Tool |
| 100 | Cast Initial Geometry | Sand Casting Line |
| 200 | Machine Bearing Faces | CNC Lathe |
| 300 | Machine Base | CNC Lathe |
| 400 | Finishing | Shakedown and Finishing |

| Routing Sheet | | |
| --- | --- | --- |
| Part Name: Top Housing | | Part No.: 6 |
| Quantity: 130 | Matl.: Low-alloy Steel, SAE 4340, cast, quenched & tempered | Planner: A. Cheshire |
| Revision No.: 1 | Date: 05/05/23 | Order No.: |
| Op. No. | Description | Machine Tool |
| 100 | Cast Initial Geometry | Sand Casting Line |
| 200 | Machine Bearing Faces | CNC Lathe |
| 300 | Machine Mating Surfaces | 3-Axis CNC Mill |
| 400 | Drill 14 x M36 x 100 mm Holes | 3-Axis CNC Mill |
| 500 | Finishing | Shakedown and Finishing |

| Routing Sheet | | |
| --- | --- | --- |
| Part Name: Shell | | Part No.: 7 |
| Quantity: 130 | Matl.: 30% glass polypropylene | Planner: A. Lokkerbol |
| Revision No.: 1 | Date: 20/04/23 | Order No.: |
| Op. No. | Description | Machine Tool |
| 100 | Polymer cast GFRP shell | Polymer casting |
| 200 | Drill four M36 holes | 3 Axis CNC mill |
| 300 | Copper oxide powder coat | Powder coating line |

| Routing Sheet | | |
| --- | --- | --- |
| Part Name: Shell Frame | | Part No.: 8 |
| Quantity: 130 | Matl.: Carbon steel, ASME SA216, Annealed | Planner: A. Lokkerbol |
| Revision No.: 1 | Date: 20/04/23 | Order No.: |
| Op. No. | Description | Machine Tool |
| 100 | Cast initial geometry | Sand casting line |
| 200 | Drill four M36 holes | 3 Axis CNC mill |
| 300 | Finishing | 3 Axis CNC mill |

| Operations List | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Part Name: Shaft | | | | | | | Part No.: 1 | |
| Revision No.: 1 | | Date: 20/04/23 | | Page 1 of1 | | | Planner: E. Dunnett | |
| Op. No. | Description | Machine Tool | Tooling | Speed (rev/min) | Feed (mm/min) | Set-up time (min) | Op. time (min) | Remarks |
| 110 | Set steel bar on lathe | CNC Lathe | Lifting hoist | | | 10.00 | 5.00 | |
| 120 | Clean entire surface with initial pass | CNC Lathe | Carbide drill bit | 300 | 17700 | 2.00 | 5.00 | |
| 130 | Turn shaft shoulders | CNC Lathe | Carbide drill bit | 300 | 17700 | 0.50 | 10.00 | |
| 140 | Take length to 370 mm | CNC Lathe | Carbide drill bit | 300 | 17700 | 0.50 | 1.00 | |
| 150 | Inspect | | | | | | 0.50 | Visual inspection |
| 210 | Machine spline | Hobbing Machine | | | 17700 | 10.00 | 30.00 | |
| 220 | Inspect | | | | | | 0.50 | Visual inspection |
| 310 | Machine keyseat | 3 Axis Mill | Carbide face mill | 300 | 17700 | 2.00 | 5.00 | |
| 320 | Inspect | | | | | | 0.50 | Visual inspection |
| 410 | Finishing | Shakedown and finishing | | | | | | Deburr and degrease |
| | | | | | Total Times | 25.00 | 57.50 | |

| Operations List | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Part Name: Arm Large Side | | | | | | | Part No.: 2 | |
| Revision No.: 1 | | Date: 20/04/23 | | Page 1 of1 | | | Planner: E. Dunnett | |
| Op. No. | Description | Machine Tool | Tooling | Speed (rev/min) | Feed (mm/min) | Set-up time (min) | Op. time (min) | Remarks |
| 110 | Produce pattern | Pattern prod. | | | | | | Pattern preperation (only done once per caster) |
| 120 | Produce bottom mould | Mould prod. | | | | | 5.00 | |
| 130 | Produce top mould | Mould prod. | | | | | 5.00 | |
| 140 | Apply refractory coating | Mould prod. | Refractory coating | | | | 1.00 | |
| 150 | Assemble sand boxes | Sand casting line | | | | | 5.00 | |
| 160 | Inject SAE 4335M steel alloy | Sand casting line | | | | | 10.00 | Ensure correct material |
| 170 | Shakeout | Shakedown and finishing | | | | | 10.00 | |
| 180 | Gates, runners, and risers removed | Shakedown and finishing | Oxy-acetylene torch | | | | 5.00 | |
| 190 | Inspect | | | | | | 0.50 | Visual inspection |
| 210 | Machine flange mating surface | 3 Axis CNC mill | Carbide face mill & jig | 300 | 12500 | 4.00# | 3.30 | #Total for machine set-up and includes jig set-up |
| 220 | Reposition workpiece | 3 Axis CNC mill | Jig | | | | | Locate on reverse face |
| 230 | Machine flange mating surface | 3 Axis CNC mill | Carbide face mill | 300 | 12500 | 2.00# | 1.50 | #Tool change time and jig set-up |
| 310 | Drill 8 x 39Ø mm through holes | 3 Axis CNC mill | Carbide drill bit & jig | 300 | 12500 | 2.00# | 5.00 | #Tool change time and jig set-up |
| 320 | Reposition workpiece | 3 Axis CNC mill | Jig | | | | | Locate on reverse face |
| 330 | Drill 6 x 39Ø mm through holes | 3 Axis CNC mill | Carbide drill bit | 300 | 12500 | 1.00# | 4.50 | #Tool change time and jig set-up |
| 410 | Finishing | Shakedown and finishing | | | | | | Deburr and degrease |
| 510 | Cover flange mating surface and holes | | | | | 0.50 | 2.00 | |
| 520 | Powder coat | Paintshop | | | | 0.50 | 2.00 | |
| 530 | Cure | Curing Oven | | | | 3.00 | 15.00 | @180°C for 15 mins |
| | | | | | Total Times | 13.00 | 74.80 | |

| Operations List | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Part Name: Arm Short Side | | | | | | | Part No.: 3 | |
| Revision No.: 1 | | Date: 20/04/23 | | Page 1 of1 | | | Planner: E. Dunnett | |
| Op. No. | Description | Machine Tool | Tooling | Speed (rev/min) | Feed (mm/min) | Set-up time (min) | Op. time (min) | Remarks |
| 110 | Produce pattern | Pattern prod. | | | | | | Pattern preperation (only done once per caster) |
| 120 | Produce bottom mould | Mould prod. | | | | | 5.00 | |
| 130 | Produce top mould | Mould prod. | | | | | 5.00 | |
| 140 | Apply refractory coating | Mould prod. | Refractory coating | | | | 1.00 | |
| 150 | Assemble sand boxes | Sand casting line | | | | | 5.00 | |
| 160 | Inject SAE 4335M steel alloy | Sand casting line | | | | | 10.00 | Ensure correct material |
| 170 | Shakeout | Shakedown and finishing | | | | | 10.00 | |
| 180 | Gates, runners, and risers removed | Shakedown and finishing | Oxy-acetylene torch | | | | 5.00 | |
| 190 | Inspect | | | | | | 0.50 | Visual inspection |
| 210 | Machine flange mating surface | 3 Axis CNC mill | Carbide face mill & jig | 300 | 12500 | 2.00# | 1.50 | #Total for machine set-up and includes jig set-up |
| 310 | Drill 6 x 39Ø mm through holes | 3 Axis CNC Mill | Carbide drill bit & jig | 300 | 12500 | 1.00# | 4.50 | #Tool change time and jig set-up |
| 410 | Finishing | Shakedown and finishing | | | | | | Deburr and degrease |
| 510 | Cover flange mating surface and holes | | | | | 0.50 | 2.00 | |
| 520 | Powder coat | Paintshop | | | | 0.50 | 1.50 | |
| 530 | Cure | Curing Oven | | | | 3.00 | 15.00 | @180°C for 15 mins |
| | | | | | Total Times | 7.00 | 66.00 | |

| Operations List | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Part Name: Bucket | | | | | | | Part No.: 4 | |
| Revision No.: 1 | | Date: 20/04/23 | | Page 1 of1 | | | Planner: E. Dunnett | |
| Op. No. | Description | Machine Tool | Tooling | Speed (rev/min) | Feed (mm/min) | Set-up time (min) | Op. time (min) | Remarks |
| 110 | Produce pattern | Pattern prod. | | | | | | Pattern preperation (only done once per caster) |
| 120 | Produce bottom mould | Mould prod. | | | | | 10.00 | |
| 130 | Produce top mould | Mould prod. | | | | | 10.00 | |
| 140 | Apply refractory coating | Mould prod. | Refractory coating | | | | 5.00 | |
| 150 | Assemble sand boxes | Sand casting line | | | | | 10.00 | |
| 160 | Inject SAE 4130 steel alloy | Sand casting line | | | | | 20.00 | Ensure correct material |
| 170 | Shakeout | Shakedown and finishing | | | | | 10.00 | |
| 180 | Gates, runners, and risers removed | Shakedown and finishing | Oxy-acetylene torch | | | | 5.00 | |
| 190 | Inspect | | | | | | 0.50 | Visual inspection |
| 210 | Machine flange mating surface | 3 Axis CNC mill | Carbide face mill & jig | 300 | 23500 | 2.00# | 3.30 | #Total for machine set-up and includes jig set-up |
| 310 | Drill 8 x 32Ø mm 100 mm blind holes | 3 Axis CNC mill | Carbide drill bit & jig | 300 | 23500 | 2.00# | 5.00 | #Tool change time and jig set-up |
| 320 | Tap 8 x M36 x 4 mm through holes with 98 mm thread depth | 3 Axis CNC mill | Carbide tap & jig | 300 | *Synchronous* | 1.00# | 5.00 | #Tool change time and jig set-up |
| 410 | Finishing | Shakedown and finishing | | | | | | Deburr and degrease |
| 510 | Cover flange mating surface and holes | | | | | 0.50 | 2.00 | |
| 520 | Powder coat | Paintshop | | | | 0.50 | 10.00 | |
| 530 | Cure | Curing Oven | | | | 3.00 | 15.00 | @180°C for 15 mins |
| | | | | | Total Times | 9.00 | 110.80 | |

| Operations List | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Part Name: Base Housing | | | | | | | Part No.: 5 | |
| Revision No.: 1 | | Date: 05/05/23 | | Page 1 of1 | | | Planner: A. Cheshire | |
| Op. No. | Description | Machine Tool | Tooling | Speed (rev/min) | Feed (mm/min) | Set-up time (min) | Op. time (min) | Remarks |
| 110 | Produce Pattern | Pattern Prod. | | | | | | Pattern Preparation (only once per caster) |
| 120 | Produce Bottom Mould | Mould Prod. | | | | | 5.00 | |
| 130 | Produce Top Mould | Mould Prod. | | | | | 5.00 | |
| 140 | Apply Refractory Coating | Mould Prod. | Refractiry Coating | | | | 1.00 | |
| 150 | Assemble Sand Boxes | Sand Casting Line | | | | | 5.00 | |
| 160 | Inject SAE 4335M Steel Alloy | Sand Casting Line | | | | | 10.00 | Ensure Correct Material |
| 170 | Shakeout | Shakedown and Finishing | | | | | 10.00 | |
| 180 | Gates, runners and risers removed | Shakedown and Finishing | Oxy-Acetylene Torch | | | | 5.00 | |
| 190 | Inspect | | | | | | 0.50 | Visual Inspection |
| 210 | Machine Bearing Faces | CNC Lathe | Carbide Turning, Boring and Facing Tools | 14 | 14 | 3.00 | 10.00 | |
| 220 | Inspect | | | | | | 0.50 | Visual inspection |
| 310 | Machine Base | CNC Lathe | Carbide Facing Tool | 14 | 14 | 2.00 | 3.00 | |
| 320 | Inspect | | | | | | 0.50 | Visual inspection |
| 410 | Finishing | Shakedown and finishing | | | | | | Deburr and degrease |
| | | | | | Total Times | 5 | 55.5 | |

| Operations List | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Part Name: Top Housing | | | | | | | Part No.: 6 | |
| Revision No.: 1 | | Date: 05/05/23 | | Page 1 of1 | | | Planner: A. Cheshire | |
| Op. No. | Description | Machine Tool | Tooling | Speed (rev/min) | Feed (mm/min) | Set-up time (min) | Op. time (min) | Remarks |
| 110 | Produce Pattern | Pattern Prod. | | | | | | Pattern Preparation (only once per caster) |
| 120 | Produce Bottom Mould | Mould Prod. | | | | | 5.00 | |
| 130 | Produce Top Mould | Mould Prod. | | | | | 5.00 | |
| 140 | Apply Refractory Coating | Mould Prod. | Refractiry Coating | | | | 1.00 | |
| 150 | Assemble Sand Boxes | Sand Casting Line | | | | | 5.00 | |
| 160 | Inject SAE 4335M Steel Alloy | Sand Casting Line | | | | | 10.00 | Ensure Correct Material |
| 170 | Shakeout | Shakedown and Finishing | | | | | 10.00 | |
| 180 | Gates, runners and risers removed | Shakedown and Finishing | Oxy-Acetylene Torch | | | | 5.00 | |
| 190 | Inspect | | | | | | 0.50 | Visual Inspection |
| 210 | Machine Bearing Faces | CNC Lathe | Carbide Turning, Boring and Facing Tools | 14 | 14 | 3.00 | 10.00 | |
| 220 | Inspect | | | | | | 0.50 | Visual Inspection |
| 310 | Machine Mating Surfaces | 3-Axis CNC Mill | Carbide Face Mill | 300 | 12500 | 3.00 | 10.00 | |
| 410 | Drill 14 x 32Ø mm x 100mm Blind Holes | 3-Axis CNC Mill | Carbide Drill Bit & Jig | 300 | 12500 | 2.00* | 5.00 | *Includes tool change and jig set-up |
| 420 | Tap 14 x M36 x 100mm Blind Holes | 3-Axis CNC Mill | Carbide Tap & Jig | 300 | *Synchronous* | 1.00* | 6.00 | *Includes tool change and jig set-up |
| 410 | Finishing | Shakedown and finishing | | | | | | Deburr and degrease |
| | | | | | Total Times | 9 | 73 | |

| Operations List | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Part Name: Shell | | | | | | | Part No.: 7 | |
| Revision No.: 1 | | Date: 20/04/23 | | Page 1 of1 | | | Planner: A. Lokkerbol | |
| Op. No. | Description | Machine Tool | Tooling | Speed (rev/min) | Feed (mm/min) | Set-up time (min) | Op. time (min) | Remarks |
| 110 | Create mold | Mould prod. | | | | | 20.00 | Pattern preperation (only done once per caster) |
| 120 | Coat mold with release agent | Mould prod. | | | | | 5.00 | |
| 130 | Mix 30% polypropylene resin with curing agent | Polymer casting line | | | | | 5.00 | |
| 140 | Inject into mold | Polymer casting line | | | | | 10.00 | |
| 150 | Cure in mold | Polymer casting line | | | | | 30.00 | |
| 160 | Open mold and remove part | | | | | | 10.00 | |
| 170 | Inspect | | | | | | 1.00 | Visual inspection |
| 210 | Drill four M36 500 mm blind holes | 3 Axis CNC mill | Dowel drill bit | 300 | 50300 | 2.00# | 2.00 | #Tool change time and jig set-up |
| 510 | Cover holes | | | | | 0.50 | 2.00 | |
| 520 | Powder coat | Paintship | | | | 0.50 | 10.00 | |
| | | | | | Total Times | 3.00 | 95.00 | |

| Operations List | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Part Name: Shell frame | | | | | | | Part No.: 8 | |
| Revision No.: 1 | | Date: 20/04/23 | | Page 1 of1 | | | Planner: A. Lokkerbol | |
| Op. No. | Description | Machine Tool | Tooling | Speed (rev/min) | Feed (mm/min) | Set-up time (min) | Op. time (min) | Remarks |
| 110 | Produce pattern | Pattern prod. | | | | | | Pattern preperation (only done once per caster) |
| 120 | Produce bottom mould | Mould prod. | | | | | 10.00 | |
| 130 | Produce top mould | Mould prod. | | | | | 10.00 | |
| 140 | Apply refractory coating | Mould prod. | Refractory coating | | | | 5.00 | |
| 150 | Assemble sand boxes | Sand casting line | | | | | 10.00 | |
| 160 | Inject carbon steel, ASME SA216 | Sand casting line | | | | | 20.00 | Ensure correct material |
| 170 | Shakeout | Shakedown and finishing | | | | | 10.00 | |
| 180 | Gates, runners, and risers removed | Shakedown and finishing | Oxy-acetylene torch | | | | 5.00 | |
| 190 | Inspect | | | | | | 0.50 | Visual inspection |
| 210 | Drill four M36 500 mm blind holes | 3 Axis CNC mill | Carbide drill bit & jig | 300 | 23500 | 2.00# | 5.00 | #Tool change time and jig set-up |
| 410 | Finishing | Shakedown and finishing | | | | | | Deburr and degrease |
| | | | | | Total Times | 9.00 | 75.50 | |

## A.3 – Assembly Routing

### Assembly Routing

| Operations List | | | | | | |
|---|---|---|---|---|---|---|
| Assembly Name: Shaft into frame | | | | | Assembly No.: 1 | |
| Revision No.: 1 | | Date: 20/04/23 | Page 1 of1 | | Planner: J. Smith | |
| Op. No. | Description | Method | Tooling/Machining/ Equipment | Limits/Fits | Op. Time (min) | Inspection |
| 101 | NU 3080 MA fitted to shaft | Bearing is induction heated 80 - 90 °C greater than the temperature of the shaft. Bearing is pressed onto shaft. | SKF TIH L33 induction heater. HAG5TT Aluminuim Gantry Tall (Lifting Solutions Group). | Shrink fit. H5. | 30.00 | Visual check for misalignement. |
| 102 | Shaft aligned | Shaft lowered through frame so 1.5 metres of shaft hangs below the top of the frame and is roughly concentrically alligned. | HAG5TT Aluminuim Gantry Tall (Lifting Solutions Group). | | 5.00 | Central axis of assembly marked on floor under the gantry so gantry can be manouvered to lower shaft from directly above that mark. |
| 103 | Bearing NU 2292 MA fitted | Bearing is induction heated 80 - 90 °C greater than the temperature of the shaft. Bearing is pressed onto shaft. | SKF TIH L33 induction heater. Kalmar super heavy forklift truck - DCG700-12LB. | Shrink fit. H5. | 10.00 | Visual check for misalignement. |
| 104 | Bearing 29464 E fitted to shaft | Bearing is induction heated 80 - 90 °C greater than the temperature of the shaft. Bearing is pressed onto shaft. | SKF TIH L33 induction heater. Kalmar super heavy forklift truck - DCG700-12LB. | Shrink fit. H6. | 10.00 | Visual check for misalignement. |
| 105 | Base housing and top housing heated | Base and top housing are induction heated 80 - 90 °C greater than the temperature of the bearings. | SKF TIH L33 induction heater. | Shrink fit J6 for bearing NU 3080 MA and NU 2292 MA, H& for bearing 29464 E . | 30.00 | Infra red gun to measure temperatures. |
| 106 | Shaft pushed into frame housing | Shaft is lowered then pressed into the frame housings. | | Shrink fit J6 for bearing NU 3080 MA and NU 2292 MA, H7 for bearing 29464 E . | 5.00 | |

| Operations List | | | | | | |
|---|---|---|---|---|---|---|
| Assembly Name: Large arm to bucket | | | | | Assembly No.: 2 | |
| Revision No.: 1 | | Date: 20/04/23 | Page 1 of1 | | Planner: J. Smith | |
| Op. No. | Description | Method | Tooling/Machining/ Equipment | Limits/Fits | Op. Time (min) | Inspection |
| 101 | Align large arm | Lift the large arm to visually align bolts and with the bucket flange. | Kalmar super heavy forklift truck - DCG700-12LB. | | 10.00 | Visual check. |
| 102 | Lock washers | Lock washers slotted onto bolts. | | | 2.00 | |
| 103 | Insert and tighten bolts | Bolts are inserted into holes and tightened incrementally, tightening opposite positioned bolts in succesively. | Stahlwille MP300-5000 Multipower Torque Multiplier 5000 Nm. | 3500 Nm torque per M36 bolt. | 5.00 | If there are any difficulties tigthening bolts, arm should be realligned. |

| Operations List | | | | | | |
|---|---|---|---|---|---|---|
| Assembly Name: Bucket to shaft | | | | | Assembly No.: 3 | |
| Revision No.: 1 | | Date: 20/04/23 | Page 1 of1 | | Planner: J. Smith | |
| Op. No. | Description | Method | Tooling/Machining/ Equipment | Limits/Fits | Op. Time (min) | Inspection |
| 101 | Allign bucket and large arm with shaft | Forklift truck with support of people allign the large arm onto the spline. | Kalmar super heavy forklift truck - DCG700-12LB. | | 10.00 | Visual check. |
| 102 | Allign small arm | Small arm alligned with support of people to allign holes for bolts of large and small arms. | | | 5.00 | Visual check. |
| 103 | Insert and tigthen bolts washers and nuts | Bolts, washers and nuts are assembled then bolts tightened incrementally, tightening opposite positioned bolts in succesively. | Stahlwille MP300-5000 Multipower Torque Multiplier 5000Nm | 3500 Nm torque per M36 bolt | 5.00 | If there are any difficulties tigthening bolts, arm should be realligned. |

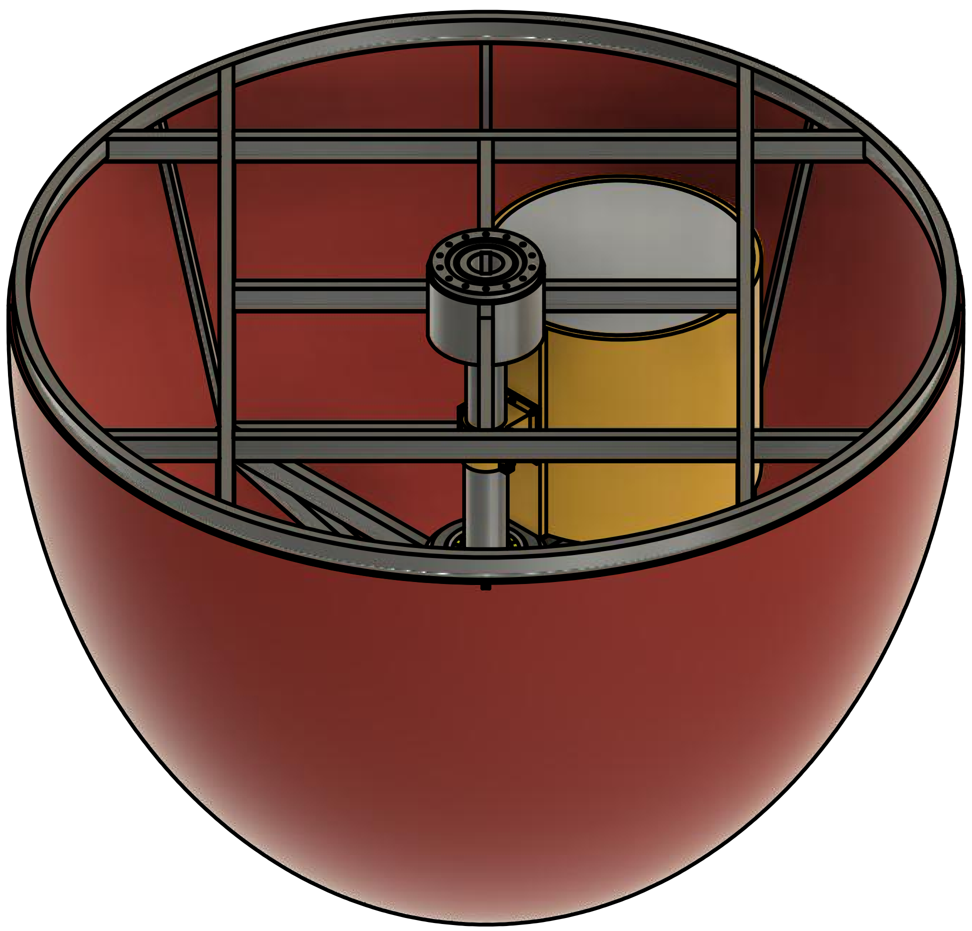
| Operations List | | | | | | |
|---|---|---|---|---|---|---|
| Assembly Name: Shell frame to Shell | | | | | Assembly No.: 4 | |
| Revision No.: 1 | | Date: 20/04/23 | Page 1 of1 | | Planner: A. Lokkerbol | |
| Op. No. | Description | Method | Tooling/Machining/ Equipment | Limits/Fits | Op. Time (min) | Inspection |
| 101 | Align shell frame | Hoist the shell frame into the shell and align it so that the bolt holes of each part are aligned | Delta DTS electric hoist, DTS5000 | | 15.00 | Visual check. |
| 102 | Insert and tighten bolts | Insert M36 bolts/nuts through the four holes and tighten | Stahlwille MP300-5000 Multipower Torque Multiplier 5000 Nm. | 3500 Nm torque per M36 bolt. | 5.00 | If there are any difficulties tigthening bolts, frame should be realligned. |

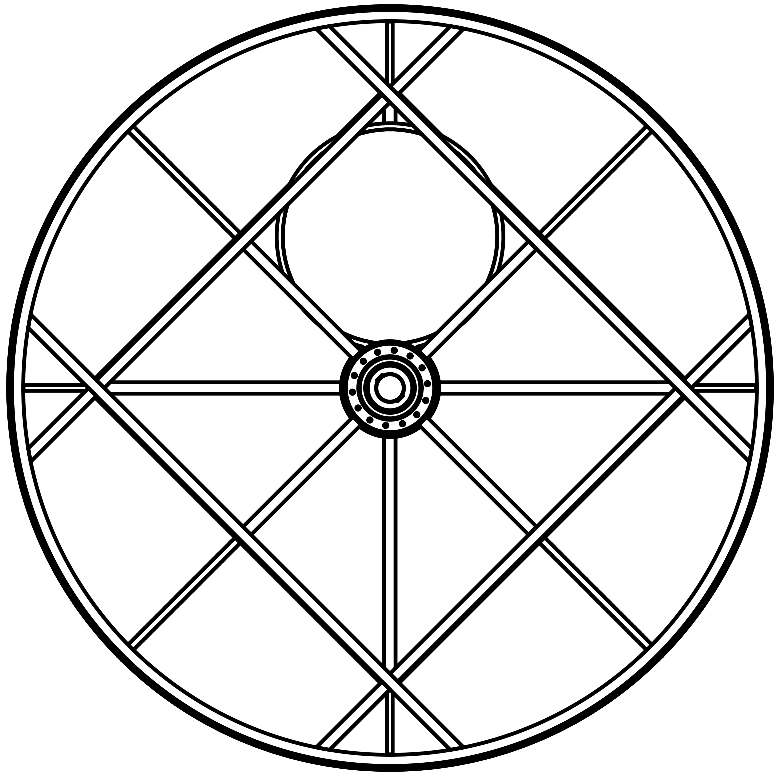
## A.4 – Minutes Summary

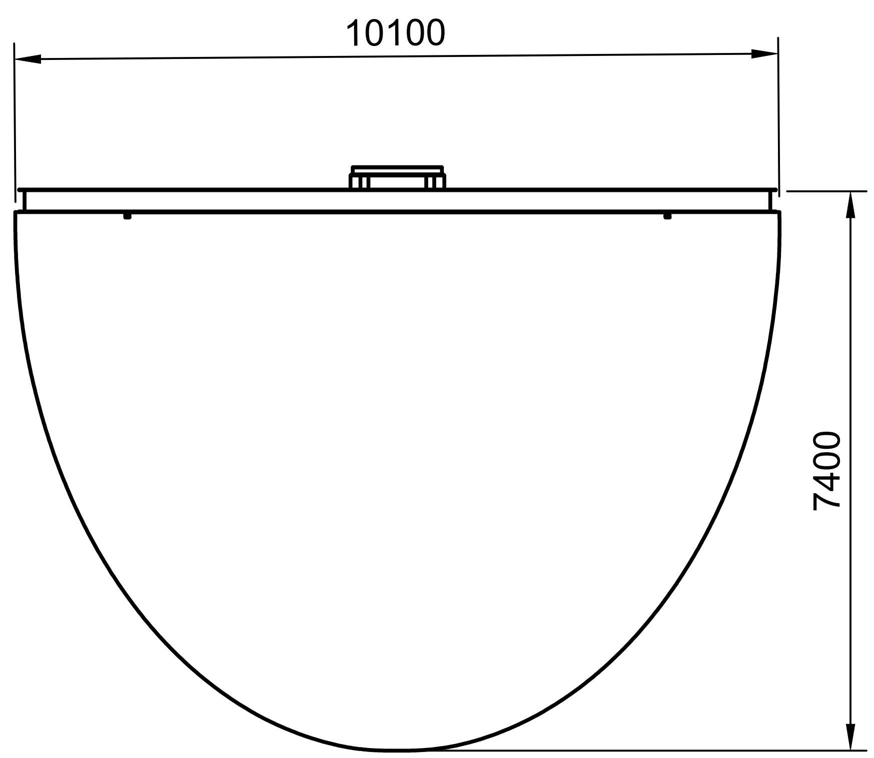
| Meeting: | Date: | Absentees: | Actions Completed: | Actions to be Taken: |
|---|---|---|---|---|
| 1 | 03/02/2023 | JRN | Established comms | Submit Challenge Preferences |
| | | | Group Leader Elected | |
| | | | | |
| 2 | 09/02/2023 | | Began idea development | Conduct research (context + ideas) |
| | | | Identified areas for research | |
| | | | | |
| 3 | 16/02/2023 | | Identified group-level project area | Conduct more focused research |
| | | | | Begin developing initial PDS |
| | | | | Look into potential stakeholders and climate change adaptation considerations |
| | | | | Start initial business case |
| 4 | 23/02/2023 | ED | PDS started | Continue PDS |
| | | | Initial business case completed (inc. stakeholders) | Conduct research specific to PDS |
| | | | Research ongoing in background | |
| 5 | 28/02/2023 | | PDS is progressing | Start presentation preparation |
| | | | Initial design calculations started | |
| | | | | |
| 6 | 02/03/2023 | | Presentation template completed | Final draft of presentation ready for 06/03/2023 |
| | | | Slide order decided and delegated | |
| | | | | |
| 7 | 07/03/2023 | | Final presentation preparations and rehearsal | Final rehearsal on 09/03/2023 morning |
| | | | | |
| | | | | |
| 8 | 16/03/2023 | | Sub-system groups and tasks finalised | Move onto design calculations |
| | | | | |
| | | | | |
| 9 | 23/03/2023 | | Report template complete | Sub-system groups to communicate over Easter and try to finish design calculations |
| | | | Deliverables over Easter determined | |
| | | | | |
| 10 | 20/04/2023 | | Progress update over Easter | Focus on progressing to validation |
| | | | Report sections delegated | Other report sections in background for now |
| | | | Prototype design started | |
| 11 | 27/04/2023 | | Prototype production started | Continue with report |
| | | | | Begin final write-up |
| | | | | |
| 12 | 04/05/2023 | | Finalising report content | Final draft to be finished before 7pm 08/05/2023 |
| | | | Compiling appendices | Prototype to be finshed by 10/05/2023, rehearsals on 10/05/2023 and 11/05/2023 |
| | | | | |

## A.5 – Engineering Drawings

Notes
- Assembly consists of 3 subassemblies: Rotating mass, Shell and the transmission/alternator
- The views show $\frac{2}{3}$ of the subassemblies including the rotating mass and shell which attaches to the underside of the platforms
- Shell Includes internal frame made from universal steel I-beams and a GFRP shell
- Rotating mass contains all the components which are the primary source of energy



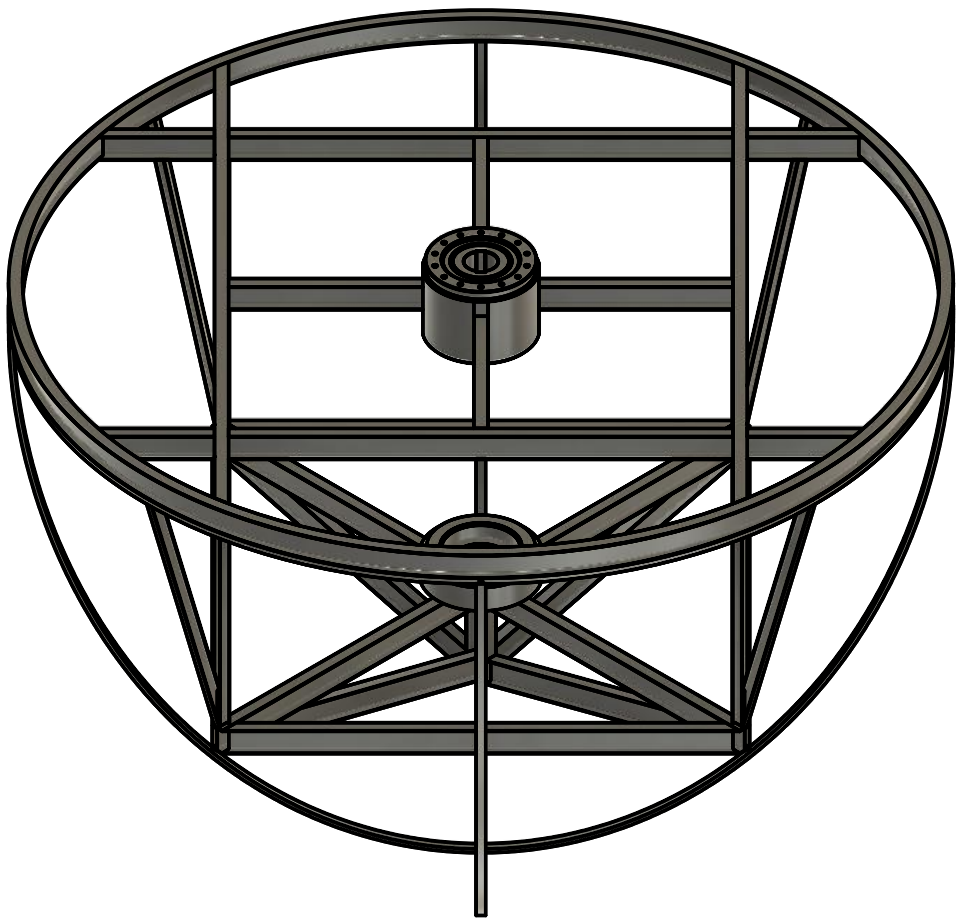


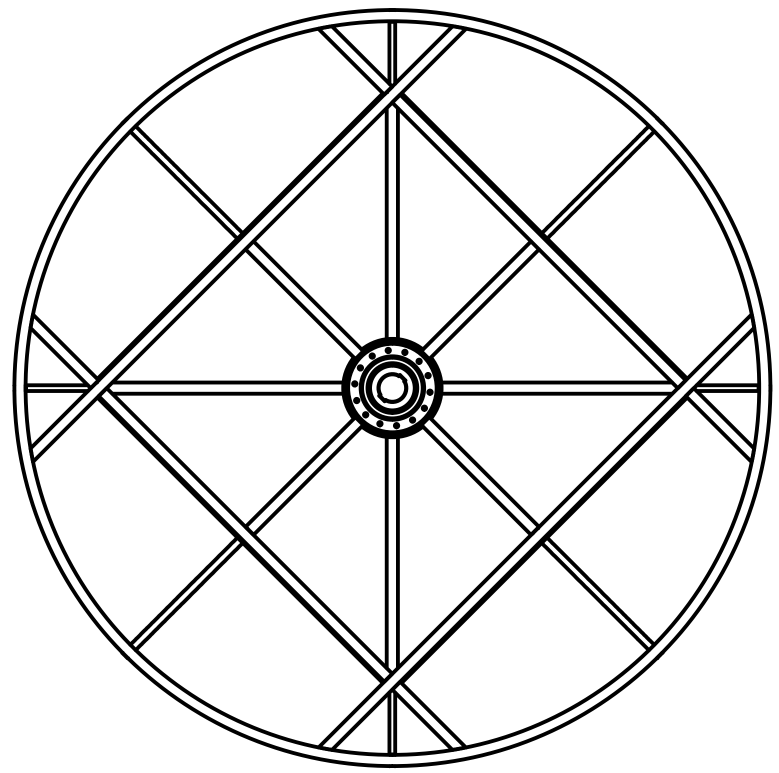


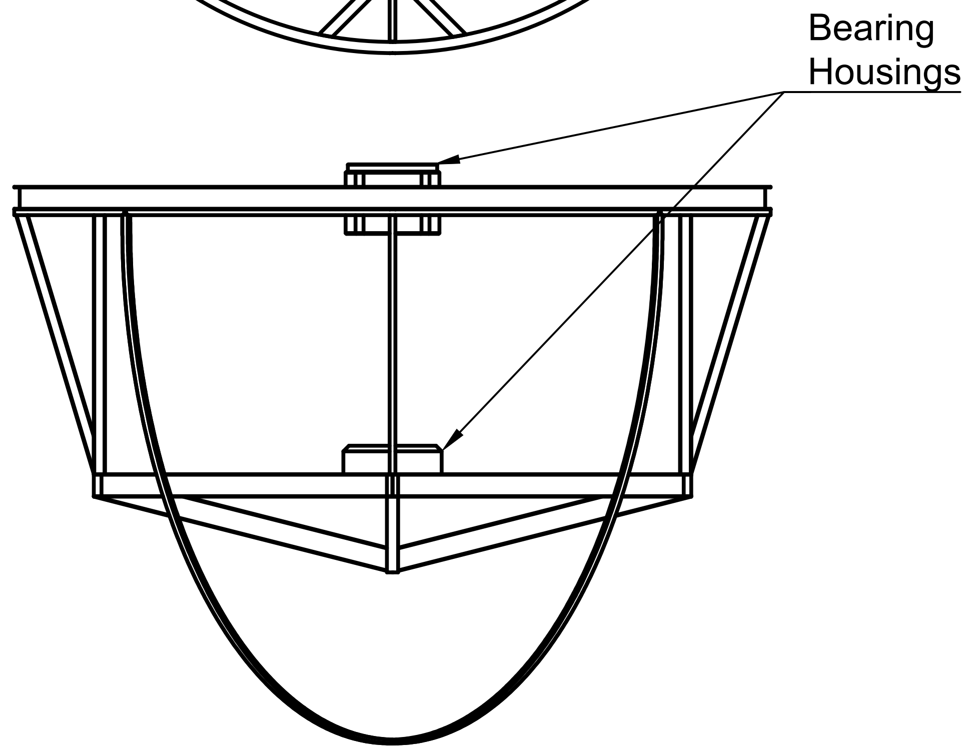

| Scale | Standard | Title | Drawn by |
|---|---|---|---|
| 1:100 | BS8888 | Final Assembly | Joe Roberts Nuttall |
| | | Components: All Components | All dimensions are in mm |
| Sheet Size: A3 | Date of issue: 07/05/2023 | Sheet: 1/5 | |

Notes

- The internal frame consists of 29 structural I-beams, a structural ring and 4 beams following te shape of the shell
- The internal frame is to be welded together via flux-cored arc welding (FCAW)
- Also Includes the bearing housing which have been marked, The upper bearing housing also houses the clutch brake



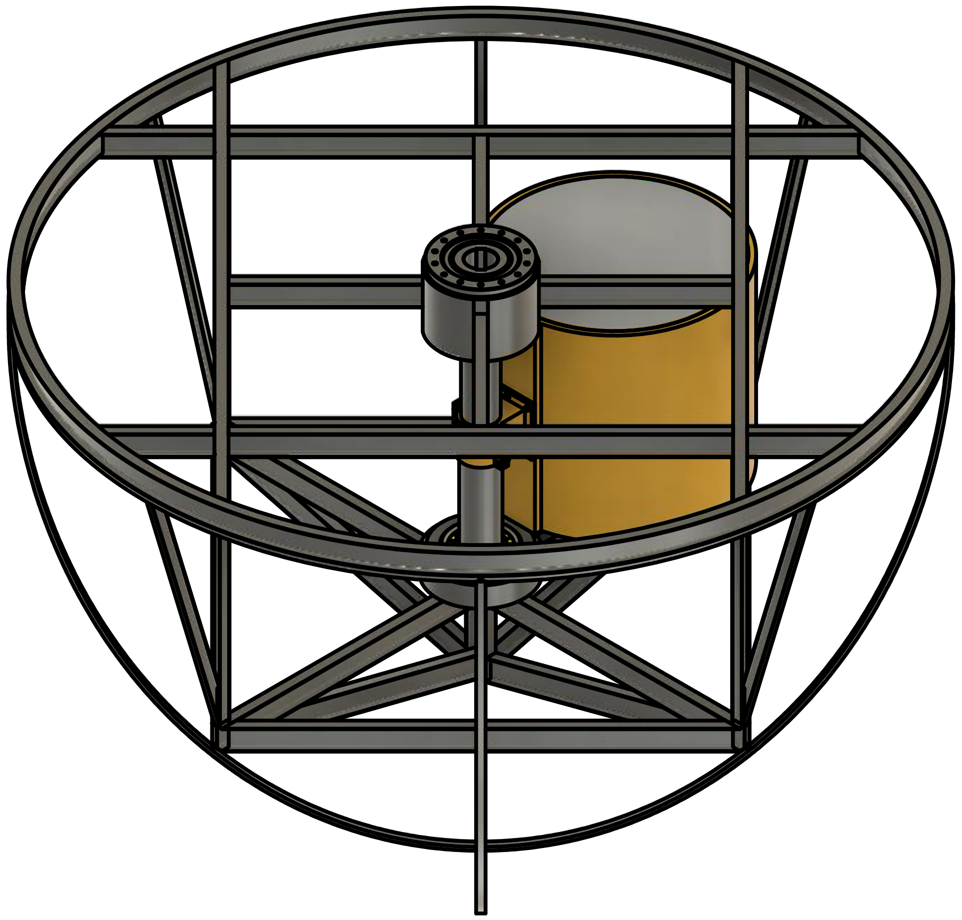


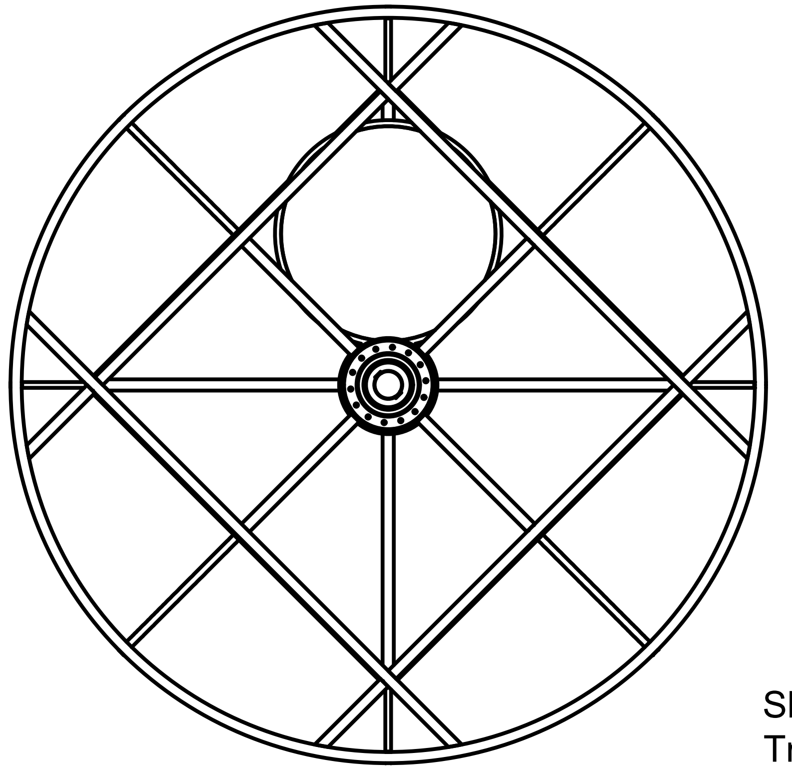


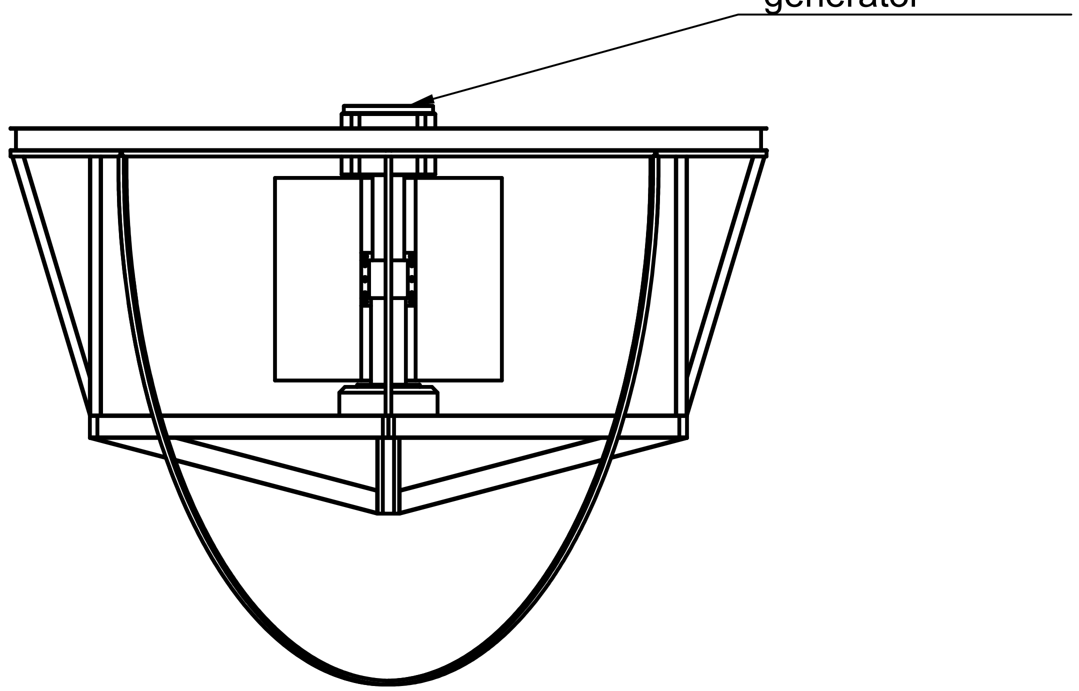

| Scale | Standard | Title | Drawn by |
|---|---|---|---|
| 1:80 | BS8888 | Internal Frame | Joe Roberts Nuttall |
| | | Components: Internal Frame | All dimensions are in mm |
| | | | Sheet Size: A3 · Date of issue: 07/05/2023 · Sheet: 2/5 |

Notes

- The rotating mass sits within the housing having the bearings as the points of attachment
- The internal frame supports the weight of the rotating mass and allows enough room for there to be no interference with the path of rotation
- The clearance allows for any displacements expected to occur within the shaft and the mass itself



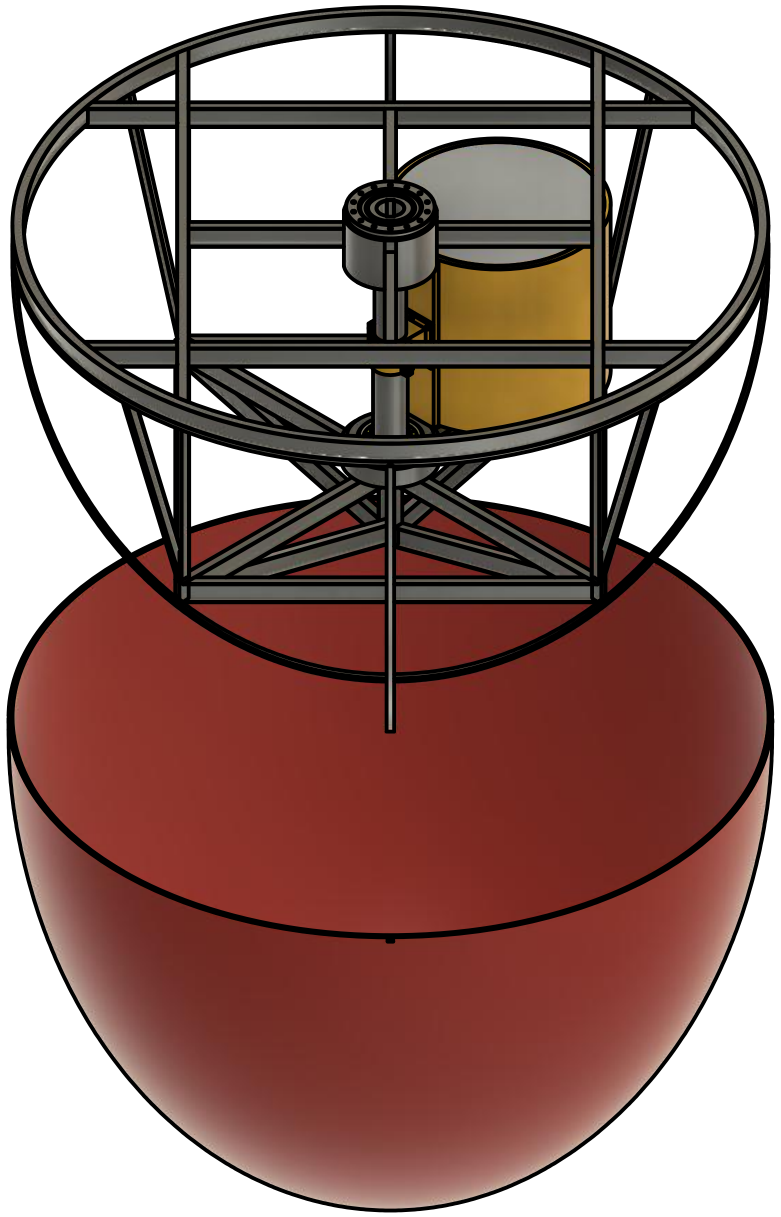


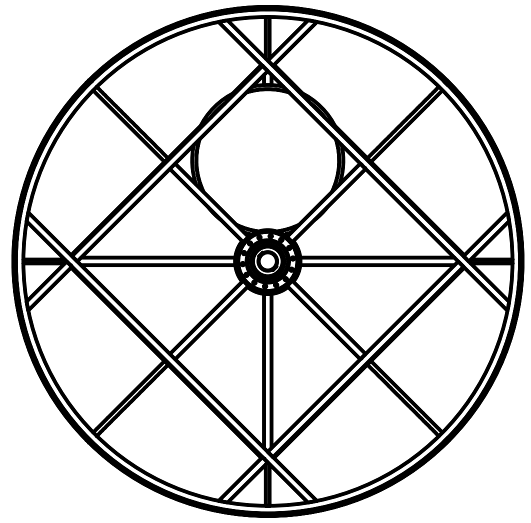


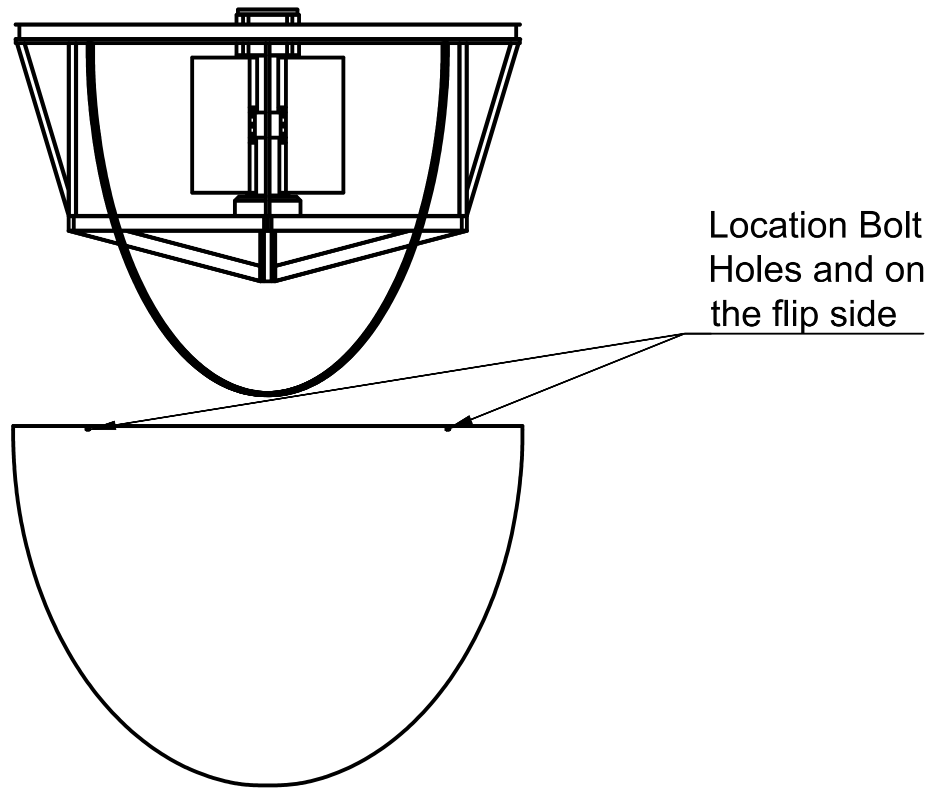

| Scale | Standard | Title | Drawn by |
|---|---|---|---|
| 1:80 | BS8888 | Internal View | Joe Roberts Nuttall |
| | | Components: Internal Frame and Mass | All dimensions are in mm |
| Sheet Size: A3 | Date of issue: 07/05/2023 | Sheet: 3/5 | |

Notes

- The shell is made from GFRP and will give the structure bouyancy to be able to hold the mass afloat and also provide some extra buoyancy to the platform
- There are 4 bolted areas for location of the shell onto the frame, these have been marked



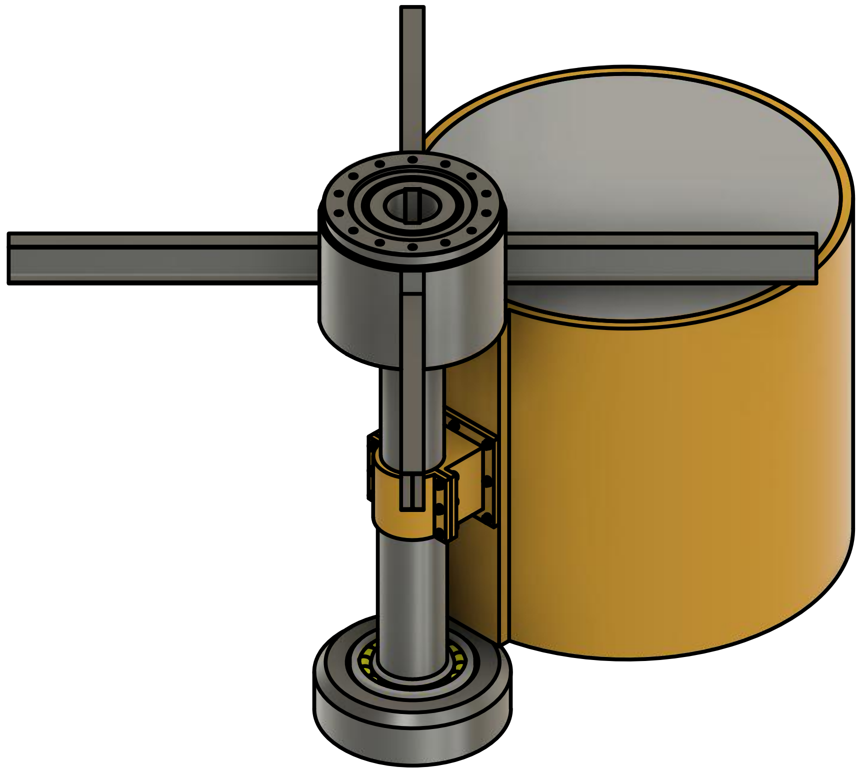


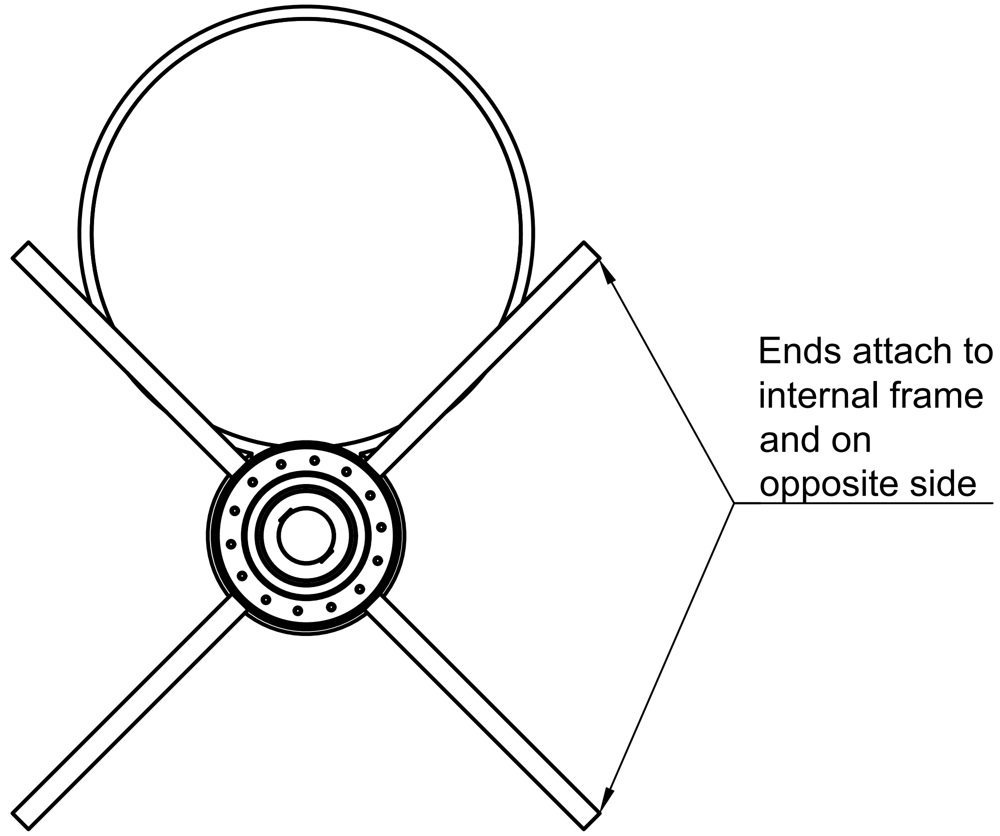


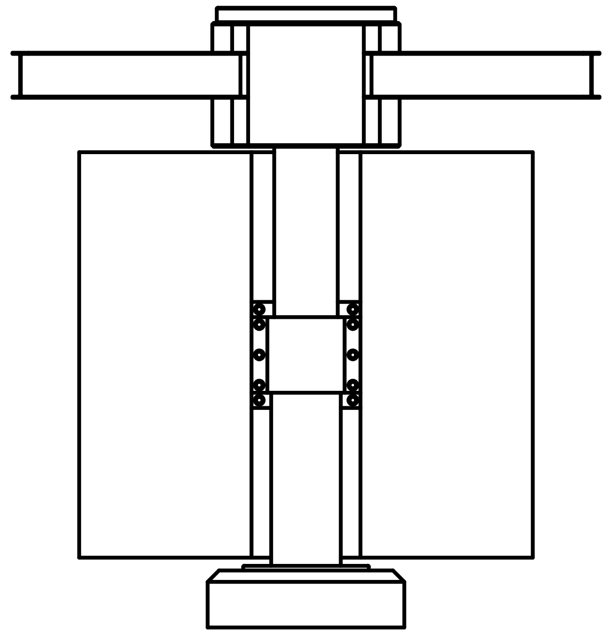

| Scale | Standard | Title | Drawn by |
| --- | --- | --- | --- |
| 1:100 | BS8888 | Final Assembly | Joe Roberts Nuttall |
| | | Components: All Components | All dimensions are in mm |
| | | | Sheet Size: A3 / Date of issue: 07/05/2023 / Sheet: 4/5 |

Notes

- This view gives a more detailed look into how the mass is housed within the internal frame
- The upper housing connects from the side to the I-beams that attach to the internal frame
- The lower housing sits upon the I-beam Frame
- The Bearings and cluthc brake fit within the housing.



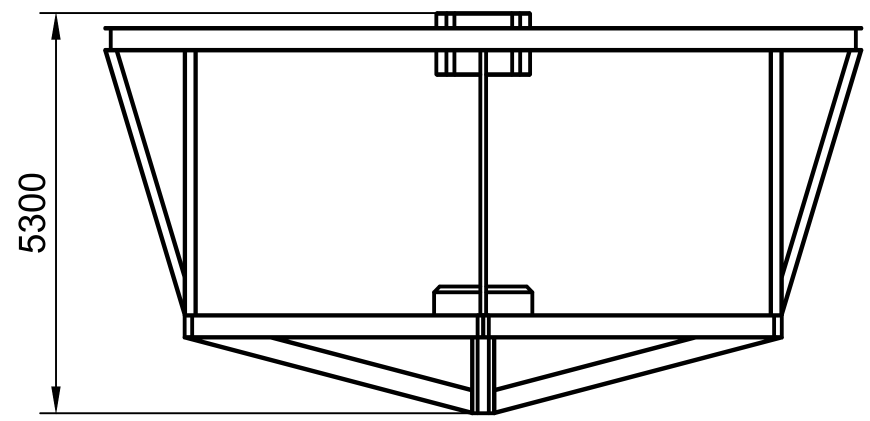


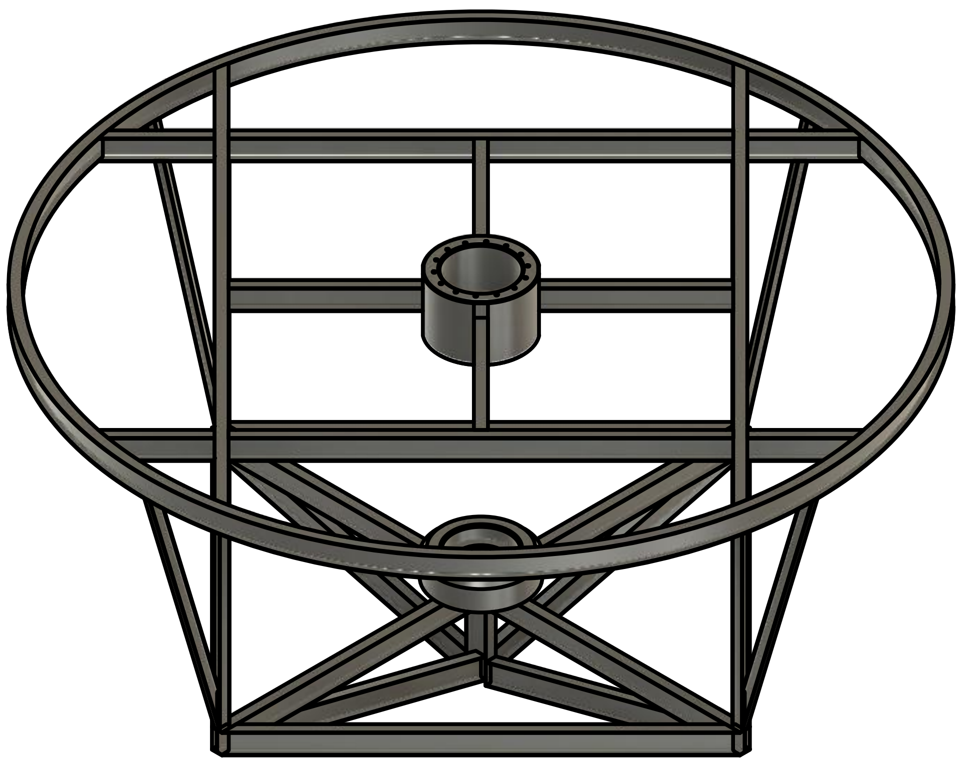



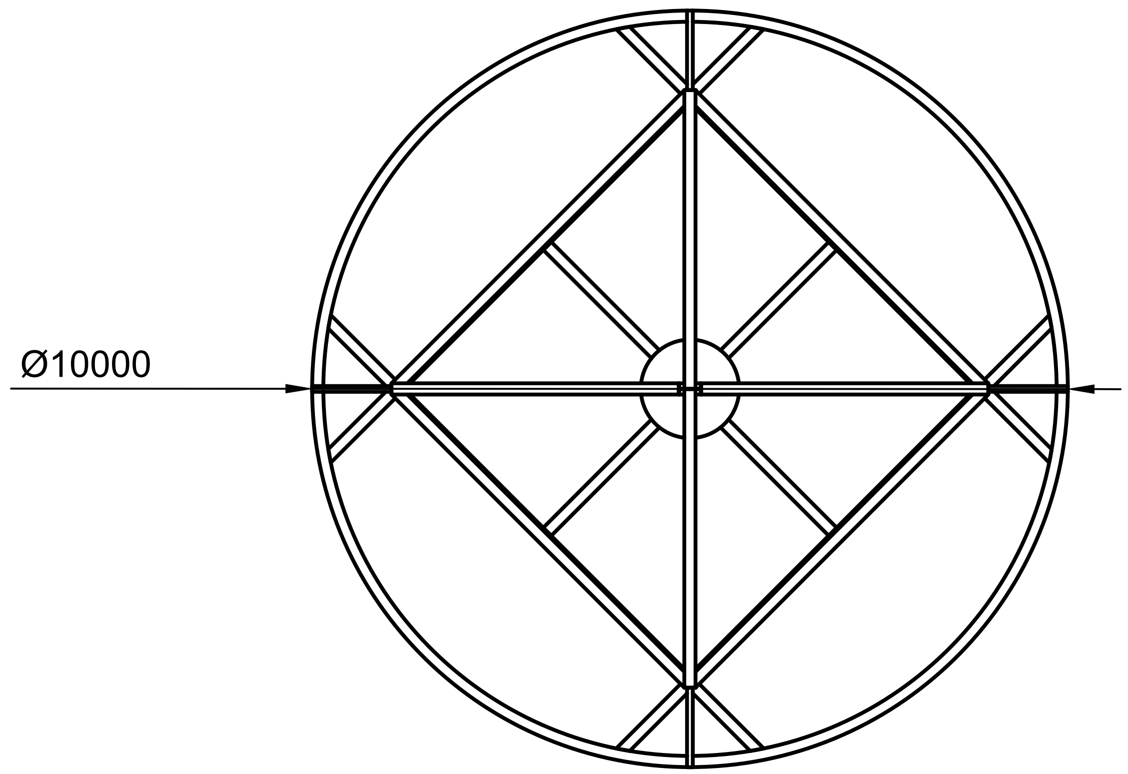
| Scale | Standard | Title | Drawn by |
|---|---|---|---|
| 1:50 | BS8888 | Detailed hosuing view | Joe Roberts Nuttall |
| | | Components: Mass and Housing | All dimensions are in mm |
| | | | Sheet Size: A3 |
| | | | Date of issue: 07/05/2023 |
| | | | Sheet: 5/5 |

Notes

- Overall dimenions of the internal frame are 10,000 mm in diameter and 5,300 mm tall
- All of the I-beams are made from universal steel
- I-beams welded together using  flux-cored arc welding (FCAW)
- The internal frame provides support to the whole structure
- Holds the housing to the bearings
- The internal frame consists of 29 structural I-beams, a structural ring and 4 beams following te shape of the shell



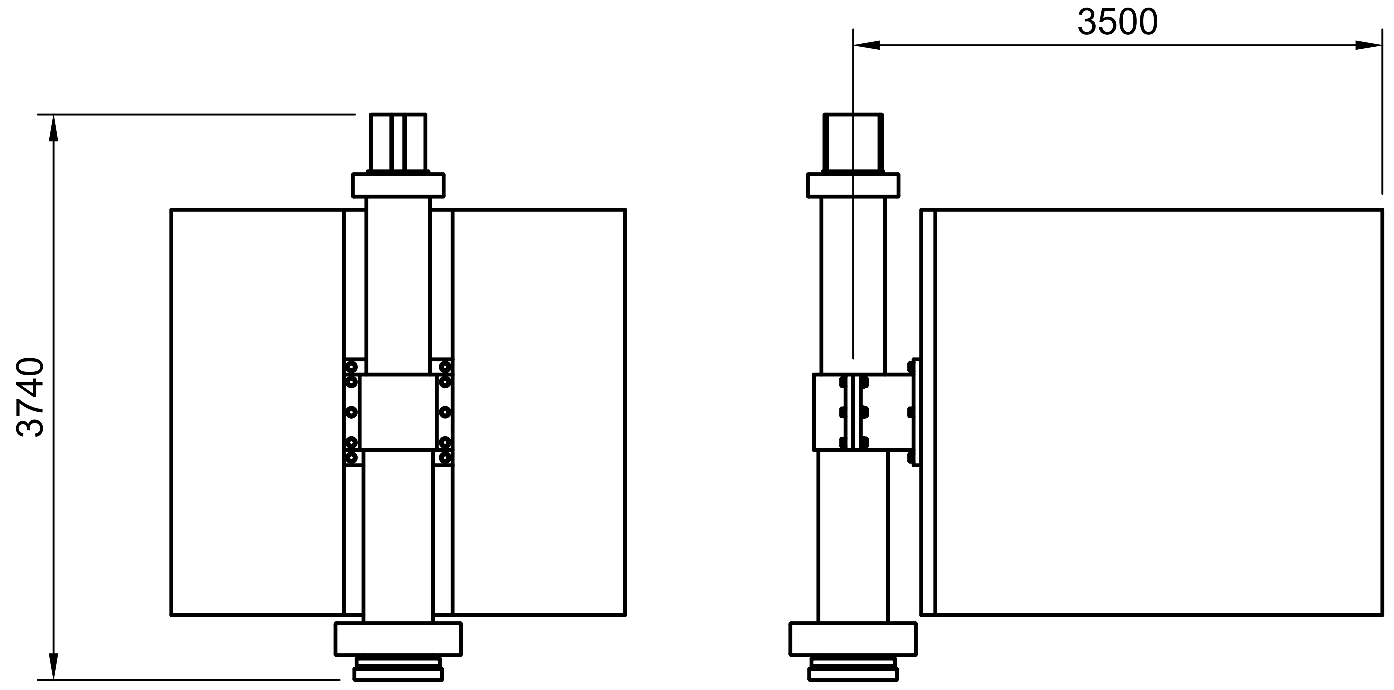



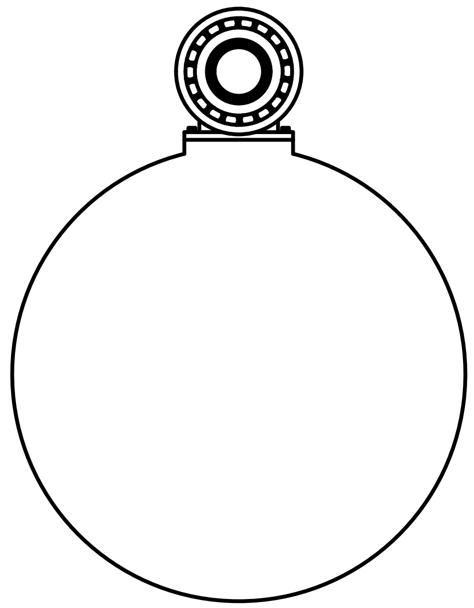


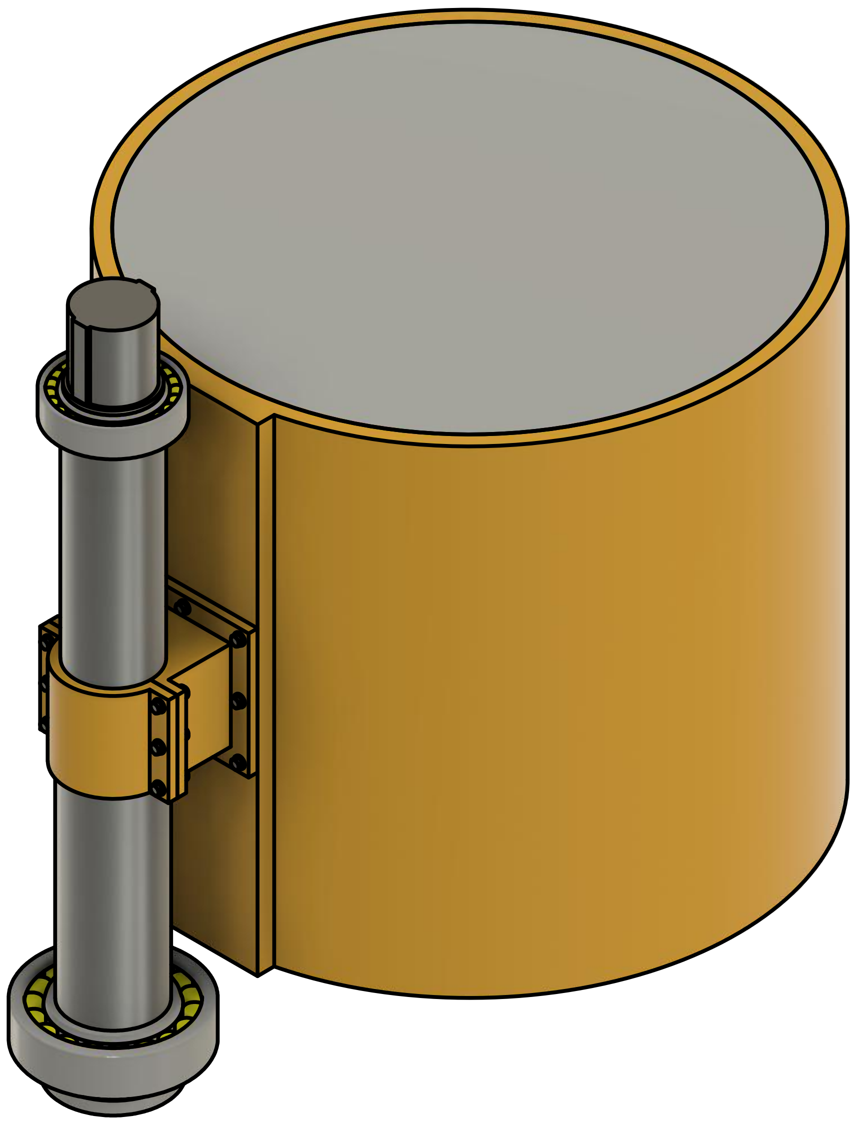

| Scale | Standard | Title | Drawn by |
|---|---|---|---|
| 1:100 | BS8888 | Internal Frame Assembly | Joseph Roberts-Nuttall |
| | | Components: Internal Frame | All dimensions are in mm |
| | | | Sheet Size: A3 |
| | | | Date of issue: 07/05/2023 |
| | | | Sheet: 1/1 |

Notes

- The rotating mass assembly includes 2 roller bearings, 1 spherical thrust roller bearing, the shaft, arm, bucket, recycled concrete and all the fixtures
- Total mass of the whole rotating mass system comes to approximately 65 tonnes
- The 3500 mm dimension relates to the axis of rotation to the edge of the mass



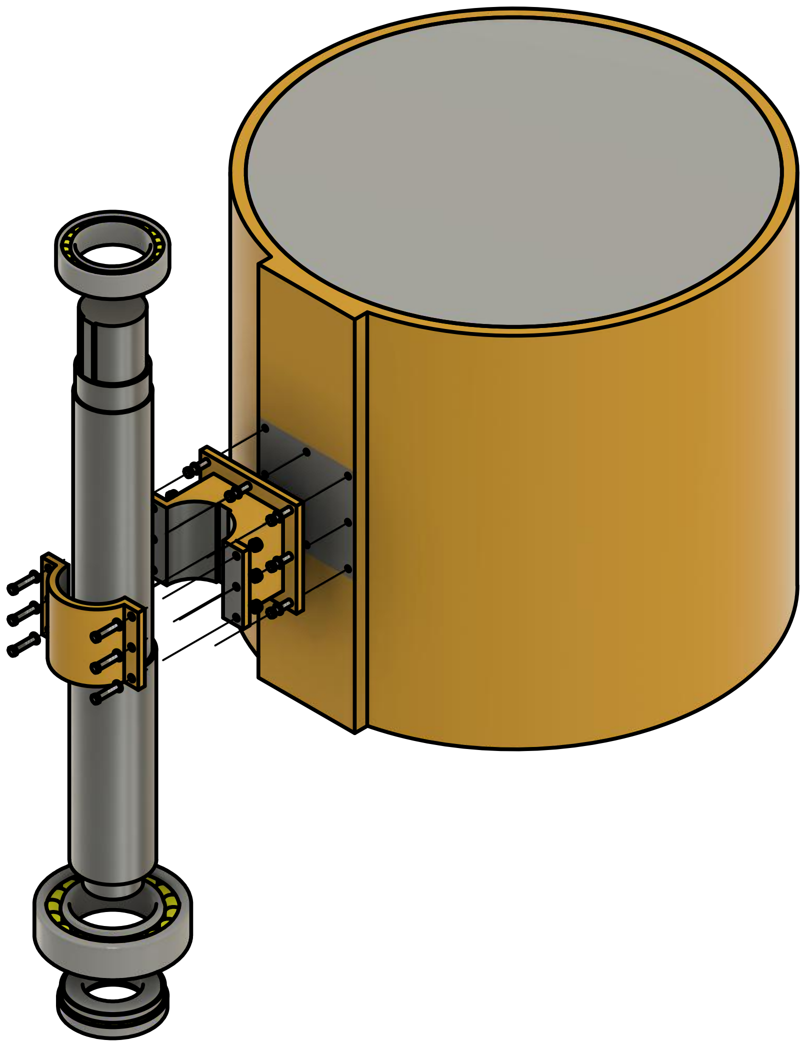


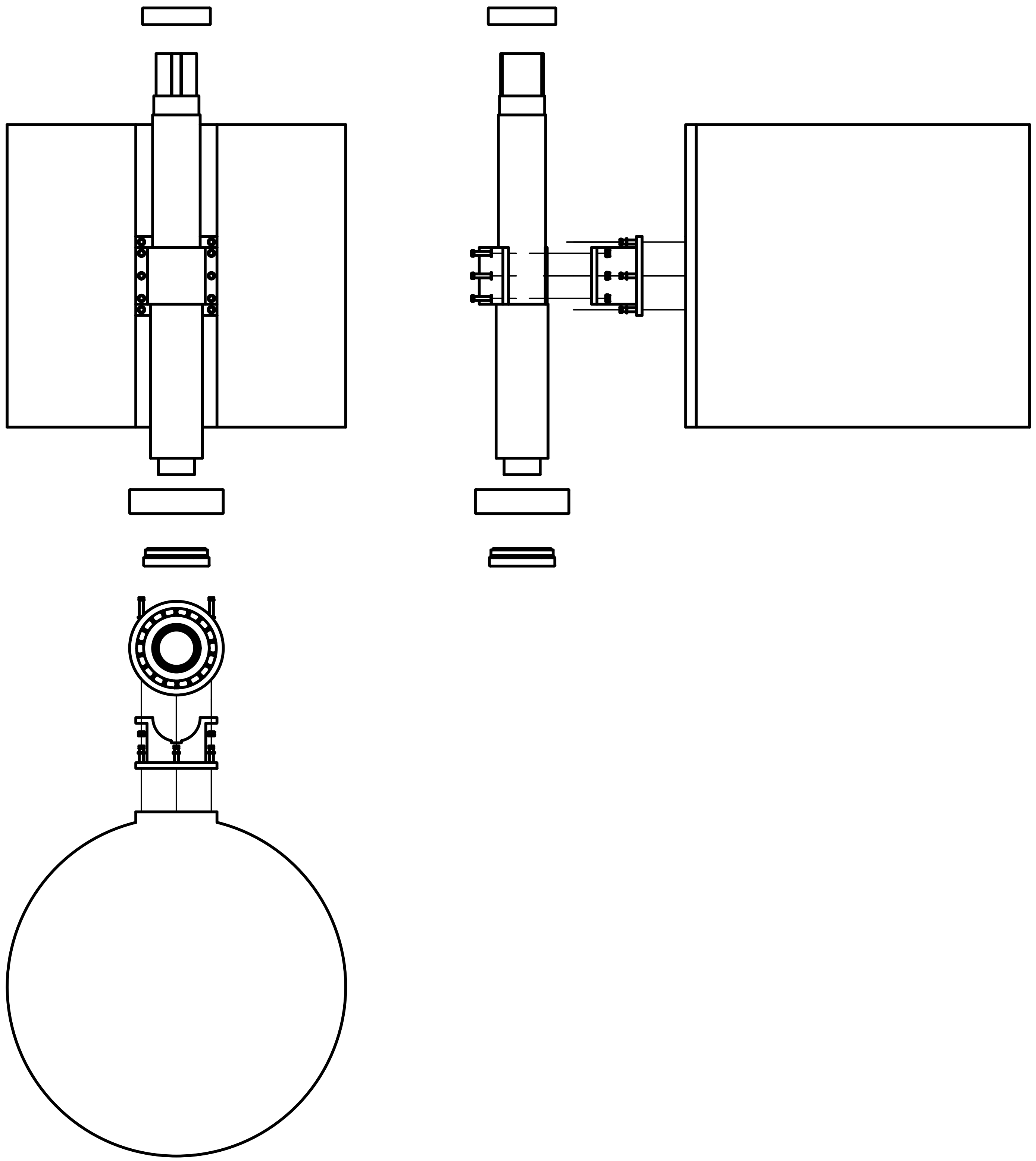
| Scale | Standard | Title | Drawn by |
|---|---|---|---|
| 1:50 | BS8888 | Rotating Mass Assembly | Joe Roberts Nuttall |
| | | Components: Rotating Mass Assembly | All dimensions are in mm |

| Sheet Size | Date of issue | Sheet |
|---|---|---|
| A3 | 07/05/2023 | 1/4 |

Notes

- This view shows how the arm is attached to the steel bucket but also how the steel bucket and arm attach to the shaft
- The arm to the steel bucket requires 8 M36 grade 10.9 bolts connected at a torque of 3500 Nm
- The arm large side to small side uses 6 M36 grade 10.9 bolts, and also nylon insert lock nuts on the other side to secure fastening
- All bolt side fixtures include lock washers

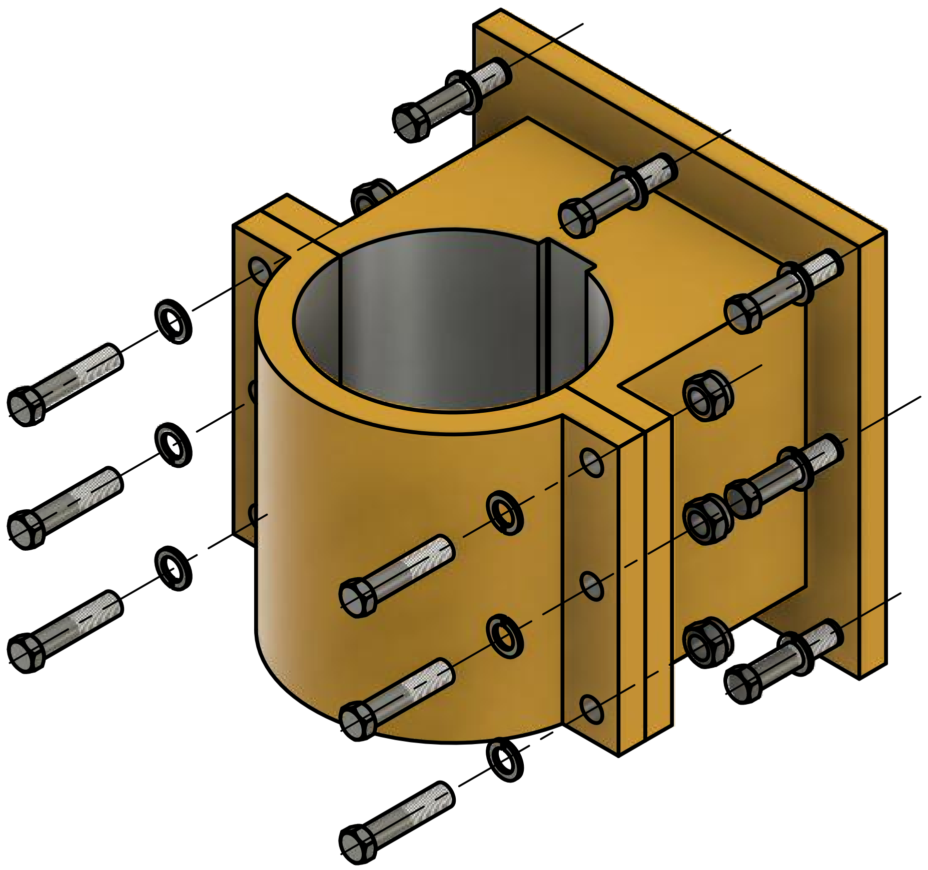


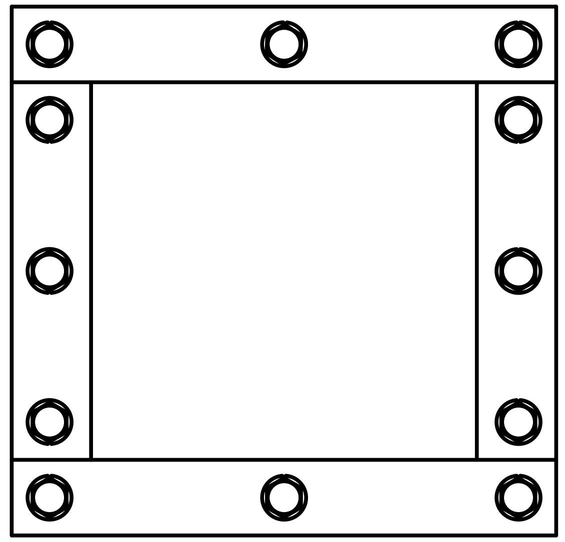


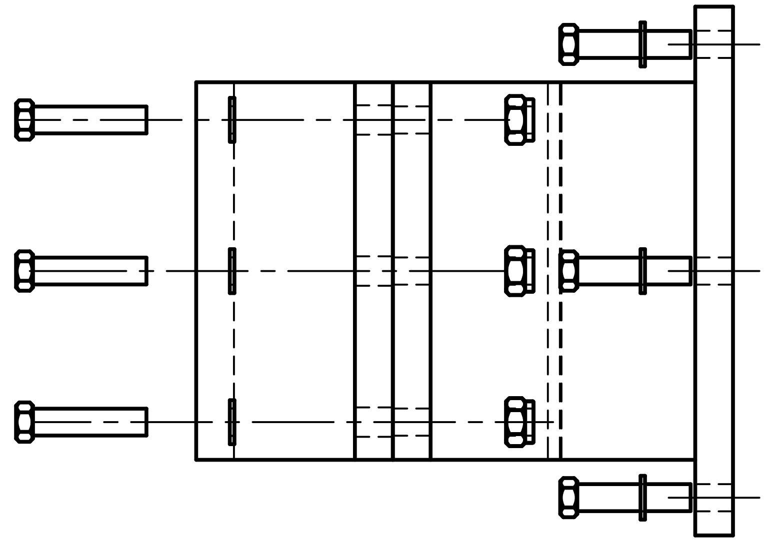
| Scale | Standard | Title | Drawn by |
|---|---|---|---|
| 1:50 | BS8888 | Mass to Shaft Connection | Joe Roberts Nuttall |
| | | Components: Rotating Mass Assembly | All dimensions are in mm |
| | | | Sheet Size: A3 |
| | | | Date of issue: 07/05/2023 |
| | | | Sheet: 2/4 |

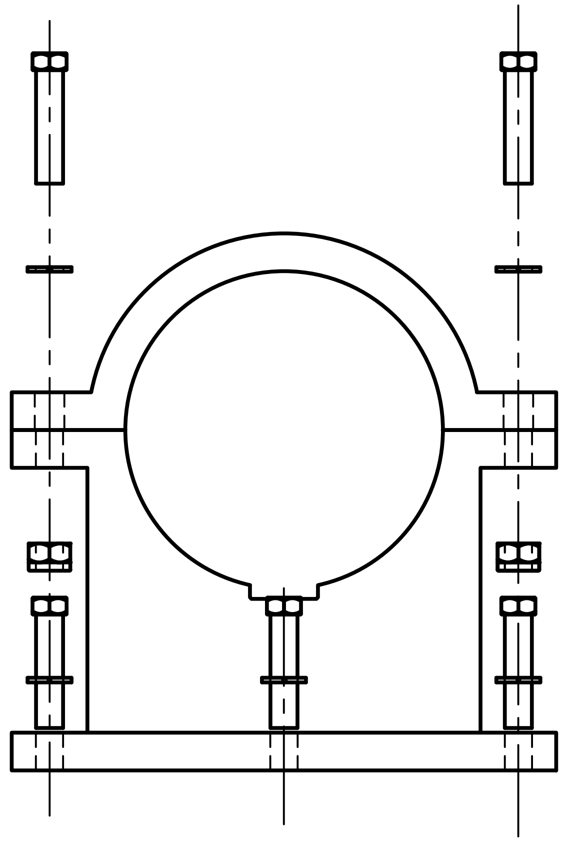
Notes

- This drawing shows a detailed view of the fixtures described on the previous sheet
- it is clear to see from the visibility of the centre times both the ordering and hat components go through each bolt hole
- from the top left view it is possible to see how the bolts are regularly spaced to allow for ease in maufacture.





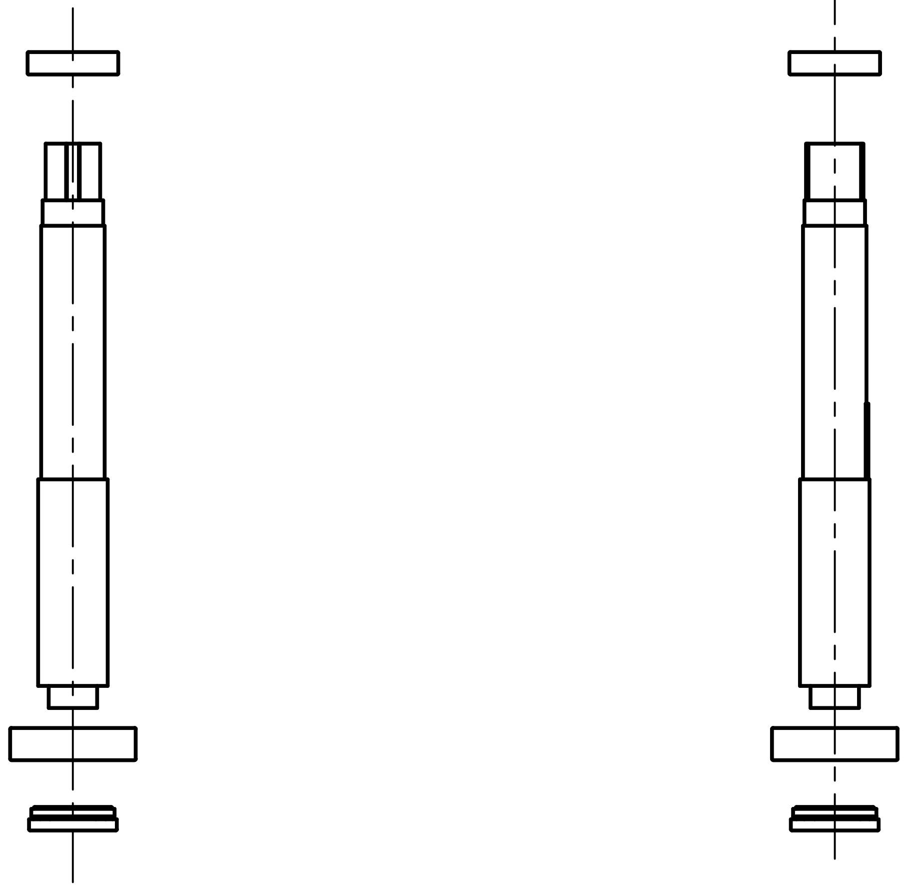


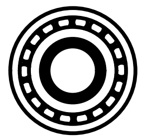


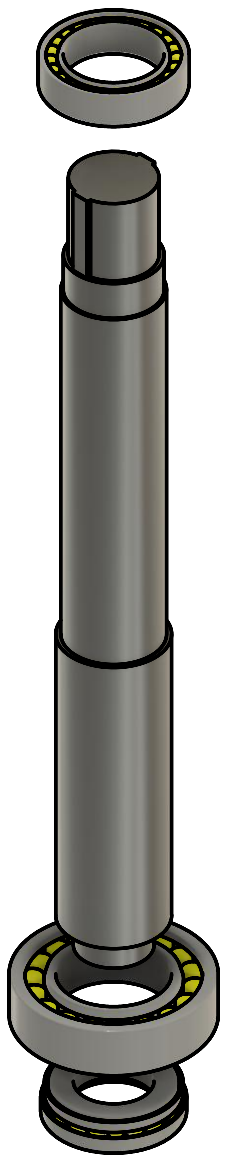
| Scale | Standard | Title | Drawn by |
|---|---|---|---|
| 1:10 | BS8888 | Bolting of Arm | Joe Roberts Nuttall |
| | | Components: Arm Sides and Fixtures | All dimensions are in mm |
| | | | Sheet Size: A3 / Date of issue: 07/05/2023 / Sheet: 3/4 |

Notes

- This view represent how the bearings are going to be slotted onto tje shaft, due to the size of the bearings a shrink fit was appropriate
- Shrink fit requires induction heating of the bearing
- Bearings all initially slotted in the housing prior to being attached to the shaft
- House shaft to bottom bearings first then top bearings last



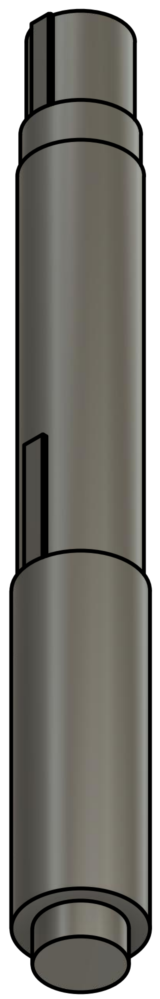




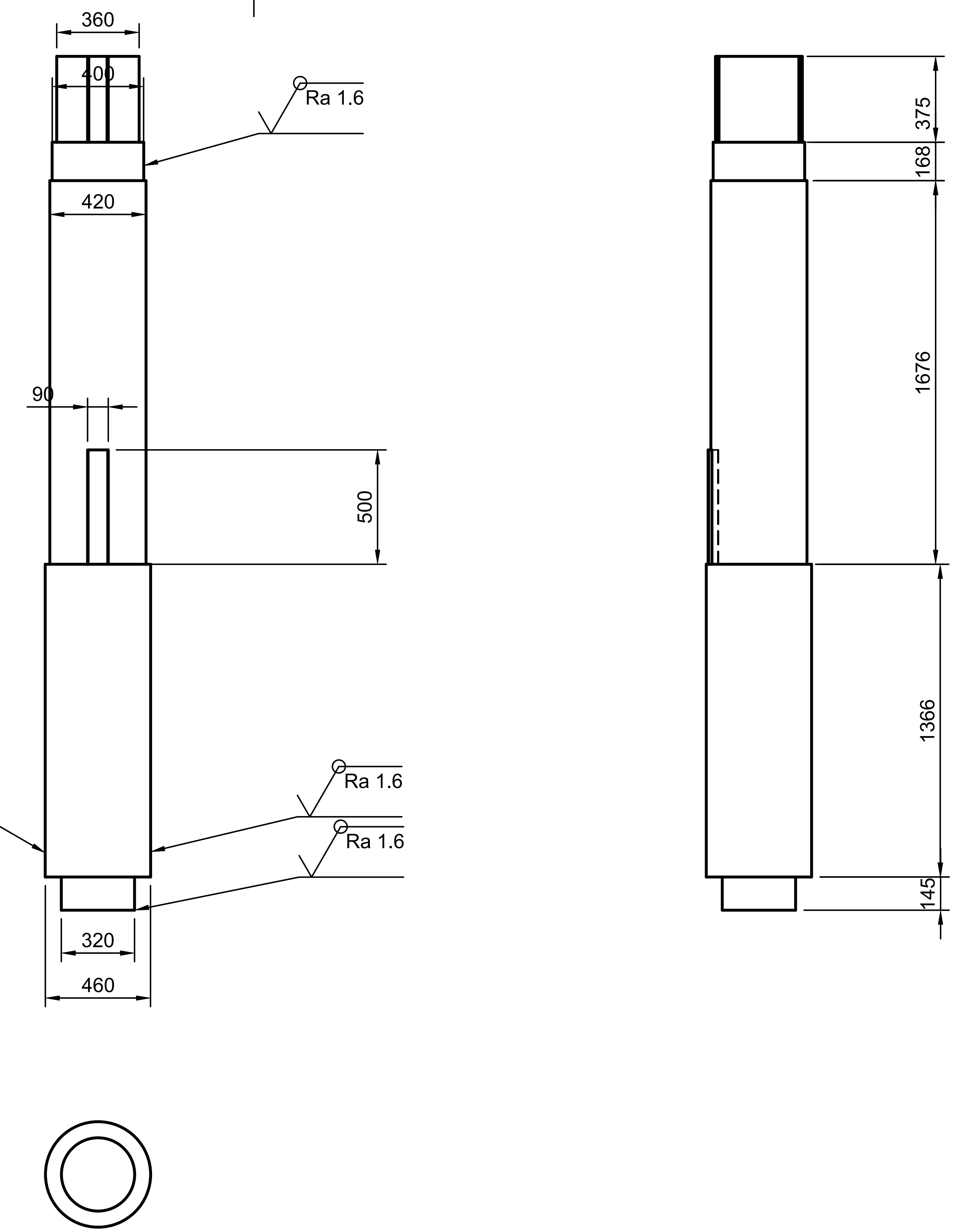
| Scale | Standard | Title | Drawn by |
|---|---|---|---|
| 1:50 | BS8888 | Shaft and Bearing Assembly | Joe Roberts Nuttall |
| | | Components: Shaft and Bearings | All dimensions are in mm |
| Sheet Size: A3 | Date of issue: 07/05/2023 | Sheet: 4/4 | |

Notes

- Critical surfaces on shaft are surfaces in contact with bearings
- Critical surfaces finish Ra 1.6
- Break all sharp edges
- All surfaces machined
- Surface finish of non critical surfaces Ra 3.2



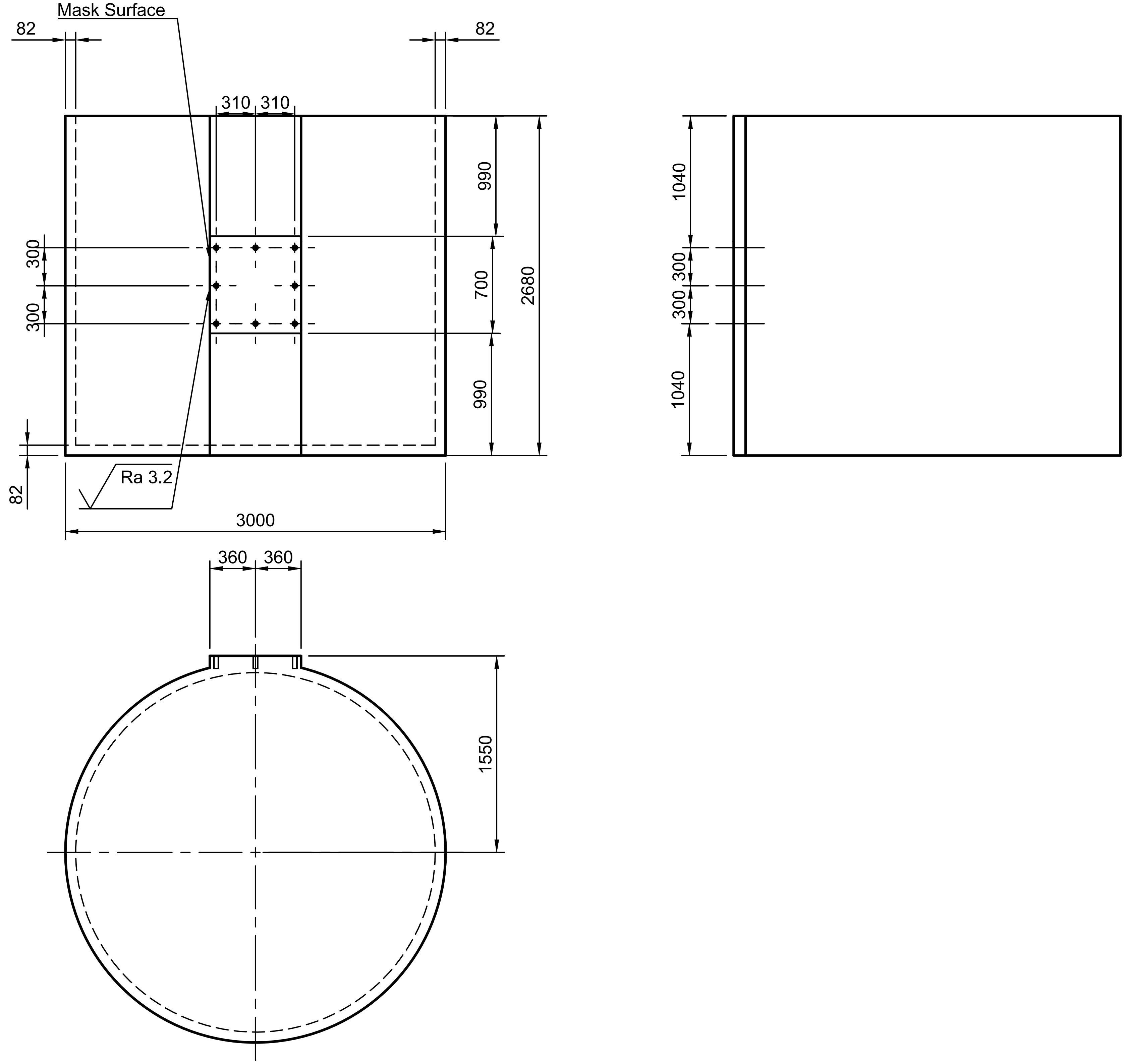
Bearing covers a height of 212 mm and is 10 mm ofset from the shoulder of the shaft

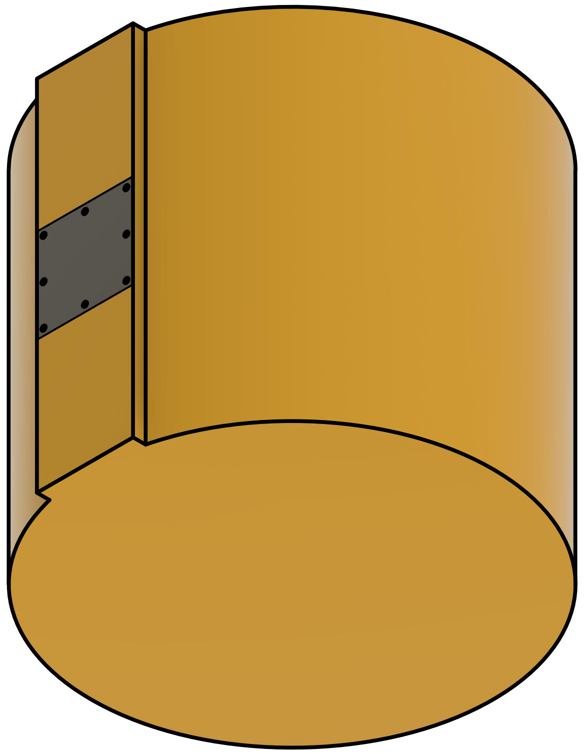



| Scale | Standard | Title | Drawn by |
|---|---|---|---|
| 1:25 | BS 8888 | Shaft Views | Joe Roberts Nuttall |
| | | Components: Shaft | Material: AISI 316 Steel |
| | | | Tolerance - ISO 2768-m (medium) |
| | | | Sheet Size: A3 · Date of issue: 16/12/22 · Sheet: 1/1 |

## Notes

- Masking required on surfaces coming in contact with others
- Masked surfaces marked
- Powder coat finish on un masked surfaces
- Once powdercoating complete remove masking
- Cast and secondary machined critical surfaces
- Critical surfaces are surfaces in contact with other surfaces
- Break all sharp edges
- All machined surfaces to an Ra of 3.2
- All holes from centre to edge of component, 50 mm



| Scale | Standard | Title | Drawn by |
|---|---|---|---|
| 1:40 | BS 8888 | Steel Bucket Views | Joe Roberts Nuttall |
| | | Components: Steel Bucket | Material: Low alloy steel, SAE 4130 |
| | | | Tolerance - ISO 2768-m (medium) |

| Sheet Size | Date of issue | Sheet |
|---|---|---|
| A3 | 16/12/22 | 1/1 |

Notes

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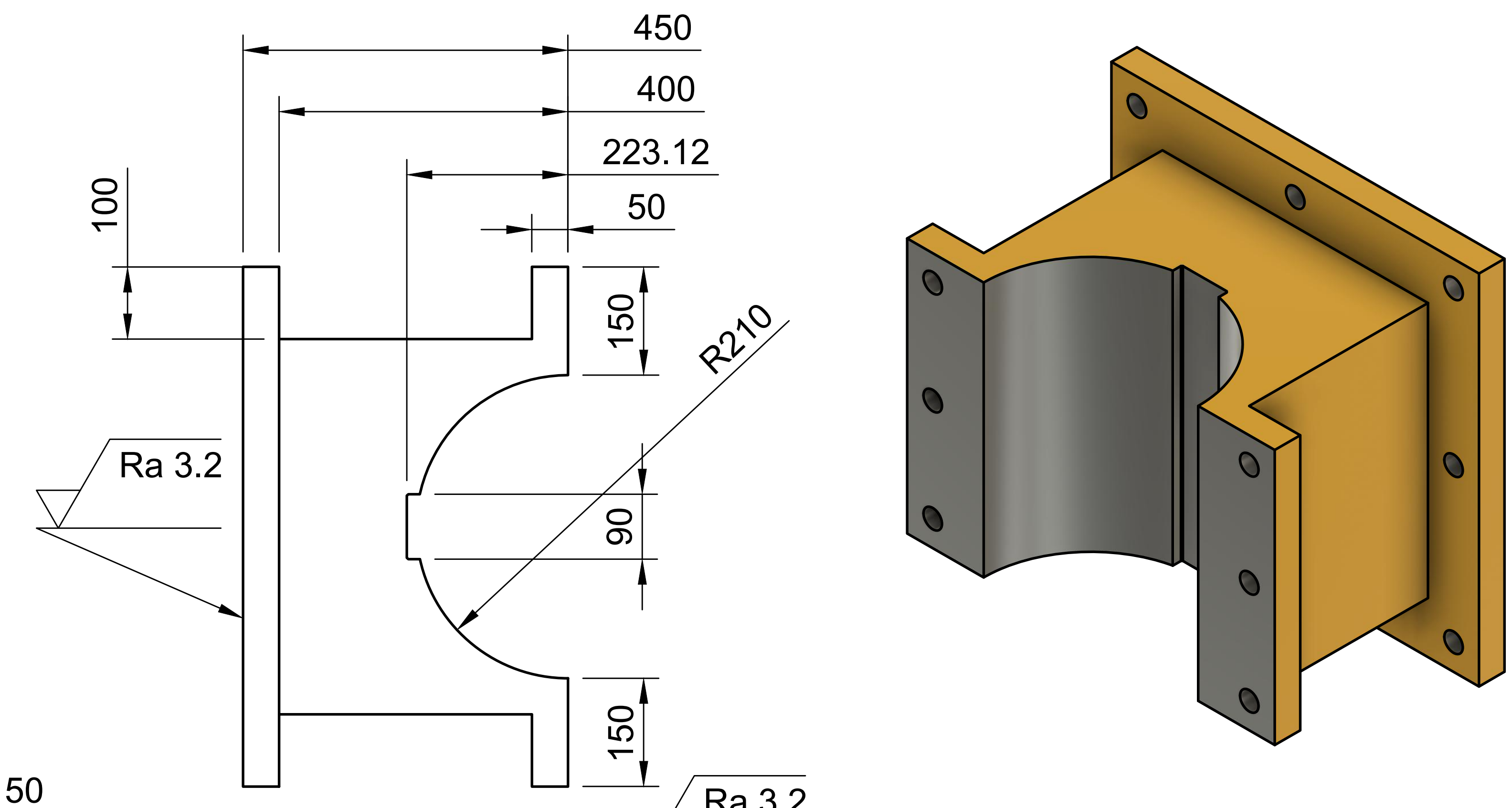
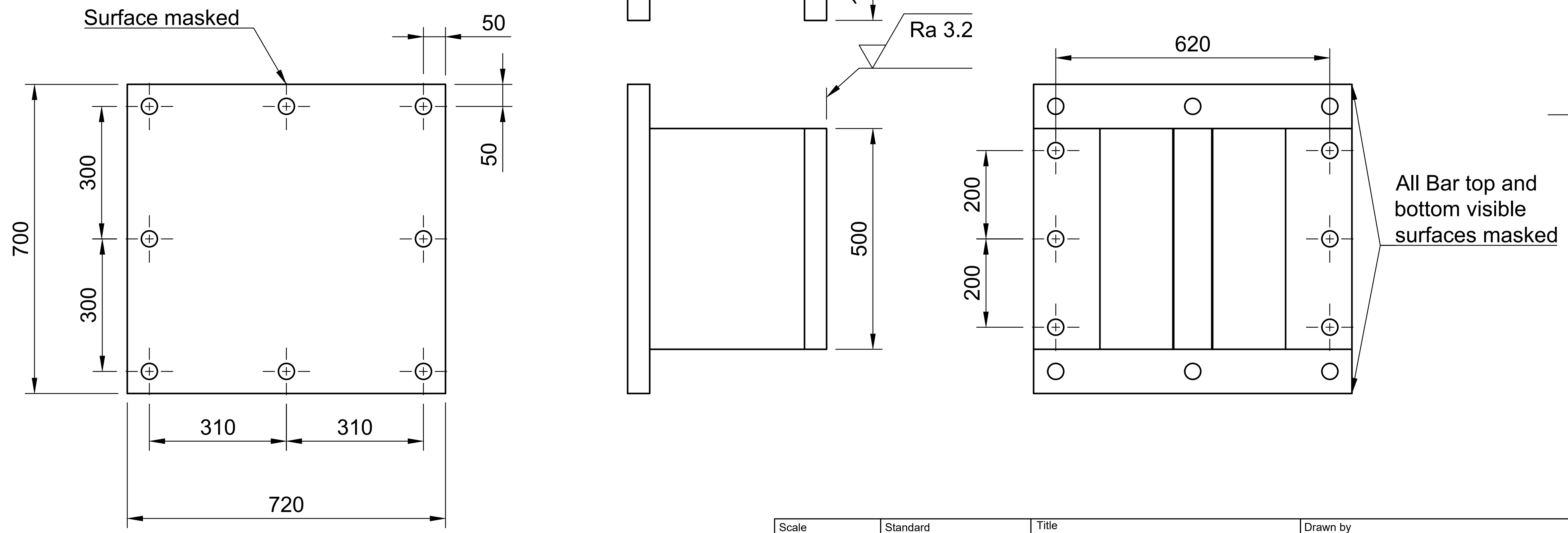
- All holes from centre to edge of component, 50 mm




| | | | |
|---|---|---|---|
| Scale 1:10 | Standard BS8888 | Title Arm Big Section Views | Drawn by Joe Roberts Nuttall |
| | | Components Arm Big Section | Material Low Alloy Steel SAE 4335M |
| | | | Tolerance - ISO 2768-m (medium) |
| | | | Sheet Size A3 / Date of issue / Sheet 1/1 |

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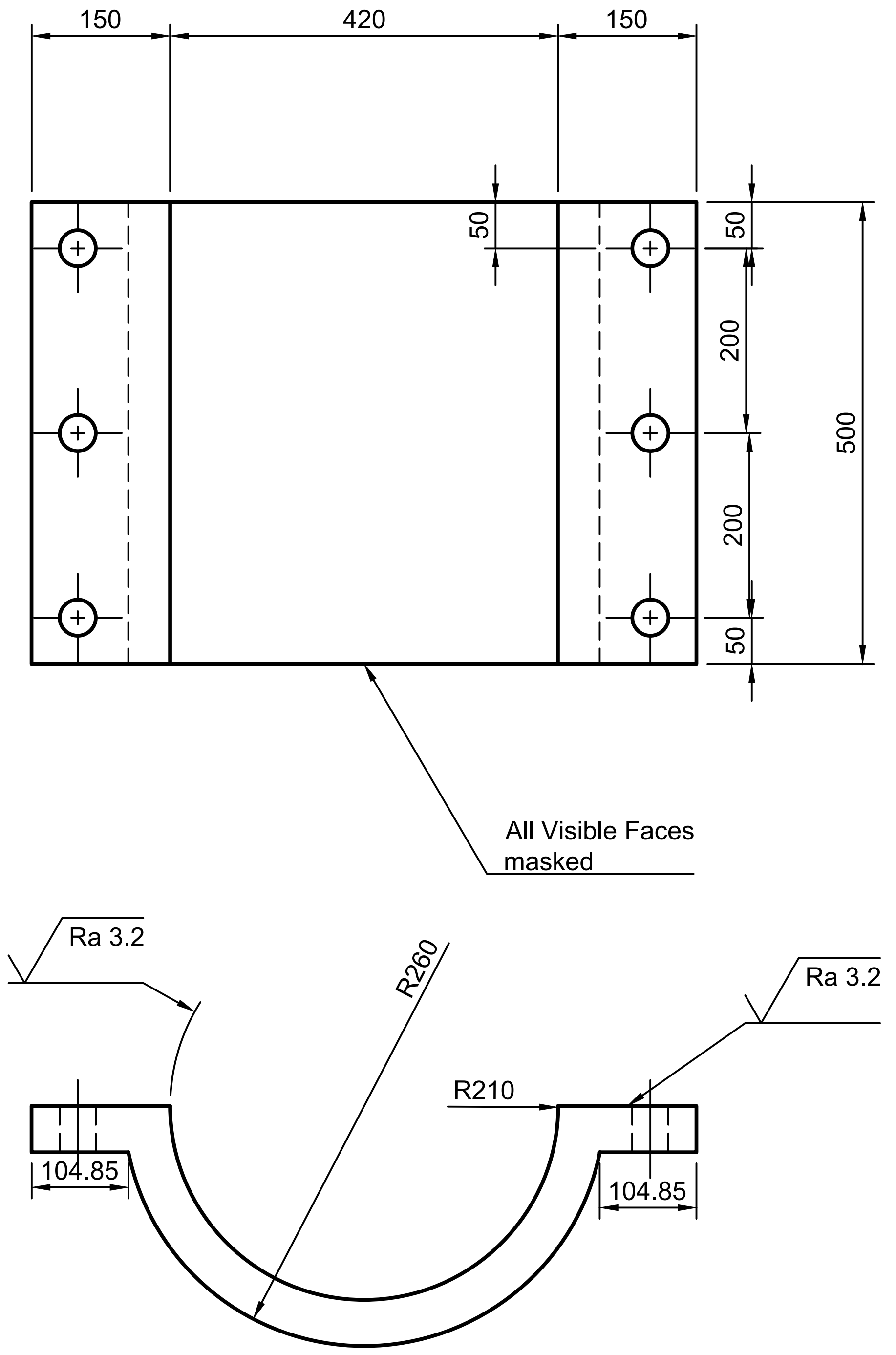
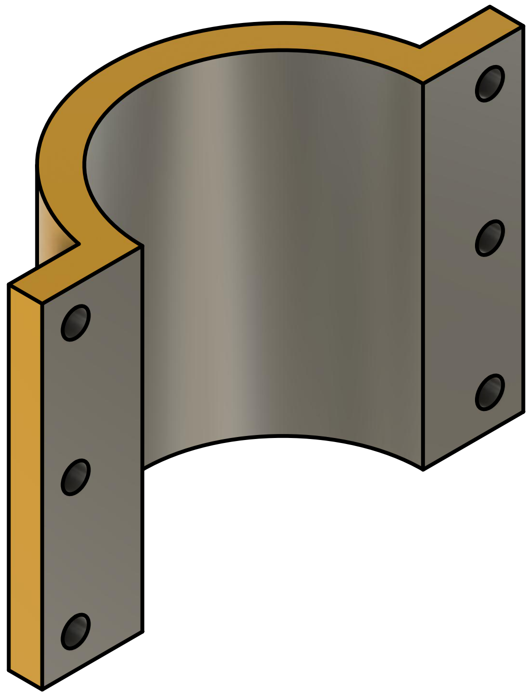
Notes

- Masking required on surfaces coming in contact with others
- Masked surfaces marked
- Powder coat finish on un masked surfaces
- Once powdercoating complete remove masking
- Cast and secondary machined critical surfaces
- Critical surfaces are surfaces in contact with other surfaces
- Break all sharp edges
- All machined surfaces to an Ra of 3.2
- All holes from centre to edge of component, 50 mm



| Scale | Standard | Title | Drawn by |
|---|---|---|---|
| 1:8 | BS 8888 | Arm Small Side Views | Joe Roberts Nuttall |
| | | Components: Arm Small Side | Material: Low alloy steel SAE M4335 |
| | | | Tolerance - ISO 2768-m (medium) |
| | | | Sheet Size: A3 · Date of issue: 16/12/22 · Sheet: 1/1 |

**University of Birmingham**

School of Engineering

# Integrated Design Project 3

## FINAL GROUP REPORT

## Mechanical Engineering

## BEng

## FLOATING PHOTOVOLTAIC SYSTEM

| | |
|---|---|
| **Team Number** | 3 |
| **Group Number** | 4 |

| Student Names | ID Numbers |
|---|---|
| Odysseas Bouziotis | 2205473 |
| Nathan Kairu | 2160369 |
| Afshin Kouhyar | 2000103 |
| Cameron Nagar | 1923347 |
| Ching Hang Ng | 2254111 |
| Alex Rankin-Landry | 2212590 |
| Lois Stevenson | 2253953 |

| Feedback | | |
|---|---|---|
| Reflecting on the feedback that we have received on previous assessments, the following issues/topics have been identified as areas for improvement: | 1 | Critically follow the mark scheme and ensure all requirements are attacked |
| | 2 | Consistent referencing throughout the document |
| | 3 | Adhere to the word count |
| In this assignment, we have attempted to act on previous feedback in the following ways: | 1 | Expanded on the design for materials and manufacture section highlighting how this was met as this was lacking |
| | 2 | IEEE referencing has been used throughout the report for information that was not original |
| | 3 | Layout has been organised to improve flow and be reader friendly |
| Feedback on the following aspects of this assignment (i.e., content/style/approach) would be particularly helpful to us: | 1 | Logical flow of the report |
| | 2 | Is the focus of the report consistently clear |
| | 3 | Effectiveness of the employed methodology to devise a functional solution |

# i. Group Management

## i.1 Work packages, group management, & contributions

Mech BEng 4's contribution to the team level solution was the design of a Floating Photovoltaic (FPV) farm. Figure 1 highlights the work distribution within the group directed at achieving a functional system.

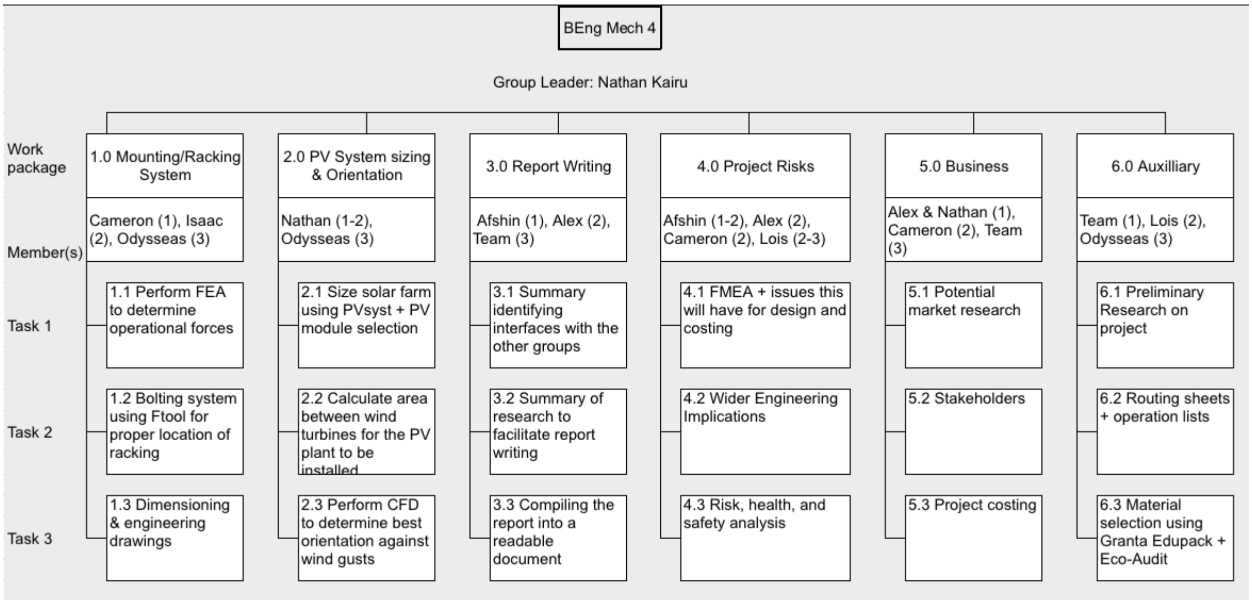
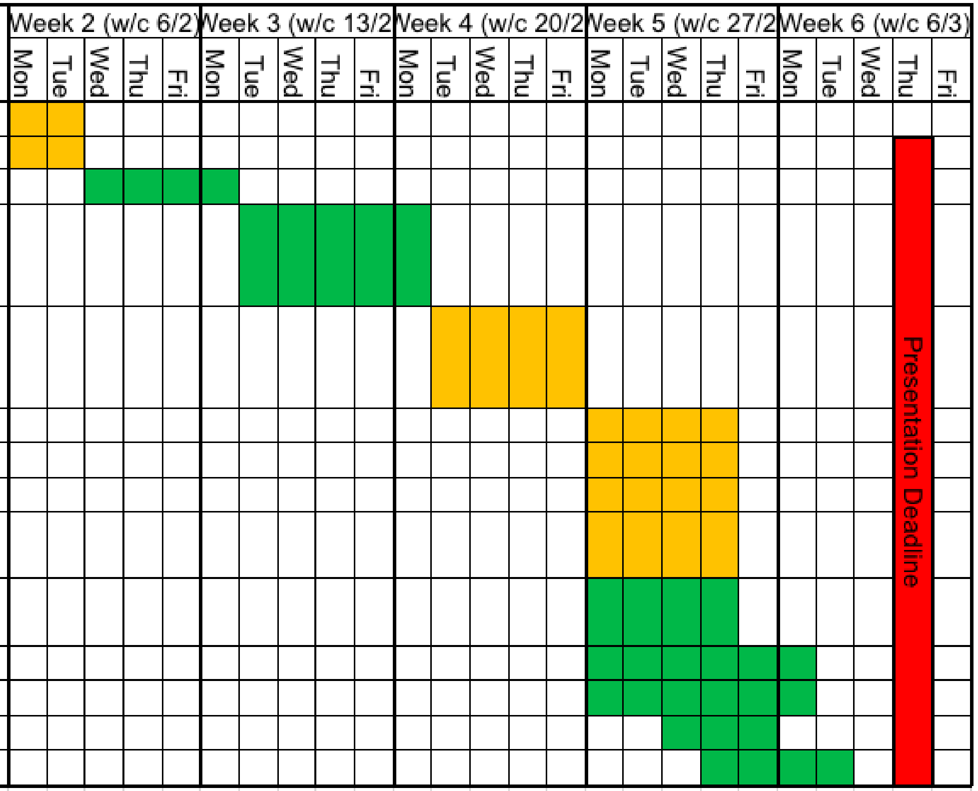



*Figure 1. Summary of work packages and member contributions to group project*

The group met on a weekly basis and where needed, had multiple meetings to ensure smooth and efficient engagement with the workload. The meetings comprised of feeding back from the group leader sessions to the group (mainly concerned with identifying interfaces), from the supervisor (that led to critical thinking about the group solution), as well as within the group (peer review). These helped identify milestones, progressing the project in the process. Streams of communications included MS Teams (collaborative working on documents and MS Teams calls to resolve any issues), WhatsApp, and in-person meetings. The meeting log can be found in **A.5 Summary of minutes.** The main tasks were recorded in a Gannt Chart (Figure 2 and 3).

| Objective | Objective Type | Start Date | End Date | Duration (Days) |
|---|---|---|---|---|
| Rank & submit challenges | Progress | 06-Feb | 08-Feb | 2 |
| Belbin & MB test | Progress | 06-Feb | 08-Feb | 2 |
| Perform research on challenge | Milestone | 08-Feb | 13-Feb | 5 |
| Review different sustainable technologies to identify group contribution to the project | Milestone | 14-Feb | 20-Feb | 6 |
| Research on solar technology identifying pertinent subsystems (particular focus on FPV) | Progress | 21-Feb | 24-Feb | 3 |
| Cooling system | Progress | 27-Feb | 02-Mar | 3 |
| Solar panel types | Progress | 27-Feb | 02-Mar | 3 |
| PV tracking systems | Progress | 27-Feb | 02-Mar | 3 |
| Maintenance + PV rules and regulations | Progress | 27-Feb | 02-Mar | 3 |
| Identify overarching interfaces with other groups | Milestone | 27-Feb | 02-Mar | 3 |
| PDS/SoR | Milestone | 27-Feb | 06-Mar | 7 |
| Concept Ideas (sketches + CAD) | Milestone | 27-Feb | 06-Mar | 7 |
| Summary of decision making | Milestone | 01-Mar | 03-Mar | 2 |
| Draft presentation + preparation | Milestone | 01-Mar | 06-Mar | 5 |

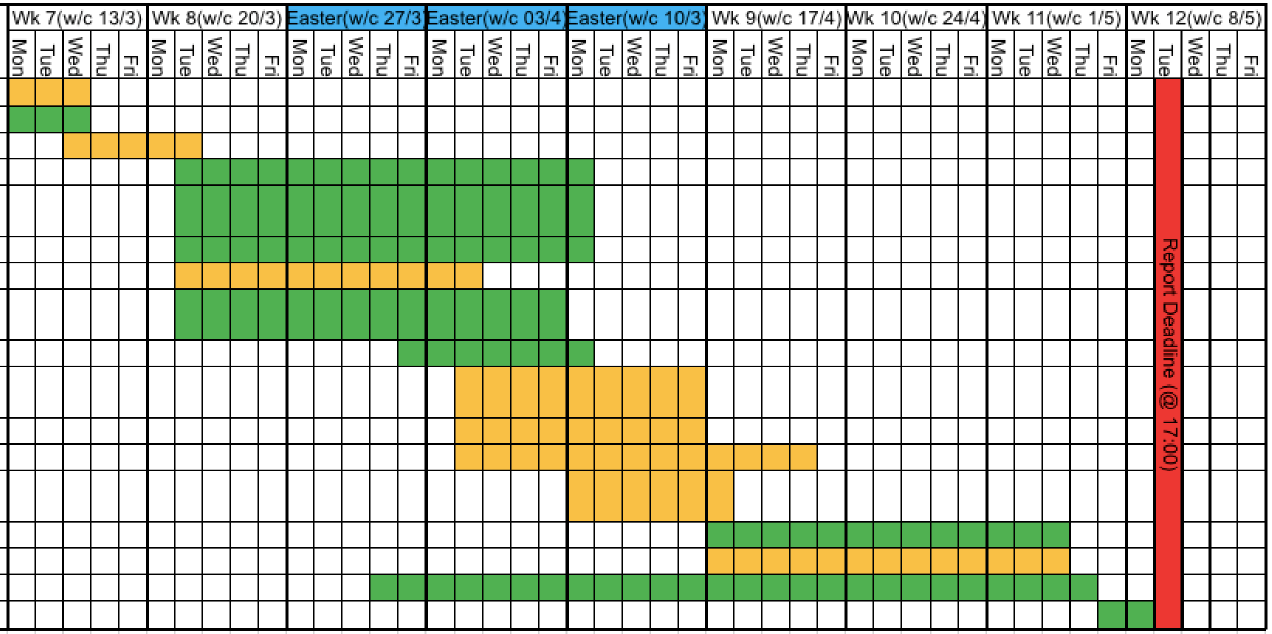



IDP3 Project Plan
BEng Mech 4

| Legend | |
|---|---|
| Objective Type | Colour code |
| Milestone | |
| Progress | |
| Deadline | |

*Figure 2. Gannt Chart summarising work plan up until week 6*

| Objective | Objective Type | Start Date | End Date | Duration (Days) |
|---|---|---|---|---|
| Review previous year reports | Progress | 13-Mar | 15-Mar | 2 |
| Collate calculation parameters | Milestone | 13-Mar | 15-Mar | 2 |
| Further research into PV systems | Progress | 15-Mar | 21-Mar | 6 |
| FEA on PV panel glass | Milestone | 21-Mar | 10-Apr | 20 |
| CFD analysis to determine optimal orientation | Milestone | 21-Mar | 10-Apr | 20 |
| Solar farm sizing using PVsyst | Milestone | 21-Mar | 10-Apr | 20 |
| Summary of decision pathway | Progress | 21-Mar | 04-Apr | 14 |
| Summary identifying high-level interfaces with other groups | Milestone | 21-Mar | 07-Apr | 17 |
| Bolting System using Ftool | Milestone | 31-Mar | 10-Apr | 10 |
| FMEA + wider engineering implications | Progress | 04-Apr | 14-Apr | 10 |
| Risk, health, and safety analysis | Progress | 04-Apr | 14-Apr | 10 |
| Routings sheet + operations list | Progress | 04-Apr | 20-Apr | 16 |
| Material screening (Edupack) + Eco-audit | Progress | 10-Apr | 17-Apr | 7 |
| Identify stakeholders | Milestone | 17-Apr | 03-May | 16 |
| Project Costing | Progress | 17-Apr | 03-May | 16 |
| Report writing | Milestone | 30-Mar | 01-May | 32 |
| Final Draft & Comments | Milestone | 01-May | 05-May | 4 |




IDP3 Project Plan
BEng Mech 4

| Legend | |
|---|---|
| Objective Type | Colour code |
| Milestone | |
| Progress | |
| Deadline | |
| Easter | |

*Figure 3. Gannt Chart summarising work plan after week 6*

## i.2 Group interfaces & Team Integration

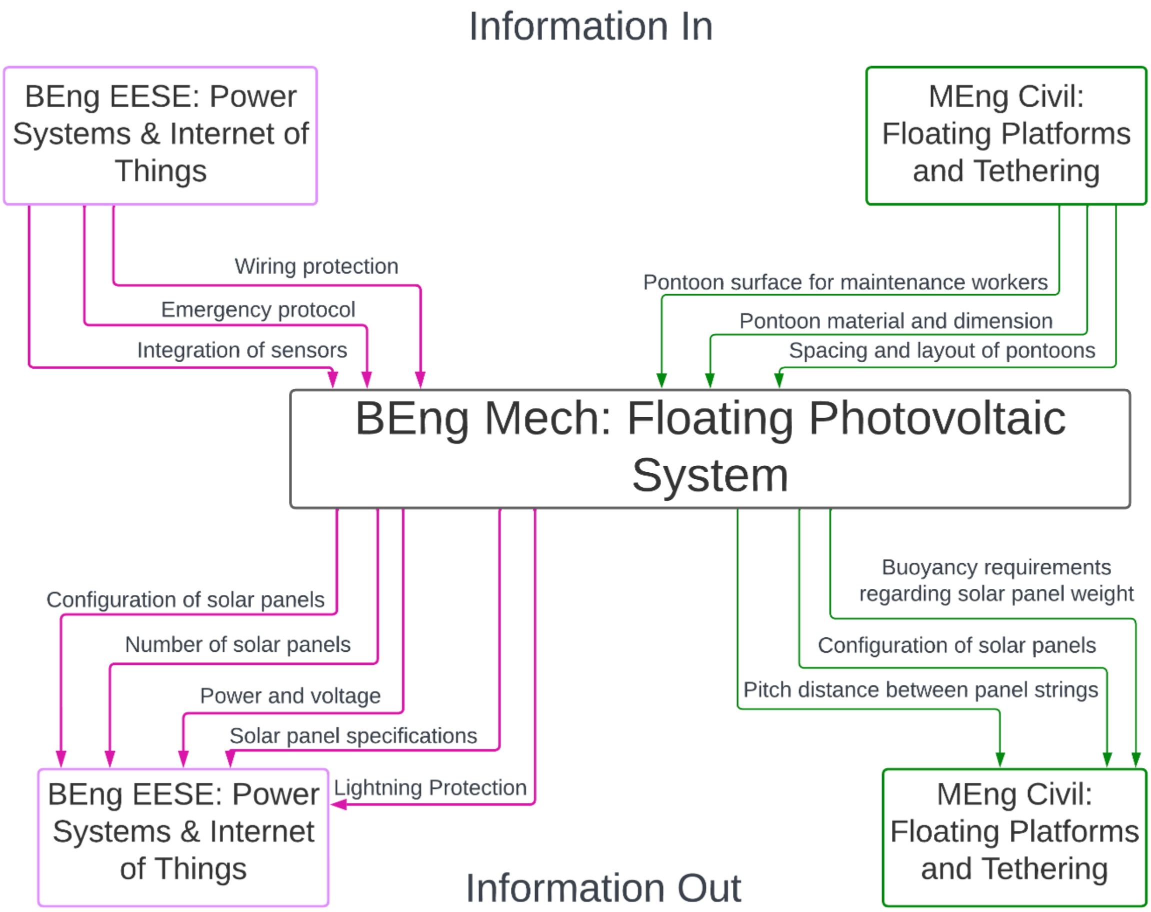



*Figure 4. Team integration flowchart*

The continuous interfaces between the groups played a critical role in ensuring that the different disciplines worked together effectively. It ensured that the system, which relied upon other groups' components, was able to be correctly integrated into the overall project. One area that can be seen on the diagram was the pontoon material and system spacing & layout, which needed numerous ratifications from Civil as further investigation was conducted by the group. Furthermore, lightning protection was found to be necessary to protect against electrical and fire damage [1]. This information was passed onto the EESE group so it could be implemented into the design.

## ii. Executive Summary

Mech BEng 4 was tasked with designing a Floating Photovoltaic (FPV) system that would work alongside MEng's rotary mass and MSc's Point Absorption wave energy converters. The three technologies will work in tandem to help boost the resilience of Star of the South wind farm (2.2 GW capacity), located in Bass Strait Australia, which overcomes the intermittency challenges of renewable energy production. In response, a 20 MWp (Megawatt peak) FPV farm was designed, requiring a total of 42,100 panels with an output of 475 W per panel. The farm was designed taking various factors into account; optimisation of orientation for maximum energy yield, design against corrosion and wind gusts, as well as compliance with the Victorian and Australian energy regulations. With an estimated 77,641.9 tonnes reduction in $CO_2$ emissions in the lifetime of 30 years, the proposed FPV farm has significant potential to provide a reliable and sustainable source of energy to contribute to Australia's renewable energy targets. After much scrutiny, the project was proved to be economically viable, physically feasible, and environmentally beneficial.

## 1. Introduction

Australia is a country that is still heavily dependent on fossil fuels for its energy production with up to 93% of its electricity being generated from fossil fuels [2]. The recent Russia-Ukraine war has led to sanctions on Russian produced oil, increasing energy prices by up to 18% [3]. As a result, inexpensive technologies with low carbon footprints are imperative to overcome these problems. To help realise the main team level objective, a consistent energy output from the sustainable offshore energy island, Mech BEng 4 focused on the design of an FPV system, adding to the wave and wind technologies on the island. Furthermore, Star of the South wind farm provides an ideal location to harness Australia's solar irradiance [4] allowing for a robust energy production system.

FPV is a nascent form of technology that's garnering commercial attractiveness thanks to the myriad of benefits provided in comparison to its ground- & roof-mounted counter parts [5]. Firstly, FPV does not require valuable land, instead, space on water bodies can be utilised [5] - this is particularly important for Australia, given Melbourne's current industrial land crisis [6]. Second, FPV has a higher energy yield owing to the cooling effect on panels from water evaporation [7]. Moreover, compared to other emerging technologies, FPV benefits from the maturity associated with PV ground- & roof-mounted technology making it easier to implement [5][7]. However, the technology's location on water makes operation and maintenance a difficult task [7]. Furthermore, challenge of water salinity that amplifies corrosion rate of materials is introduced for offshore application [7]. Other challenges include mechanical stresses and strains due to wave action and wind gusts all of which need addressing to ensure a resilient and functional design of the plant.

# 2. Product Design

## 2.1 Product Design Specification (PDS)

*Table 1. Product Design Specification for a Floating Photovoltaic system*

| Aspect | Description |
|---|---|
| **Aesthetics** | Performance and ergonomic design requirements outweigh aesthetics with minimal visual pollution |
| **Costs** | High costs will be involved as high-quality material as well as moderate-high maintenance schedules are required to warrant reliability and performance |
| | Utilise standard parts where applicable and source components from Australian based companies to minimise costs |
| **Weight and size** | Weight of single racking string (including panels) should be around 2 tonnes |
| | Modular design should fit within rectangular pocket area of 2.22 $km^2$ created by four wind turbines with a ground coverage ratio > 30 % [8] |
| **Environment** | Parts should be made from corrosive resistant material to prevent water pollution |
| | Components should be disposed of according to Australia's and Victoria's best practice recommendations |
| | Use non-toxic detergent for module cleaning and where toxic detergent is unavoidable, use spill containment |
| | Technology is to be renewable and sustainable with no extra energy input |
| **Life cycle** | With proper maintenance, solar farm should have an operational life of 25-30 years coinciding with that of the wind farm |
| **Performance** | The plant should be able to generate 20 MWp of electricity |
| | Modules should be sourced from reliable manufacturers and have efficiency of ≈20% [9] |
| | Shading losses should be minimised to 3% of total energy output [9] |
| | Sensors should be used to monitor plant performance allowing for data acquisition for energy output control to the grid |
| | Standard parts & materials, where applicable, should be used for ease of replacement and repair to minimise system downtime |
| | Panels should be able to withstand max temperature of up to 40 °C before disruption to performance and a max of 60 °C before electrical damage [10] |
| **Quantity** | Total number of modules should be able to produce the required 20 MWp of electricity |
| **Safety** | Live wires should be electrically insulated to prevent risk of shock to the maintenance and operations personnel |
| | Ensure proper bolting of panel to racking, and racking onto the pontoon to prevent flip-over of solar assembly as a result of wind gusts |
| | Australia and Victoria safety regulations should be followed (such as the s AS/ NZS 5033 standards [11] |
| | Lightning protection system should be installed to protect components from risk of short circuits and fire hazards |
| **Maintenance** | System design should accommodate for walkways on pontoons for easier accessibility for workers |
| | Preventive checks should be performed at a predetermined interval i.e., monthly, quarterly, yearly, Corrective checks when break downs occur, and Predictive checks based on sensor outputs to ensure smooth system operation |

| | |
|---|---|
| **Material** | Corrosion resistant and recyclable material are to be used to extend system life span and for sustainability purposes respectively |
| | Racking: light weight, high fracture/yield strength, high young's modulus, and cheap material |
| | Clamps: high young's modulus, hardness, durability and strength |
| | Bolts, nuts, and washers: high shear strength, strength and toughness, high hardness, fatigue strength and corrosion resistance |
| | The glass protective layer should accommodate for the panel's strength and toughness, high transmittance, high durability, low reflectance |

## 2.2 Considerations

Table 2 and 3 highlight the initial considerations in terms solar harnessing technologies and technologies capable of improving system yield respectively. However, these were discarded for reasons presented in the Tables.

*Table 2. Complementary technologies to the FPV system*

| Cogeneration technology | Why it was disregarded |
|---|---|
| Cogeneration technologies **Concentrated Solar Power (CSP):** light concentration for heat generation [12] | • Requires thermal storage to meet peak energy demand making it more expensive.<br>• Fossil fuel dependent<br>• Cooling of heat conversion systems requires large volumes of fresh water.<br>• Risk of explosion and water pollution due to use of synthetic oils. |
| **Photovoltaic Thermal Cooling (PVT):** heat harnessing through thermal collectors [13] | • Complex and expensive for large scale application<br>• The heat storage capacity of this technology does not profit to the plant as this storage is not applicable to the system. |

*Table 3. Additional FPV components*

| Technology | | Why it was disregarded |
|---|---|---|
| **Solar tracking system:** maximise energy yield by tracking path of the sun [14] | | • Expensive and complex for large scale application<br>• Fragile components and assembly<br>• High maintenance requirements |
| **Wave compensation system:** stabilise panel orientation and maximise energy yield [15] | | • Expensive for large scale application<br>• Fragile components and assembly increasing maintenance costs<br>• High maintenance requirements |
| **Panel Cooling Methods:** panel temperature decrease to increase output | **Phase Change Material Layers** [16] | • High maintenance requirements<br>• High costs (130£/m²)<br>• Flammability risks<br>• Heavy (25 kg/panel)<br>• Leakage risks |

| | | |
|---|---|---|
| efficiency and limit damage | **Thermoelectric Cooling Devices** [17] | • Expensive for large scale application<br>• Requires input of power which would lower overall plant power output |
| | **Cooling Fins** [18] | • Additional maintenance requirement<br>• Immature technology<br>• Additional costs |

Ultimately, the choice to implement a Photovoltaic derived system, FPV, was due to the simplicity of the technology in terms of number of components, low maintenance requirements, short installation periods, technology maturity, as well as operation on water.

## 2.3 Product Overview

The total capacity of the FPV system is 20 MWp requiring 42,100 panels each producing 475 W. In a single string, which corresponds to 1 racking assembly, there are 25 PV modules. In total, there are 1,684 strings and a single pontoon will have 25 modules x 13 strings. To ensure location of panels onto the racking, M8 bolts and clamps have been used following the manufacturer's installation manual [19]. Furthermore, strings have been evenly spaced at a pre-determined pitch to minimise inter-row shading of panels as well as to provide walkways for maintenance and operations personnel. Figure 5 provides a simple schematic of a single PV module which is to be scaled up to meet the specified total quantity of 42,100 panels. The plant will be situated between 4 wind turbines taking up a total area of approximately equal to 0.45 km². For illustrative purposes, Figure 6 provides a scale perspective of the plant with respect to the area between the wind turbines.

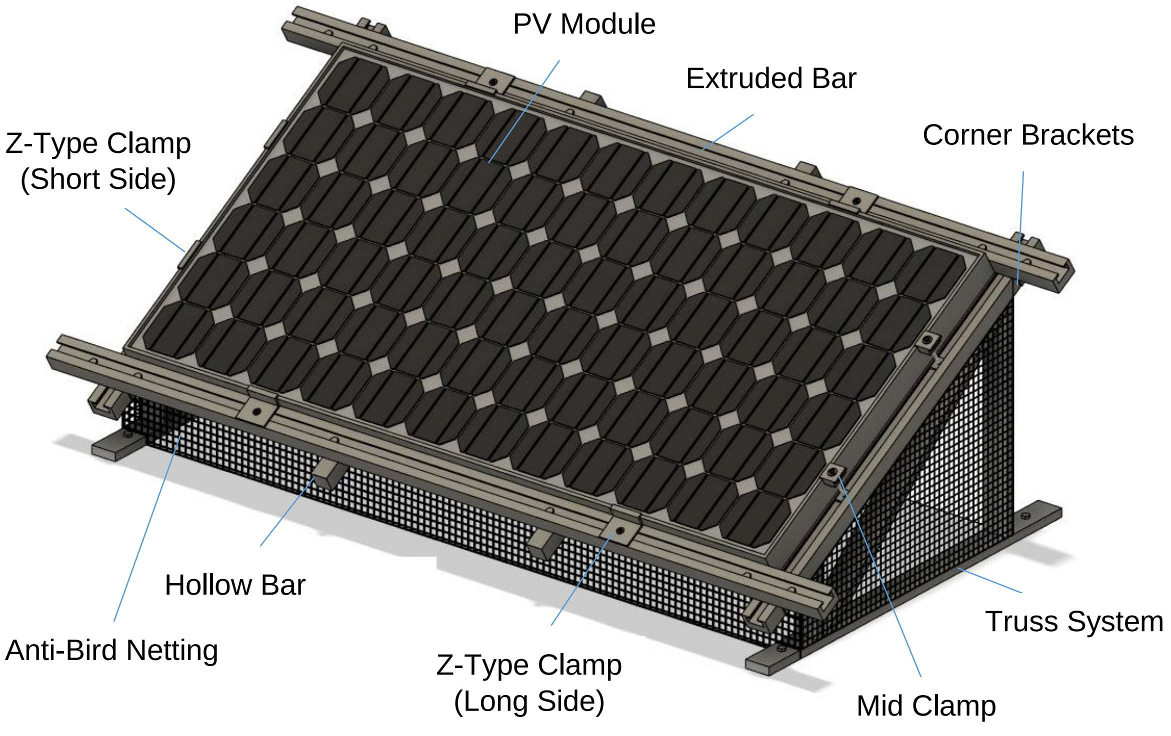



*Figure 5. Module and Racking Schematic for one Solar Panel.*

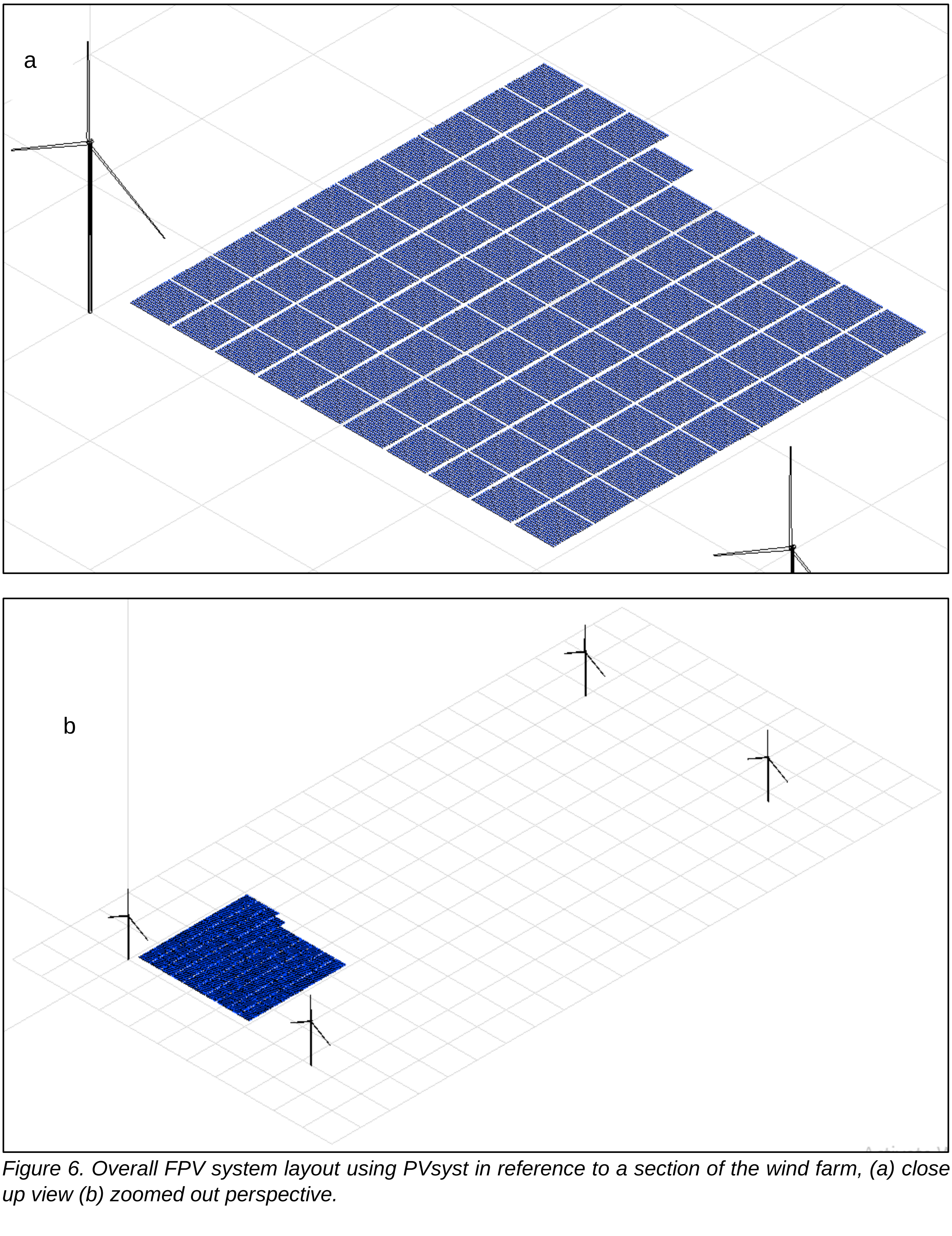



*Figure 6. Overall FPV system layout using PVsyst in reference to a section of the wind farm, (a) close up view (b) zoomed out perspective.*

## 2.4 Out-sourced components

This section provides details on the most compelling outsourced components. It was required that the suppliers had a strong presence in Australia (or subsidiaries) to minimise cargo transportation costs, and in the case of system downtime, quick reaction time for maintenance. Full details on auxiliary outsourced components can be found in the **A.2 Bill of Materials.**

**PV module:**

It was important that the modules were designed to meet minimum requirements of certification for module safety (IEC 61730) and design (IEC 61215), with an additional test for resistance against salt-mist corrosion (IEC 61701) for offshore application [7]. To that end, the SPR-MAX6-475-COM (475 W) model (Figure 7) with 22.3% efficiency from Maxeon Solar Technologies was selected [20]. The module is made of 72 cells from monocrystalline silicon cell technology (known for highest efficiency in the market [21]. Figure 8 provides a snippet of the warranties, certifications, and compliance the selected solar panel achieves.

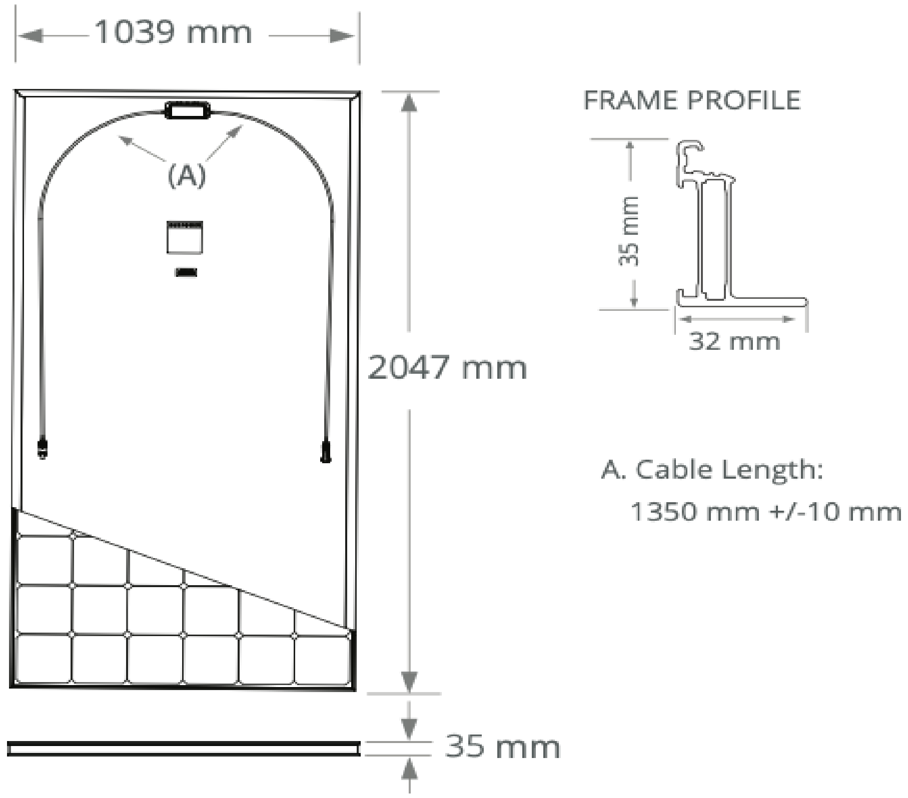



*Figure 7. [20] SPR-MAX6-475-COM overall dimensions*

| | |
|---|---|
| Standard Tests[3] | IEC 61215, IEC 61730 |
| Quality Management Certs | ISO 9001:2015, ISO 14001:2015 |
| Ammonia Test | IEC 62716 |
| Desert Test | IEC 60068-2-68, MIL-STD-810G |
| Salt Spray Test | IEC 61701 (maximum severity) |
| PID Test | 1500 V: IEC 62804 |
| Available Listings | TUV |
| IFLI Declare Label | First solar panel labeled for ingredient transparency and LBC-compliance.[4] |
| Cradle to Cradle Certified™ Bronze | First solar panel line certified for material health, water stewardship, material reutilisation, renewable energy & carbon management, and social fairness.[5] |
| Green Building Certification Contribution | Panels can contribute additional points toward LEED and BREEAM certifications. |
| EHS Compliance | RoHS, OHSAS 18001:2007, lead free, REACH SVHC-163 |

*Figure 8. [20] SPR-MAX6-475-COM Maxeon Solar Technologies warranties, certifications, and compliance*

**Pyranometers:**
Reliable system monitoring and automatic data acquisition (in terms of plant yield) can benefit from simultaneous measurements of solar irradiance with the help of pyranometers to maintain high level performance, reduce downtime, and ensure rapid fault detection [9]. For multi-megawatt plants (20 MW+), it is recommended to use 4 pyranometers in locations not susceptible to shading. The CMP10 pyranometer from KIPP & ZONEN was selected [22].

**Protective netting:**
Bass Strait, Victoria is a popular seabird habitat [23] where birds may cause electrical damage on panels such as hot spots because of shading created by soiling from nesting and droppings [20]. Meshed netting has been shown as an effective method which complies with environmental and wildlife protection regulations. As a result, Quatra's (25 m x 1.2 m) [24] net was selected.

## 3. Design for Materials and Manufacture

For ease of manufacture and assembly of the racking a modular design was used, in which the components were split into three main parts: truss system, extruded bars and hollow bars (see Figure 5). The modular design of the truss system allows for automated welding to be used minimising the usage of bolts and nuts that could potentially weaken the structure. Furthermore, the vertical bars that appear in the truss system were equally spaced for symmetry, and placed towards the centre to avoid narrow regions when manufacturing that could lead to localised stress concentrations. The extruded bar was to be manufactured using a purlin machine which includes roll forming, cutting, and drilling. The choice of machinery was selected due to the integrated methods which has the advantage of reduced costs, complexity, and less space requirements on the production floor. The simplicity of design, such as the hollow rectangular structure was selected to reduce weight (for float buoyancy purposes) and material waste. The hollow shape creates rails for the T-nuts to be slotted. The necessary drilling of the holes that mount the racking to the pontoon were assured to be on flat surfaces and away from potential cavities to allow for ease of manufacture and lower chances of damage to component. Additionally, the dimensions of all the bars were standardised to lower manufacturing costs and facilitate sourcing.

The clamps were designed and fitted to the exact dimensions of the racking and the PV module's frame. The holes of the clamps were centred and designed symmetrically to equally distribute the expected stresses while drilling. Holes were standardised at M8 for ease of manufacture. Chamfers were used on the external corners to lower manufacturing costs and avoid locations for stress concentrations. The slots of the extruded bars and of the truss extruded bars possess consistent internal dimensions to accommodate the T-nuts. Thus, a standard T-nut (M8, 10 x 40 x 40 mm) was selected for this application and used for all the clamps.

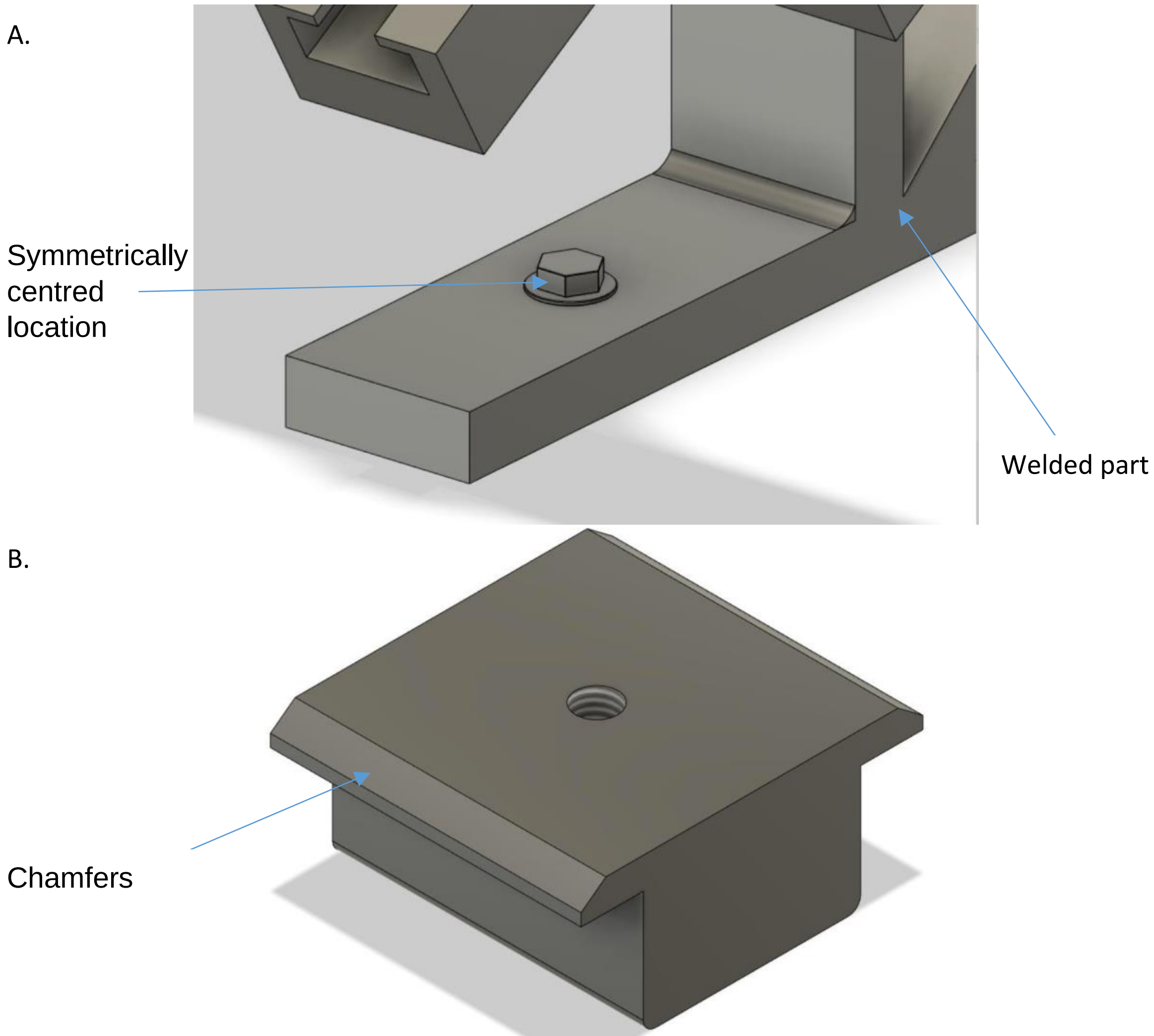



*Figure 9. A: location of drilled hole; B: middle clamp chamfers*

The main reason for custom manufacture of these components was due to the limitations of existing standard parts on the market. The standard material of the required parts was A2 stainless steel, which would not be able to withstand the harsh marine environment. Material analysis using Granta Edupack (Figure 9), determined that Stainless Steel AISI 316, was the most appropriate material for the racking. It fits the corrosion, recyclability, and durability requirements highlighted in the product design specification. The material has already been implemented for offshore solar panels and maritime applications thanks to the addition of molybdenum that boosts the corrosive resistant properties [25]. The material's key mechanical properties are listed in Table 4. The associated engineering drawings, bill of materials, manufacturing processes, and assembly procedures for the components are provided in the **Appendix (A.1 - A.4).**

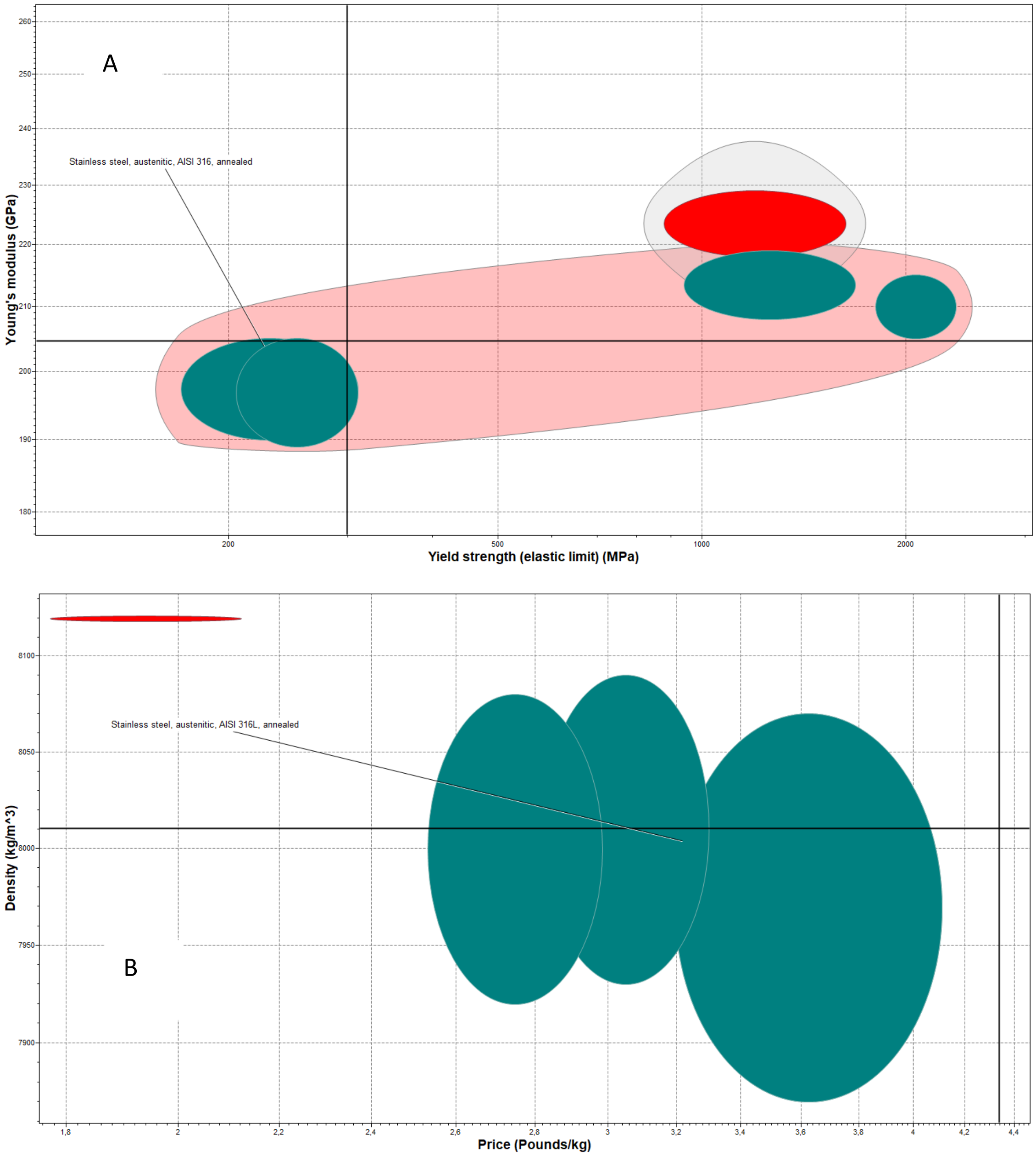



*Figure 10. Material selection: A, Young's modulus against Yield Strength; B, Density against Price*

*Table 4. Stainless Steel AISI 316, annealed properties*

| Material Property | Value |
|---|---|
| **Young's Modulus** | 189 to 205 GPa |
| **Density** | 7.87E+03 to 8.07E+03 kg/m$^3$. |
| **Yield Strength** | 205 to 310 MPa |
| **Tensile Strength** | 515 to 620 MPa |
| **Compressive Strength** | 205 to 310 MPa |
| **Poisson's Ratio** | 0.265 to 0.275 |

# 4. Technical Evaluation and Detail Design

## 4.1 Plant Design & Sizing

### 4.1.1 Simulation Setup

The design and sizing of the Floating Photovoltaic (FPV) farm was performed using PVsyst software which is commonly used in industry [9 and advised by S. Khan, shereen.khan@stern-energy.com, Stern Energy, 11/04/2023]. For this a plant location (Figure 11), a PV module (SPR-MAX6-475-COM model) were selected for input.

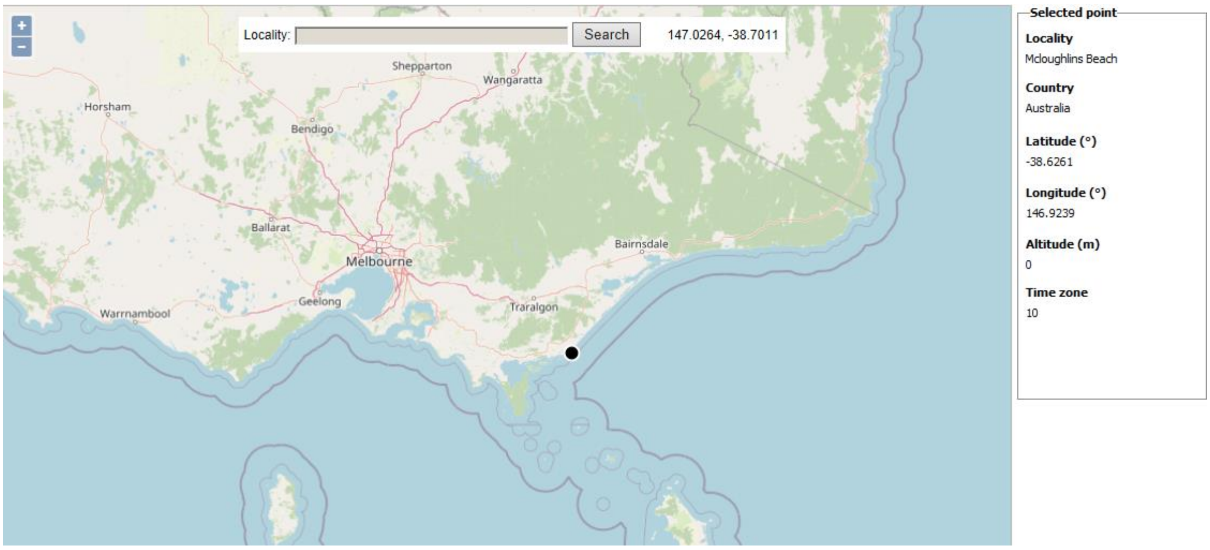



*Fig 11. Bass Strait site location in PVsyst*

To produce realistic results, meteorological data pertaining to the plant's location was synthetically generated from PVsyst for the past 10 years (Figure 12).

| | Global horizontal irradiation | Horizontal diffuse irradiation | Temperature | Wind Velocity | Linke turbidity | Relative humidity |
|---|---|---|---|---|---|---|
| | W/m² | W/m² | °C | m/s | [-] | % |
| January | 270.0 | 129.7 | 20.0 | 4.80 | 3.203 | 65.6 |
| February | 246.9 | 109.4 | 19.5 | 4.70 | 3.200 | 70.1 |
| March | 198.9 | 79.4 | 17.5 | 4.38 | 2.976 | 72.4 |
| April | 140.0 | 57.4 | 14.2 | 3.80 | 2.849 | 78.5 |
| May | 92.1 | 39.0 | 11.5 | 4.10 | 2.709 | 80.9 |
| June | 71.9 | 38.1 | 8.7 | 3.90 | 2.637 | 86.7 |
| July | 83.1 | 38.3 | 8.3 | 4.09 | 2.628 | 83.2 |
| August | 114.1 | 57.3 | 9.2 | 4.40 | 2.702 | 79.0 |
| September | 163.1 | 62.9 | 11.1 | 4.59 | 2.988 | 76.5 |
| October | 220.0 | 96.9 | 13.6 | 4.50 | 2.987 | 72.4 |
| November | 269.7 | 104.0 | 16.0 | 4.59 | 3.014 | 72.3 |
| December | 292.1 | 119.0 | 18.1 | 4.80 | 3.085 | 67.2 |
| **Year** | **179.8** | **77.5** | **14.0** | **4.4** | **2.915** | **75.4** |

**Global horizontal irradiation year-to-year variability 3.1%**

*Figure 12. Bass Strait synthetically generated data in PVsyst, averaged over the years 1999-2013*

### 4.1.2 PV Module Azimuth & Tilt

To determine the module orientation (azimuth & tilt - see Figure 13) and pitch that would provide satisfactory yield while also having a lower ground coverage ratio (GCR, to improve land economy), an optimisation simulation was carried out using PVSyst Software. In the Southern hemisphere, for optimum energy yield, solar panels are recommended to face North (0° azimuth) [7].

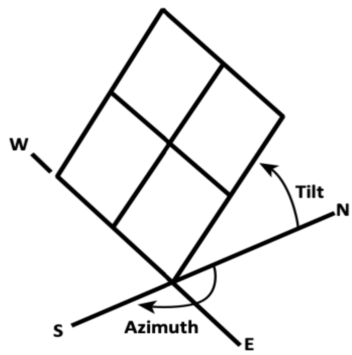



*Figure 13. Tilt and azimuth definition for a PV array facing south [9]*

In the simulation, the pitch (distance between to strings of panels) was varied from 2 - 6 m and tilt angle 0 - 50°. A string's pitch of 1 m was not considered because it produced unacceptable levels of inter-row/mutual shading that effectively lowered the system yield. The simulation results allowed to evaluate the effect of PV orientation on shading loss (Figure 14) and the energy output from the arrays (in DC form) (Figure 15). These were considered the most important parameters from an energy production perspective.

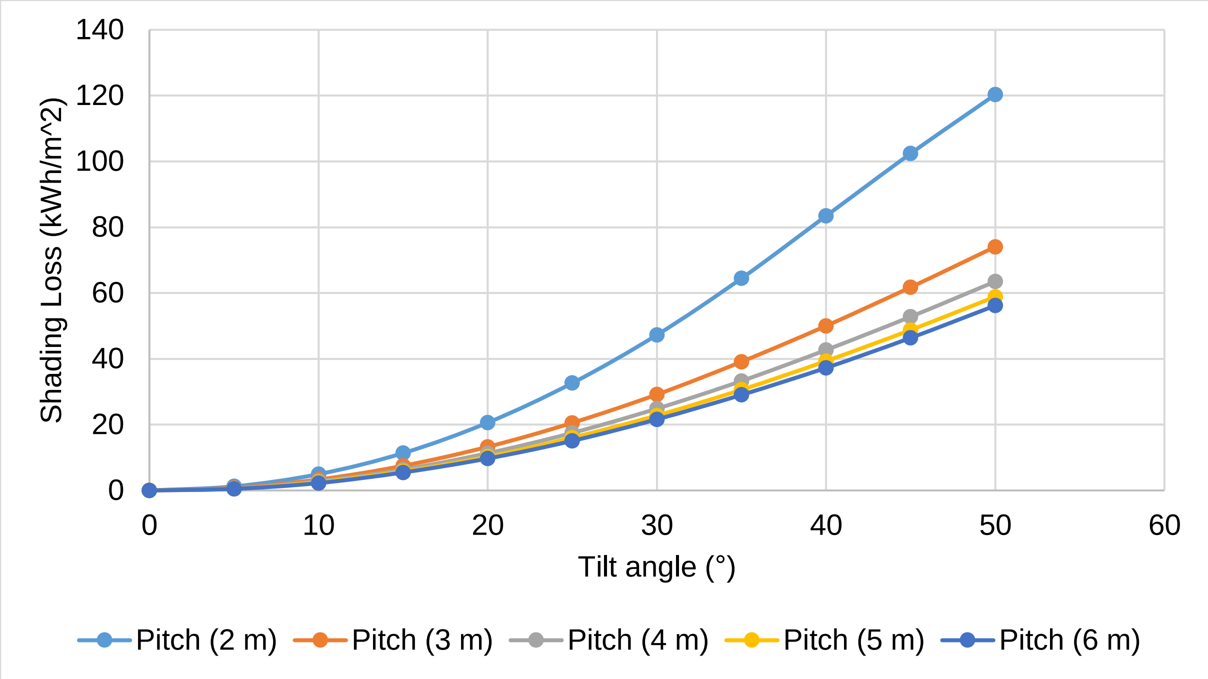



*Figure 14. System shading loss as a function of the tilt angle for varying pitch sizes*

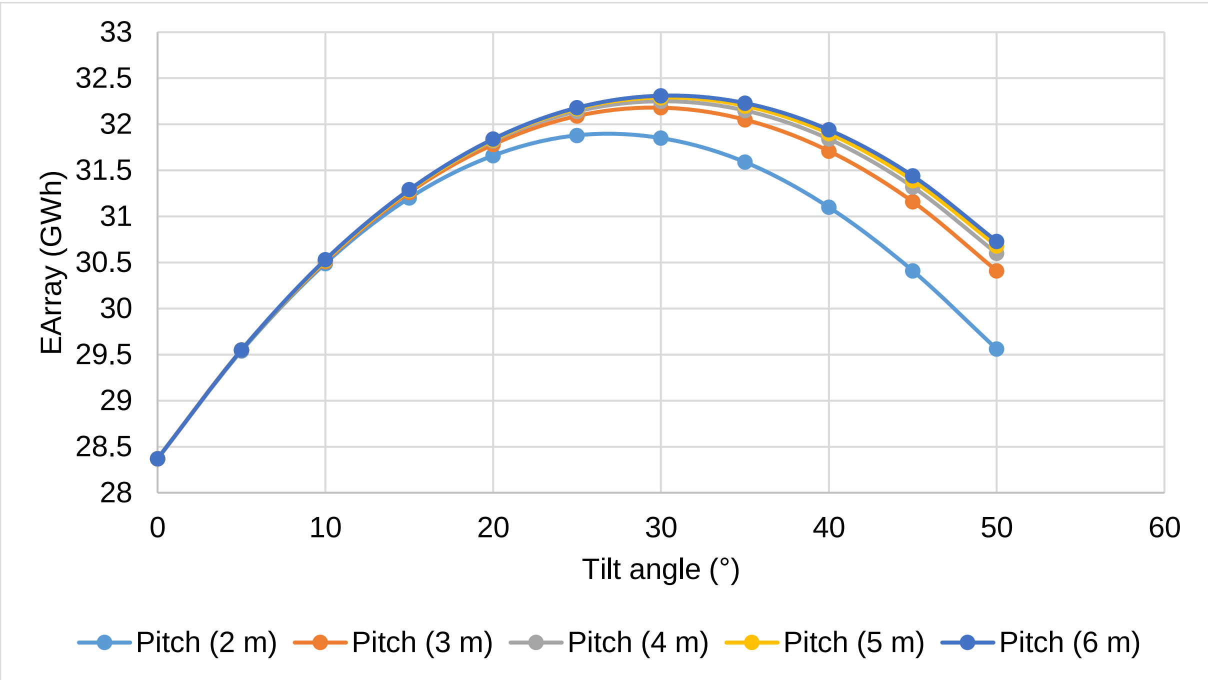



*Fig 15. DC energy output at the exit of module arrays as a function of the tilt angle for varying pitch sizes*

From Figure 15, it can be observed that an increase in pitch yielded better results across all the set tilt angles. However, this does not account for the GCR. From this, a pitch size of 3 m was selected as it provides a competitive system performance output comparable to higher pitch sizes (4,5,6 m) as well as a satisfactory GCR of 40%. A 30° module tilt angle produced the highest energy yield for all but the 2 m pitch size. Furthermore, it is recommended that the modules be mounted in a landscape mode if they are more prone to partial shading [26]. This is mainly attributed to the architecture of bypass diodes in a PV module which are installed along the module width.

### 4.1.3 Plant Performance & Layout Results

The selected plant location, PV module type as well as the pitch and orientation settings were used to predict overall plant performance. The FPV farm was designed to produce 20 MWp of electricity. As a reference, the current largest FPV farm produces 389 MWp of electricity [27]. For these inputs, the simulation determined that 42,100 PV modules rated at 475 W were required to produce 20 MWp. The number of PV modules in series and number of strings are directly dependent on inverter power rating. As a result, purely for system design and sizing purposes, a 2000 W generic inverter from PVsyst database was assumed. This resulted in 25 modules in series and 1684 strings. Finally, the plant layout (see Figure 6, Product Overview) was designed to account for inter-row shading as well as near object shadings (in this case wind turbines). This overall system performance simulations results were specified in Figure 16.

| | GlobHor kWh/m² | DiffHor kWh/m² | T_Amb °C | GlobInc kWh/m² | GlobEff kWh/m² | EArray kWh | E_Grid kWh | PR ratio |
|---|---|---|---|---|---|---|---|---|
| **January** | 200.9 | 96.46 | 19.99 | 193.6 | 179.3 | 3259430 | 3207731 | 0.829 |
| **February** | 165.9 | 73.53 | 19.47 | 173.0 | 160.7 | 2925172 | 2880071 | 0.832 |
| **March** | 148.0 | 59.13 | 17.52 | 174.9 | 163.6 | 2990838 | 2942903 | 0.841 |
| **April** | 100.8 | 41.28 | 14.19 | 134.3 | 125.7 | 2330033 | 2293164 | 0.854 |
| **May** | 68.5 | 28.95 | 11.46 | 106.1 | 98.9 | 1861490 | 1830351 | 0.863 |
| **June** | 51.8 | 27.44 | 8.65 | 80.8 | 75.3 | 1434250 | 1409971 | 0.872 |
| **July** | 61.8 | 28.48 | 8.32 | 98.0 | 91.2 | 1739965 | 1712213 | 0.874 |
| **August** | 84.9 | 42.56 | 9.22 | 117.7 | 110.1 | 2093316 | 2060908 | 0.875 |
| **September** | 117.4 | 45.30 | 11.14 | 146.0 | 136.6 | 2554854 | 2512963 | 0.861 |
| **October** | 163.7 | 72.12 | 13.57 | 178.3 | 165.8 | 3081212 | 3033970 | 0.851 |
| **November** | 194.2 | 74.87 | 16.00 | 191.3 | 177.7 | 3255858 | 3203140 | 0.837 |
| **December** | 217.3 | 88.54 | 18.13 | 204.0 | 189.3 | 3451920 | 3398327 | 0.833 |
| **Year** | 1575.2 | 678.68 | 13.94 | 1798.0 | 1674.3 | 30978340 | 30485711 | 0.848 |

**Legends**

| | | | |
|---|---|---|---|
| GlobHor | Global horizontal irradiation | EArray | Effective energy at the output of the array |
| DiffHor | Horizontal diffuse irradiation | E_Grid | Energy injected into grid |
| T_Amb | Ambient Temperature | PR | Performance Ratio |
| GlobInc | Global incident in coll. plane | | |
| GlobEff | Effective Global, corr. for IAM and shadings | | |



*Figure 16. Plant performance simulation results*

The 'EArray' column specifies the energy output from the plant, which is in DC form, required for electrical storage. The Table provides overarching results pertaining to system performance including 'Egrid' (energy injected to the grid if an inverter were used) as well as the performance ratio which is effectively the efficiency of the inverter conversion from DC to AC.

As observed from Figure 12, the irradiance values never reach 1000 W/m², which is the peak value reachable. The implications of this is that the plant will not be able to achieve the rated plant capacity of 20 MWp. Using total 'EArray' yearly value of 30,978 MWh from Figure 16, and the farm total yearly operational hours of 4160 (found from PVSyst), it was determined that on average 7.45 MW per annum is produced from the farm.

## 4.2 Panel Tilt Validation

As previously mentioned, a 30 degrees panel tilt angle provided optimal energy yield. Two panel layouts exist in the industry: the single, and gable roof layout. Gable roof layouts can be implemented to withstand strong wind conditions. However, single roof layouts provided better energy yield as all the panels align with optimal azimuth. CFD simulations were run to determine the system's capability to resist critical wind conditions for this specific tilt angle and single roof layout. In the Bass Strait region, the maximum recorded wind speeds have reached up to 35 m/s [28]. The wind force simulations were produced for front and back flow directions. The results produced are shown in Figure 17 and the force results for each axis are summarized in Table 5.

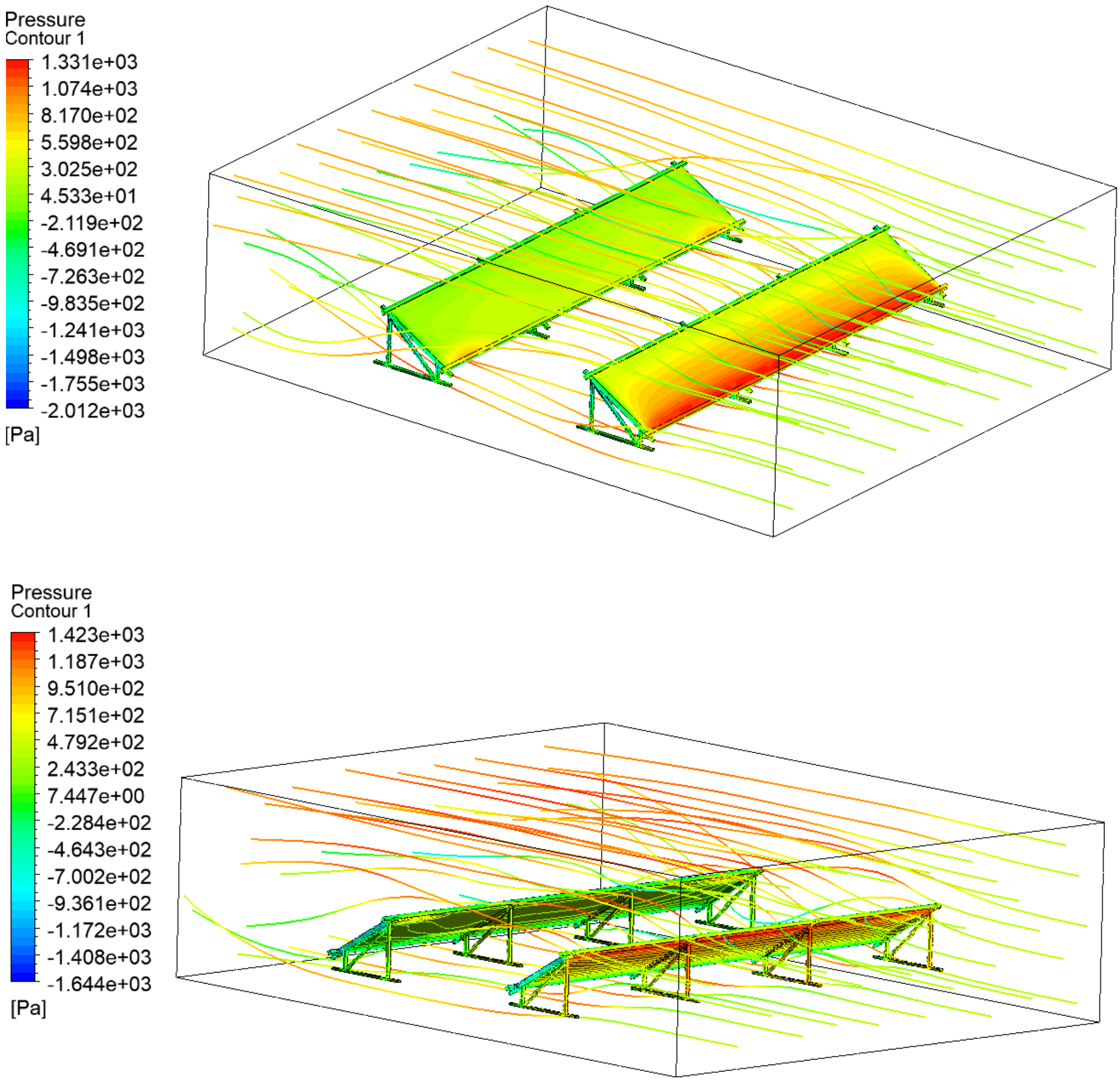



*Figure 17. Simulation results with front and back wind speed direction*

*Table 5. Simulation numerical results*

| Wind Speed Direction | X axis Force (N) | Y axis Force (N) | Z axis Force (N) | Max Pressure (Pa) |
|---|---|---|---|---|
| **Front flow** | -0.1 | 7794 | -12614 | 1331 |
| **Back flow** | -2.32 | -8124 | 12775 | 1423 |

The wind induced force on the surface of the panels had a maximum pressure of 1331 and 1423 Pa for the front and back flow respectively. Sunpower Maxeon 6 handbook specified that the PV modules can withstand maximum pressures of 2400 Pa [20]. This enabled the tilt angle and roof layout for maximum energy yield performance to be validated.

## 4.3 Glass Panel Material Validation

The PV module is composed of layered components comprised of a back sheet, a frame, solar cells, an encapsulant, a glass panel. In industry, a protective glass is commonly layered onto the module to withstand the weather conditions. However, a major contributor to the decrease in the lifetime and efficiency of the solar panel is the damage to the silicon cells through the displacement of the overlaying glass panel and encapsulant [29][30] Wind forces can cause the glass to deform and induce stress on the cells. Tempered glass was implemented on the 'Sunpower Maxeon 6' PV module. Its high strength, durability, and high transmissivity, allows for high performance efficiency [31] and makes it a commonly used glass on the market. The properties of this material are listed Table 6.

*Table 6. Glass panel and encapsulant material properties [Granta Edupack]*

| Part | Material | Young's Modulus (GPa) | Poisson's Ratio | Density (kg/m$^3$) |
|---|---|---|---|---|
| **Glass** | Tempered Glass | 73 | 0.21 | 2510 |
| **Encapsulant** | Ethylene-Vinyl Acetate (EVA) | 0.011 | 0.49 | 922 |

Finite element analysis was conducted on the glass and encapsulant using the ABAQUS software to measure the displacement induced by the Bass Strait's maximum wind speeds. The maximum wind forces previously mentioned [28], and material properties were applied for simulation. To simulate the fixed frame, a fixed boundary condition was set to edges of the plate whilst linear-elastic and isotropic assumptions were made for the material. The frame's induced stress and displacement resulting from the simulation are shown Figure 18 and 19.

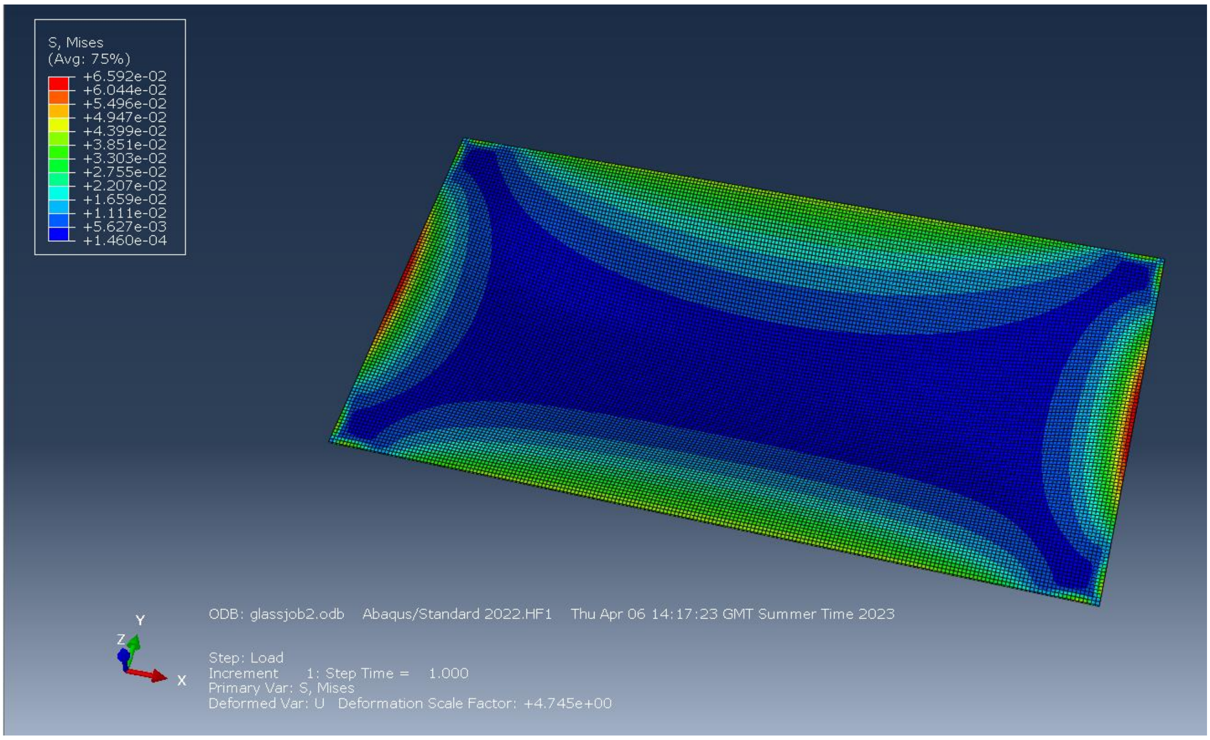



*Figure 18. Stress analysis*

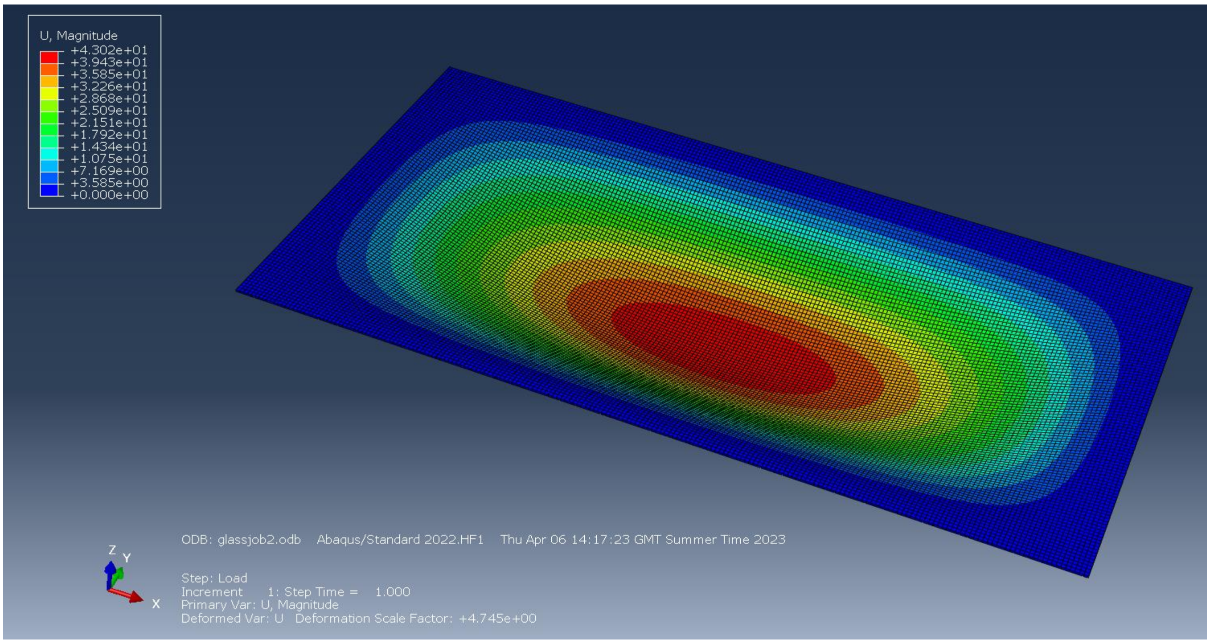



*Figure 19. Displacement analysis*

The maximum stress of 65.9 kPa occurs at the edges of the glass (Figure 18) inducing a maximum displacement of 43 mm (Figure 19).  As a reference, a study completed indicated that a displacement of 54 mm induces a stress of 142 MPa on the silicon cells. Silicon has a yield strength of 180 MPa [32]. This range is not exceeded by the simulation results. This allowed validation of the single tempered glass installation to be implemented onto the PV module, which optimised efficiency performance and limited wind induced damage.

## 4.4 Racking Structure Evaluation

### 4.4.1 Determining the Wind Forces – Back Flow

As specified by the PVSyst simulation, the racking structure was designed to support 25 solar panels. To assess the anchoring forces required to withstand the wind induced forces, the drag and lift forces were calculated through a CFD simulation. The wind flow was simulated towards the back of the panel, as this creates the highest uplifting forces on the anchoring bolts. Conditions comprised of a wind force with a maximum speed of 31 m/s were defined at Bass Strait Boxing Day Storm [28]. Hence, the simulation was conducted with a speed of 35 m/s (for unforeseen circumstances), as shown in Figure 20. The drag and lift forces were determined as 1235 N and 2015 N respectively.

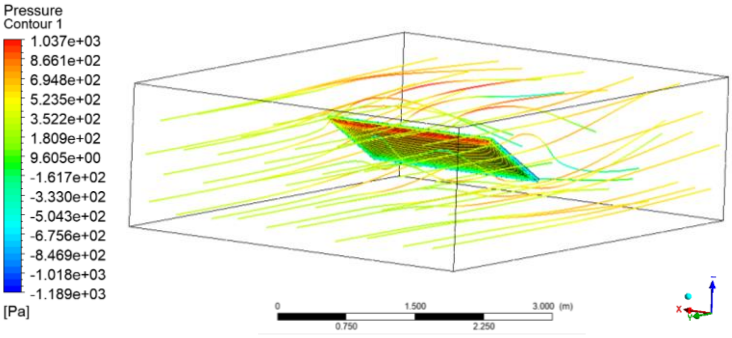



*Figure 20. CFD simulation of 35 m/s wind load on a single panel*

However, correction was required for the simulated drag and lift forces in correspondence to offshore conditions, as topographic factors, velocity pressure coefficient, wind directionality factor, and gust effects were not considered. Equation 1 from the American Society of Civil Engineers 7-10 [33] was utilised to overcome these limitations.

$$\mathrm{F_{d,l}} = 0.613 \times \mathrm{K_z} \times \mathrm{K_{zt}} \times \mathrm{K_d} \times \mathrm{V}^2 \times \mathrm{G} \times \mathrm{C_{d,l}} \times \mathrm{A} \qquad (1)$$

Where; $\mathrm{F_{d,l}}$ is the drag or lift force (N), $\mathrm{K_z}$ is the velocity pressure exposure coefficient, $\mathrm{K_{zt}}$ is the topographic factor, $\mathrm{K_d}$ is the wind directionality factor, $\mathrm{V}$ is the wind speed (m/s), G is the gust effect factor, $\mathrm{C_{d,l}}$ is the drag or lift coefficient, and $\mathrm{A}$ is the panel-projected area treated as an aerofoil (m$^2$).

With the aid of the CFD results, the drag and lift coefficients were determined as 0.774 and 1.263 from Equations 2 and 3.

$$\mathrm{C_d} = \frac{2\times \mathrm{F_d}}{\rho\times \mathrm{A}\times \mathrm{V}^2} = \frac{2\times 1235}{1.225\times(2.047\times 1.039)\times 35^2} = 0.774 \qquad (2)$$

$$\mathrm{C_l} = \frac{2\times \mathrm{F_l}}{\rho\times \mathrm{A}\times \mathrm{V}^2} \frac{2\times 2015}{1.225\times(2.047\times 1.039)\times 35^2} = 1.263 \qquad (3)$$

Where: $Cd$ is coefficient of drag, $Fd$ is drag force (N), $\rho$ is the air density (kg/m$^3$), $A$ is the projected area treated as an aerofoil ($\mathrm{m}^2$), and $V$ is the wind velocity (m/s).

$K_z$, was determined using Equation 4 below.

$$K_z = 2.01(\frac{z}{z_g})^{\frac{2}{\alpha}} \quad (4)$$

Where; $z$ is the height above ground (taken as 4.5 meters if it is lower than 4.5 meters), α, and $z_g$ are parameters related to the exposure category D.

The parameters were taken in correspondence to the exposure category in Tables 7 and 8 based on the nature of the location [33].

*Table 7. Exposure categories*

| Exposure | Description |
|---|---|
| **B** | "Urban and suburban areas, wooded areas or other terrain with numerous, closely spaced obstructions that have the size of single-family dwellings or larger." |
| **C** | "Open terrain with scattered obstructions that have heights generally less than 30 ft (9.1 m). This category includes flat, open country and grasslands." |
| **D** | "Flat, unobstructed areas and water surfaces. This category includes smooth mud flats, salt flats, and unbroken ice." |

*Table 8. Parameters correlated to the exposure categories.*

| Exposure | $\alpha$ | $Z_g$ (ft) | $Z_g$ (m) |
|---|---|---|---|
| **B** | 7 | 1200 | 365.76 |
| **C** | 9.5 | 900 | 274.32 |
| **D** | 11.5 | 700 | 213.36 |

Exposure Category D was allocated to the plant due to its exposure "over open water for at least a mile" [33] $K_{zt}$ was and taken as 1 as this system does not meet the conditions of escarpment, ridges, or hills [33]. The wind's directionality factor was selected as 0.85 due to the open signs and lattice framework of the racking. The gust effect factor was selected as 0.85 due to the structure being rigid [33].

Finally, the determined factors were input into Equation 1 as follows:

$$F_d = 0.613 \times 1.027 \times 1 \times 0.85 \times 35^2 \times 0.85 \times 0.774 \times (2.047 \times 1.039) \times 25 = 22.9\ kN \quad (5)$$

$$F_l = 0.613 \times 1.027 \times 1 \times 0.85 \times 35^2 \times 0.85 \times 1.263 \times (2.047 \times 1.039) \times 25 = 37.4\ kN \quad (6)$$

The corrected lift and drag forces encountered by the 25 series panels racking per racking were calculated as 2752.74 N and 4491.87 N respectively.

### 4.4.2 Determining the Anchoring Forces

Having completed this study, the $F_{y1}$ and $F_{y2}$ forces induced by the wind were determined (Figure 21).

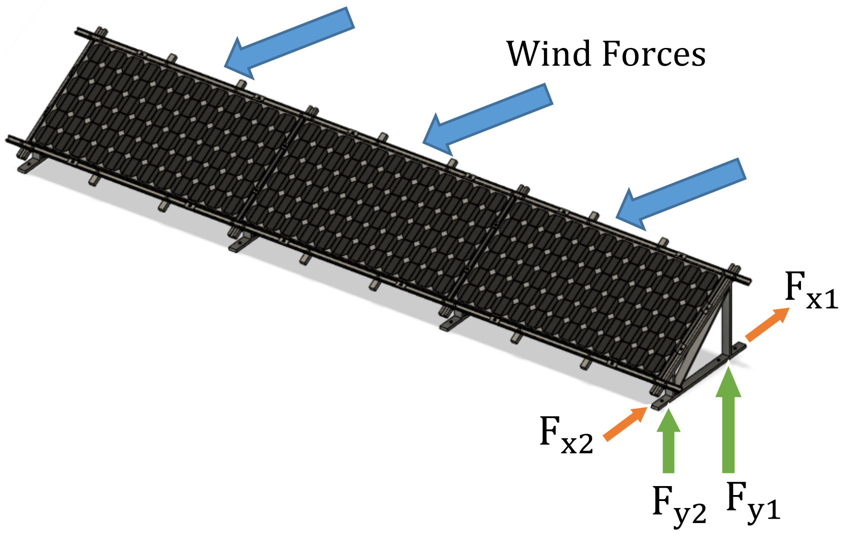



*Figure 21. Forces acted upon the racking system.*

The CFD simulations show that the wind pressure was concentrated at the top 0.12 m of the panel's back plate (Figure 20, region in red). Equation 7 below determined that the force concentration represented 70.38% of the total induced force.

$$Force\ distribution\ (\%)_{max} = Force\ distribution\ (\%)_{ave} + \frac{Pressure_{max} - Pressure_{ave}}{Pressure_{max}}\ (\%) \qquad (7)$$

$$= Force\ distribution\ (\%)_{ave} + \frac{\left(Pressure_{max} - \frac{Force_{resultant}}{Area_{normal}}\right)}{Pressure_{max}}$$

$$= 50\% + \frac{1037 - \frac{\sqrt{22939.5^2 + 37432.3^2}}{(2.047)(1.039)(25)}}{1037}$$

$$= 70.38\%$$

Having determined the force distribution over the panel, two-dimensional structural simulations were conducted for two different racking bracing methods (see Figure 22) using the FTool software. The weights of the panels (22.7 kg) were also inputted for simulation.

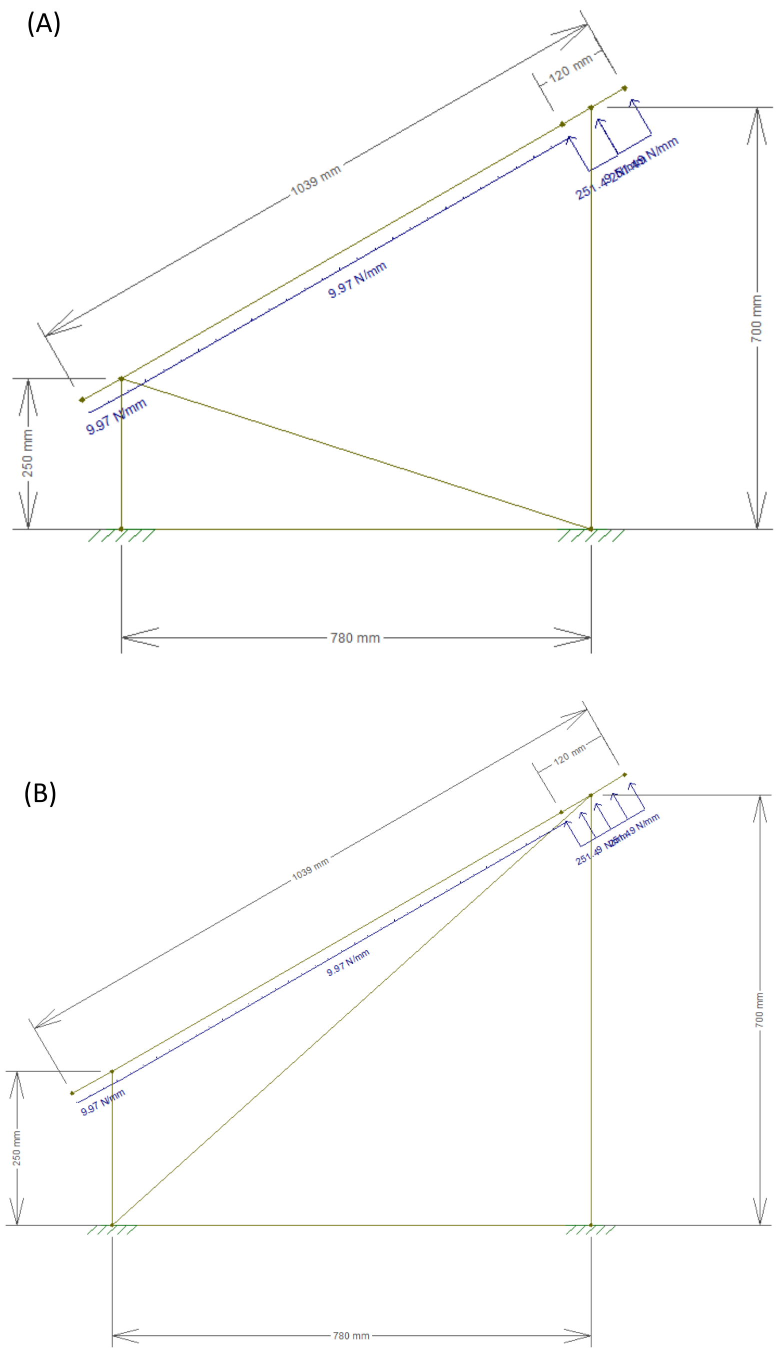



*Figure 22. (A) Bracing method 1. (B) Bracing method 2*

The anchoring force simulations results are summarized in Table 9. These results were converted into values per leg to which one anchoring bolt was then assigned.

*Table 9. Simulated structural results on the racking anchoring legs for different bracing methods.*

| Results per parameter | $F_{y1}$ (N) | $F_{y2}$ (N) | $F_{x1}$ (N) | $F_{x2}$ (N) | $Moment_1$ (Nm) | $Moment_2$ (Nm) |
|---|---|---|---|---|---|---|
| Bracing Method 1 | 45083 | 10924 | 821 | 18894 | 246 | 439 |
| Bracing Method 2 | 45762 | 11604 | 21235 | 520 | 153 | 3 |
| **Results per leg** | **$F_{y1}$ (N)** | **$F_{y2}$ (N)** | **$F_{x1}$ (N)** | **$F_{x2}$ (N)** | **$Moment_1$ (Nm)** | **$Moment_2$ (Nm)** |
| Bracing Method 1 | 1734 | 420.2 | 31.6 | 726.7 | 9.5 | 16.9 |
| Bracing Method 2 | 1760 | 446.3 | 816.7 | 20 | 5.9 | 0.12 |

The overall 'Bracing 1' forces displayed lower overall forces. For each anchoring bolt that resisted $F_{y1}$ and $F_{x1}$, the permissible tension and shear forces were 1734 N and of 420.2 N; and 31.6 N and 726.7N for $F_{y2}$ and $F_{x2}$.

From these results, Liebig Anchor AB A4 M8 stainless steel anchoring bolts were selected, as the allowable tensile and shear forces reached up to 7.1 kN. Also, a maximum bending moment of 32.1 Nm with effective embedment depths of 65 mm on non-cracked C20/25 concrete which was the pontoon material selected by the Civil group. These specifications exceeded the maximum encountered tensile and shear loads by 309% and 769.3%, and 90% for the allowable bending moments respectively. This provided a sufficient factor of safety in unforeseen cyclic motion induced by tidal movement on the floating structure.

## 4.5 Structure Fatigue Analysis

### 4.5.1 Wind Cyclic Loading

An analysis was performed on one racking string to determine its capability to withstand the wind's cyclic loading. As the wind cyclical patterns were difficult to simulate, this study considered one wind load at speed of 35 m/s (maximum Bass Strait recorded speed) every minute for 25 years. From this, the following total number of loadings (cycles) was determined Equation 8):

$$\text{N° Cycles} = 60 \text{ X } 24 \text{ X } 365 \text{ X } 25 = 1.3\text{E} + 07 \quad (8)$$

### 4.5.2 Racking Fatigue Analysis

Utilising the SkyCiv software, a 2D structural analysis was performed on one of the 26 truss structures within a string (see Figure 25) to determine the critical loading section per truss. The input wind force was concentrated on the lower part of the panel as shown in the CFD simulation below (see Figure 23).

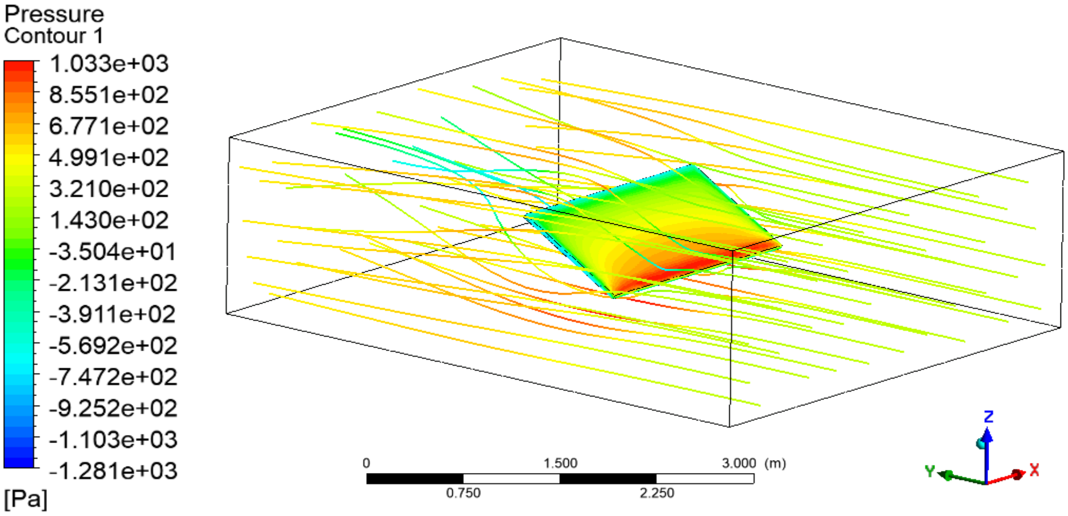



*Figure 23. CFD analysis of wind gusts with 35 m/s from the frontal face of a single panel*

This force was assumed to be uniformly distributed along the racking. From this, the simulated racking's internal stress results are depicted in Figure 26.

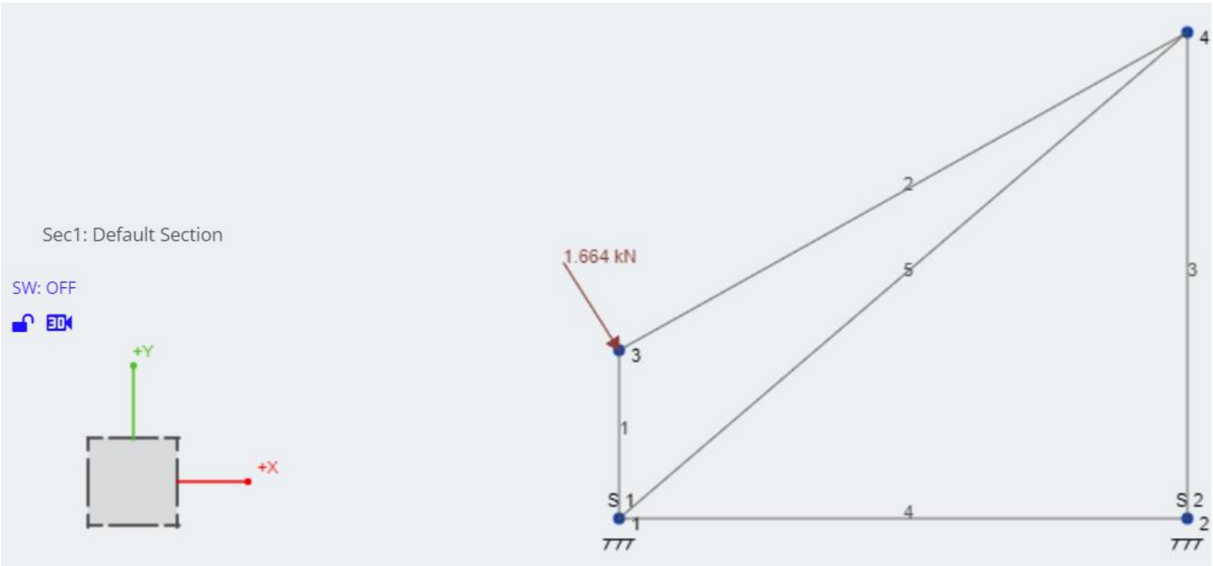



*Figure 25. Racking Bracing 1 Structure*

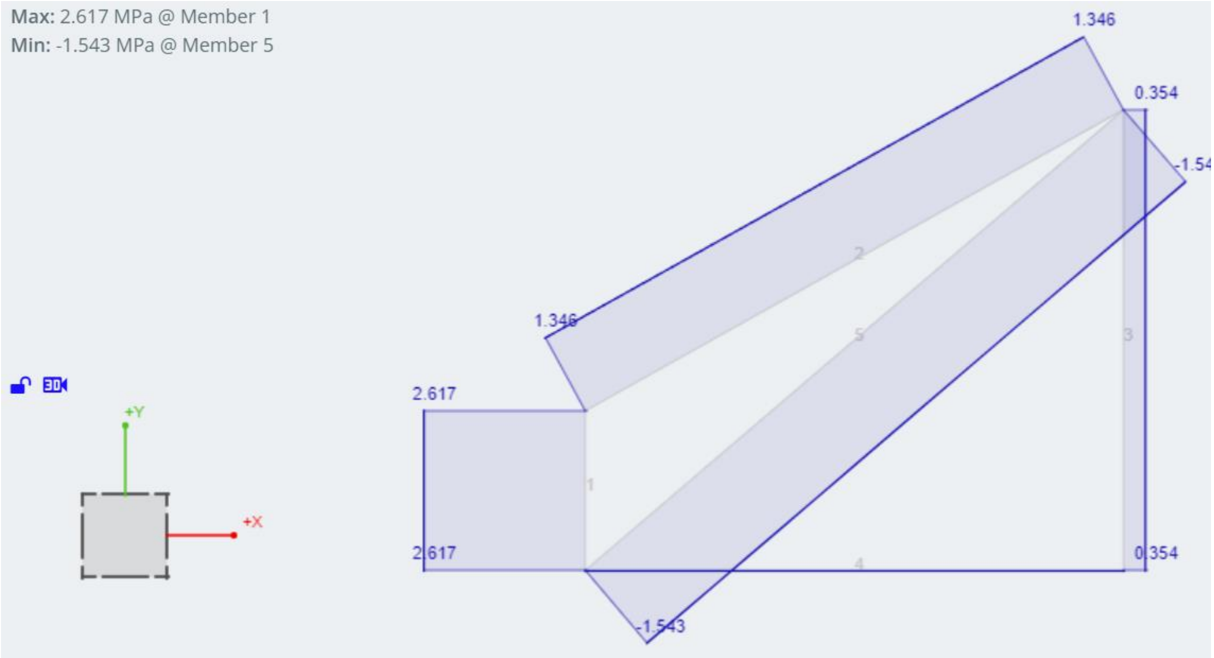



*Figure 26. Simulation Stress Results*

The maximum stress was of 2.617 MPa. To determine if the racking structure will be able to reach its desired life length of 25 years, the S-N curve for the racking's AISI 316 Stainless Steel was utilised as seen Figure 27. This relates the number of cycles to failure to an applied stress range.

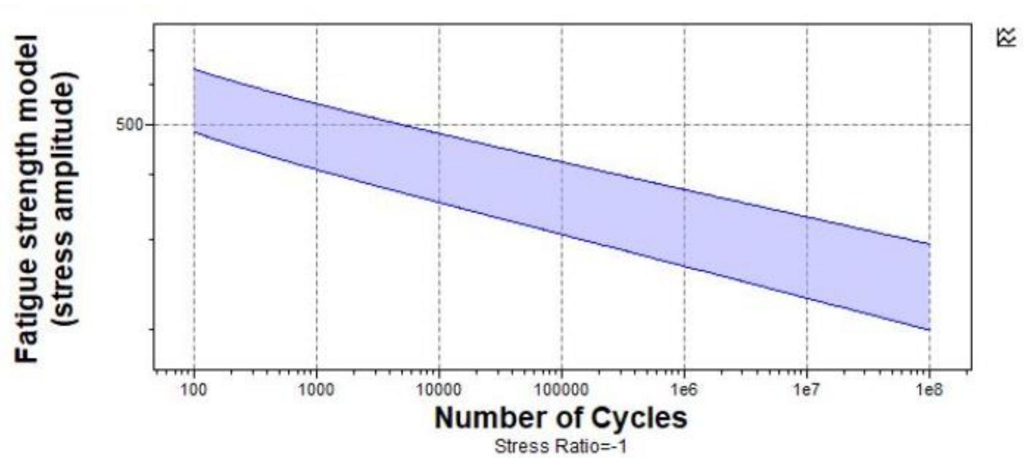



*Figure 27. AISI 316 Stainless Steel S-N Curve (Granta Edupack)*

The stress results appeared much lower than the maximum indicated fatigue strength for the calculated 1.3E+07 cycles. This advised that the racking structure was designed to withstand the specified wind cyclic loading for at least 25 years.

### 4.5.3 PV module Fatigue Analysis

For the PV module, fatigue analysis was conducted on the glass panel. The previously calculated results indicated a maximum stress of 65.9 KPa on the glass (see Glass Panel Material Validation). As indicated by the Granta Edupack software, the S – N curve for tempered glass, for 1.3E+07 cycles, the maximum stress ranges between 29-32 MPa which was well above the simulation results. This indicated that the panel glass structure will be able to withstand the specified wind cyclic loading for at least 25 years. For this analysis, the wind pattern and force distribution assumptions caused limitation in simulation accuracy. To account for this, critical conditions were simulated.

# 5. Wider Engineering Implications

## 5.1 PESTLE Analysis (Political, Economic, Social, Technological, Legal, Environmental)

*Table 10. PESTLE analysis*

| Political | Economic | Social | Technological | Legal | Environmental |
|---|---|---|---|---|---|
| The project helps to work towards the following legislative goals:<br><br>•Australian Government has the Australian Energy Target Act (2015) with a target of net zero emissions by 2050 [34]<br><br>•State of Victoria has the goal of achieving 95% of its energy from renewable resources by 2035 [35] | •Job creation from initial construction as well as ongoing maintenance.<br><br>•Tax breaks available to allay the costs: Australian government has a A$20 billion investment plan for renewable energy generation [36]<br><br>•Cost of power infrastructure will be less as the project will utilise the pre-existing distribution network for Star of the South. | •Victorian residents are experiencing increases energy prices due to various factors such as the Russian invasion of Ukraine and supply chain disturbances – project will supply, cheap renewable solar power [35]<br><br>•Less visual pollution as the solar farm is located offshore. | •FPV technology has never been implemented on sea water [37]<br><br>•If the project is successful, the technology may revolutionise renewable energy technology as future solar farms can be placed in areas of the ocean that receive high sun exposure.<br><br>•Potential drawbacks such as corrosion from high exposure to seawater have been mitigated in the design. For example, using a marine grade 300-series stainless steel for the racking and panel frame. | •Australia and Victoria energy regulations have been adhered to. Further information on the legal implications have been addressed in section 8.7. | •Potential effects on aquatic ecosystems, bird migration and water quality [38]<br><br>•To reduce environmental damage, the project is using a biodegradable cleaning solution for the solar panels.<br><br>•The renewable energy sources will mitigate anthropogenic climate change – something that has devastated local marine and wildlife populations. [39]<br><br>•Attaching the project to Star of the South will mean that there is little extra damage to the local wildlife as very few extra cables will be required. |

## 5.2 Human Factors and Health & Safety Considerations

Being within 3 nautical miles of Australian coastline the FPV system must adhere to Australian legislation [40]. With the Bass Strait recently being declared suitable for offshore wind energy [41], licensing can now be obtained which would last for 40 years once obtained [41].

Guidance for the project was outlined by the Offshore Electricity Infrastructure Act 2021 and associated regulations. These cover the construction, operation, and decommissioning processes of an offshore electricity infrastructure. Chapter 6 of the OEI Act 2021 outlines all the relevant the health and safety laws [41].

Before construction a safety plan should be completed, including various risk assessments. Automation is crucial for optimal performance, communication, and emergency shut down procedure. Decommissioning of the facility can be provided by National Offshore Petroleum Safety and Environmental Management Authority NOPSEMA [42]. Further recommendations for large-scale renewable facilities can also be supported by Building Research Establishments BRE publications [43].

*Table 11. A list of standards appropriate for the project*

| Standard Notation | Brief Description |
|---|---|
| **AS/ NZS 5033:2021 [11]** | address installation and safety requirements of PV modules |
| **AS/ NZS 61724.1:2020**<br><br>**AS/ NZS IEC 61829:2020** | outline monitoring of performance through review of current-voltage characteristics. |
| **AS/ NZS 62894: 2020** | provide information for safe optimisation of integrating the energy source to the grid, through the use of inverters. |
| **SA/ SNZ TS 62446.3:2020** | Inspection of quality of the photovoltaic modules for abnormalities to prevent fire risk. |

Additionally, it was key to consider the ethical aspects of the project. For instance, wildlife management ensured to use non harmful methods to prevent bird soiling and damage with the use of netting. Marine-friendly cleaning solutions will ensure the marine life is not subject to toxic materials. Additionally, holding frequent local community meetings, can assure concerns and problems are addressed. Finally, the security of the on-plant workers was ensured by providing secure equipment and an accessible working site.

## 5.3 Environmental Considerations

### 5.3.1 Product Eco-Audit

Eco-audit analyses were performed on the racking and the PV module to evaluate environmental impact throughout their entire life cycle. The simulation results performed for one racking string were shown and summarized in Figure 28 and Table 12.

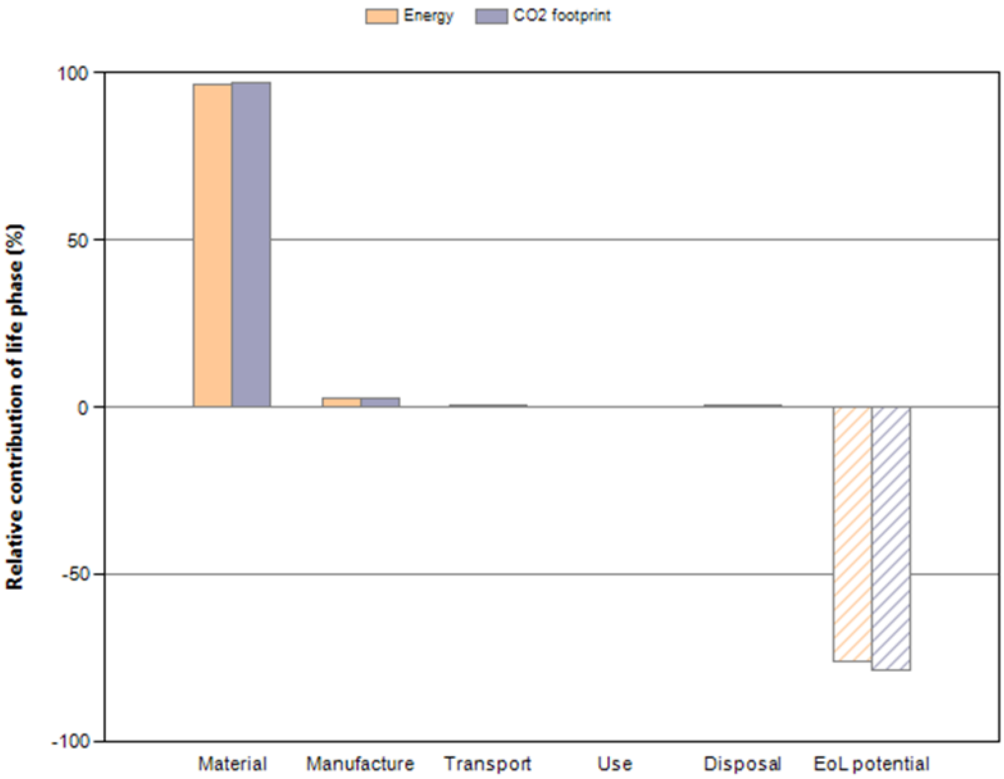



*Figure 28. Relative Contribution of Life Phase (%) for the Racking (source: Granta Edupack)*

*Table 12. Energy and CO2 Footprint for one racking string (from Granta Edupack)*

| Phase | Energy (MJ) | Energy (%) | CO2 footprint (kg) | CO2 footprint (%) |
|---|---|---|---|---|
| **Material** | 2.77E+05 | 96.3 | 2.41E+04 | 96.9 |
| **Manufacture** | 8.18E+03 | 2.8 | 613 | 2.5 |
| **Transport** | 15.3 | 0.0 | 1.1 | 0.0 |
| **Use** | 0 | 0.0 | 0 | 0.0 |
| **Disposal** | 2.38E+03 | 0.8 | 167 | 0.7 |
| **Total (for first life)** | 2.88E+05 | 100 | 2.49E+04 | 100 |
| **End of life potential** | -2.19E+05 | - | -1.95E+04 | - |

These resulted in 4.87E+05 GJ and 9.3 Mt of $CO_2$ produced for the racking.
The simulation for the eco-audit of PV modules accounted for every component including the frame, the silicon cells, the encapsulant, the back plate, and the glass panel. The results were shown and summarized in Figure 29 and Table 13.

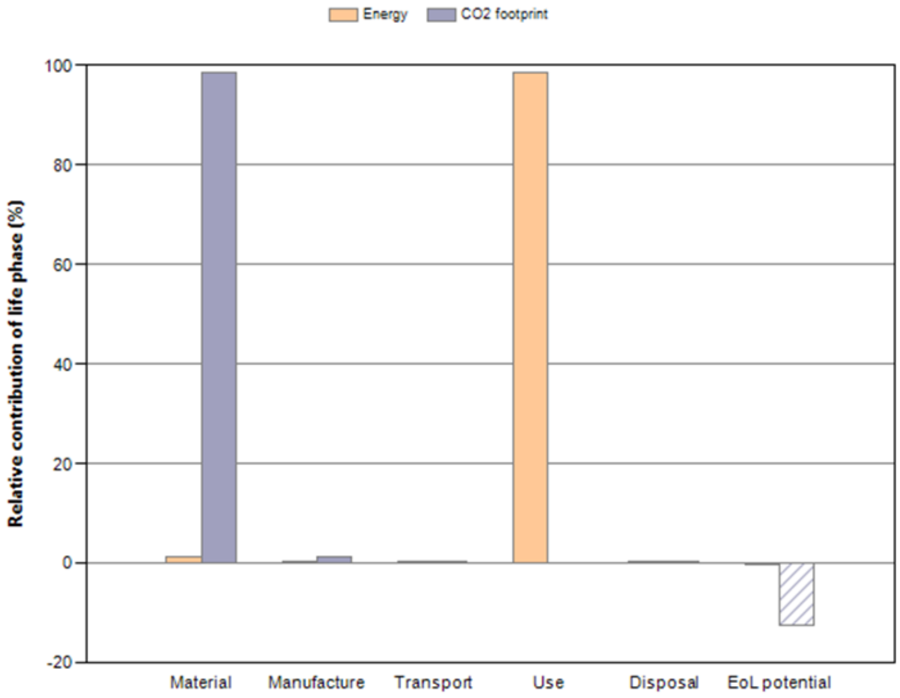



*Figure 29. Relative Contribution of Life Phase (%) for the Solar Panel*

*Table 13. Energy and CO2 Footprint for one PV module*

| Phase | Energy (MJ) | Energy (%) | CO2 footprint (kg) | CO2 footprint (%) |
|---|---|---|---|---|
| **Material** | 7.66E+03 | 1.3 | 571 | 98.5 |
| **Manufacture** | 104 | 0,0 | 7.84 | 1.4 |
| **Transport** | 0.102 | 0.0 | 0.00735 | 0.0 |
| **Use** | 5.68E+05 | 98.6 | 0 | 0.0 |
| **Disposal** | 11.5 | 0.0 | 0.808 | 0.1 |
| **Total (for first life)** | 5.75E+05 | 100 | 580 | 100 |
| **End of life potential** | -1.01E+03 | - | -72.6 | - |

These result in 24.2E+06 GJ and 24.4 Mt of $CO_2$ produced by the total amount of panels.

Figure 30 below, details the 'PVSyst' software prediction of the amount of $C0_2$ emissions saved by the plant during its operating lifetime.

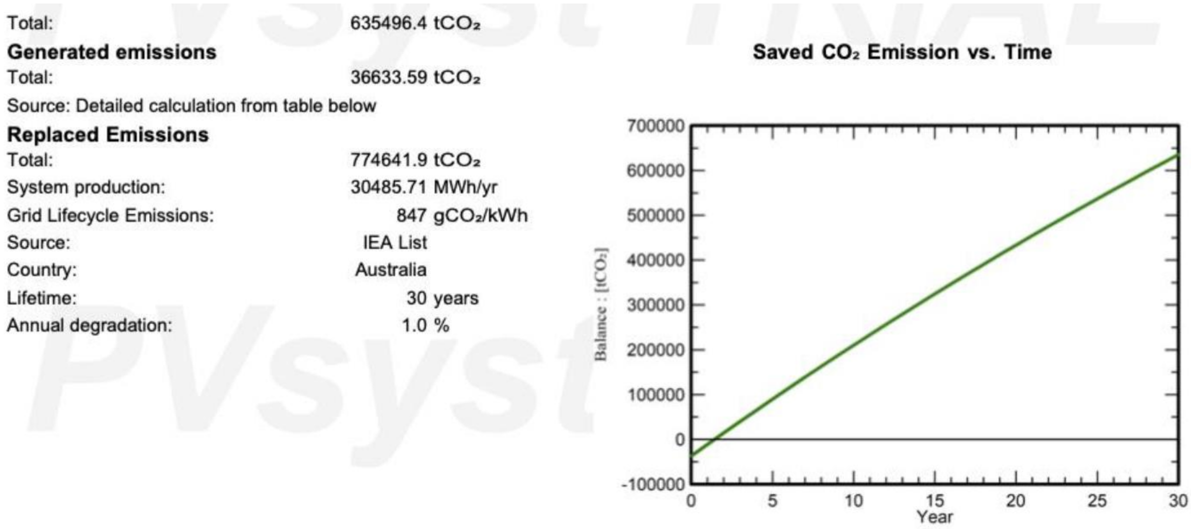



*Figure 30. PVSyst software simulation $C0_2$ count for the plant*

For the targeted 25 years of operation, the plant was predicted to save an amount of 774,641.9 $tC0_2$ in emissions.

### 5.3.2 Product End of Life Management

Silicon PV panels have an output decline of 0.5% per year. Below, 60% of operating efficiency it is generally advised to change the panel. The materials selected can be reused allowing for solely the solar cell layer to be changed limiting material waste [44].
PV decommissioning methods include recycling, refurbishing, or landfilling. However, recycling processes for silicon cells are very expensive and much more expensive than landfilling. Decommissioning procedures need to be greatly regulated since PV modules are contain hazardous substances [45].

As detailed in the PDS, the following has been prioritised: the use of recyclable components, limiting panel efficiency decline, protection from damage and high temperatures, regular maintenance, and high-quality material selection.

The Australian government and Department of Climate Change, Energy, the Environment and Water, is working on a national scheme planned for PV module decommissioning. This will need to be followed once in place [46]. The end-of-life management will also need to respect Victorian government instructions which currently only bans e-waste from landfill which includes solar panels [47, 48].

## 5.4 Ergonomic Evaluation

Table 14. Ergonomic evaluation

| Ergonomics in question | Yes | Maybe | No | Suggested actions and/or Comments |
|---|---|---|---|---|
| Are the walkways on the floating structure suitable for safe and efficient movement | X | | | The pontoons will hold 450 solar panels each. Due to spacing between solar panels to avoid shading, there is also provisions in place for there to be adequate space between arrays |
| Are the inner solar panels in the arrays reachable by workers without having to stretch, bend or do anything with excessive strain | X | | | Yes, as the arrays will be 2 x 9 meaning the solar panel is always on the edge of the array |
| Are the workers knowledgeable in proper body mechanics to reduce strain on lower back whilst working on the solar panels | | X | | Due to the laborious nature of certain tasks, workers must be given training to ensure they do not overexert themselves where it is not necessary |
| Will the workers be able to work safely in sunnier conditions | X | | | PPE will be provided including sunglasses and suncream |
| Will workers be safe from adverse weather conditions whilst working on pontoons | X | | | The pontoons can stay stable during choppy conditions, when there is extreme weather work will not be conducted |
| Will maintenance boats be able to dock on the pontoon safely with easy access to and from the boat | X | | | The pontoon will have mooring points for the boat to connect to, and the boat will have a walkway to go from to and from the pontoon |
| Will there be provisions for an inclusive work environment for those who are physically disabled | | | X | Although every care has been taken to ensure it is a safe working environment, due to the physical nature of the work, the pontoons not having wheelchair access, and the dangerous nature of the sea, it would not be prudent to employ those who are physically disabled to work on the pontoons |
| Is the work schedule manageable? | X | | | The work rotation shall be on a 1 week on, 1 week off rotation with 2 separate teams, with 2 weeks on 1 week off during the peak bird season to accommodate for the increased soiling potential from the birds. Workdays should include regular breaks for meals, water, and rest. |
| Is the pontoon surface going to have provisions against slippage? | X | | | The pontoon needs to have high grip flooring as there may be sea spray coating the surface and therefore create an extremely slippery surface |

| | | | | |
|---|---|---|---|---|
| Are damaged solar panels easily accessible and replaced? | X | | | Due to the panels having clamps which separate them, it is easy to remove the solar panels from their fixing for repair or replacement. |

## 5.5 Maintenance Schedule

Table 15. Maintenance schedule

| Component/ sub-system | Action | Frequency | Comments |
|---|---|---|---|
| **Cleaning** | Solar panels to be cleaned using Gentle cleaning solutions and soft brushes to be used to avoid damaging the surface of the solar panels. | Every 2 months, increased to once per month during bird migration season, September to April | Cleaning must take place every 2 months to take into account the higher rate of soiling. Angle of solar panels allows for rainfall to aid in self-cleaning for minor soiling [49]<br><br>Harsh cleaning material should not be used as it will damage the glass and the coated module surface [5] |
| **Float** | Verify:<br>• There is no damage and wear.<br>• Buoyancy has not been compromised.<br>• Wildlife has not nested on the structure. | Every 2 months | If any damage is detected repairs or replacement is necessary before the buoyancy is compromised and material lost. |
| **Solar Panels** | Verify:<br>• There are no surface defects such as glass fractures, moisture penetration, corrosion.<br>• Diodes are working correctly to prevent hotspots.<br>• There are no signs of wear or damage on the cables and other components of the wiring system[49]. | Every 2 months | Any damaged or worn components should be replaced including the PV cells, inverters, or electrical connectors.<br><br>If any performance issues are detected by the sensors, a more in-depth troubleshooting of the solar panel should occur, including if there is excessive performance degradation. |

| | | | |
|---|---|---|---|
| **Anchoring system** | Verify: there are no signs of wear or damage, including corrosion | Every 2 months | Any worn or damaged components should be replaced. |
| **Mount** | Verify:<br>• There is no corrosion on the mount.<br>• The mounting is still able to hold the weight of the PV system.<br>• Netting is not torn or compromised which would allow wildlife to nest on the floating structure | Every 2 months | Any worn or damaged components should be replaced, in this case nut and bolts. |
| **Repairs and Replacements** | Extra inventory should be kept of all parts, especially those which are more likely to damaged. | As needed | Although materials have been selected to last the full life of the site, defects in manufacture and assembly may lead to a shorter life |
| **Pyranometer** | Pyranometer should be calibrated following the manufacturers guidelines to ensure accurate results are being obtained | Every 2 years | Should the data being received be deemed likely to be inaccurate at any time, an unscheduled calibration should take place [22] |
| | Pyranometers have a service life of 10 years and should be replaced accordingly | Every 10 years | Manufacturers recommendations of 10 years should be followed. Should the pyranometer be faulty before 10 years has passed it should be replaced. Data received from the pyranometer can inform this decision. |

## 5.6 Future Design Considerations

The addition of cooling fins, attached to the back of the solar panel, increases the total surface area at the back of the panel, allowing heat to dissipate more easily, thereby improving efficiency. The decrease in temperature with the use of fins can reach 50% [29]
Solar tracker could be implemented to continuously direct the solar panels towards the sun with a potential power increase of up to 30%. However, a cost-benefit analysis needs to be performed as the installation and maintenance of tracking technologies can incur high costs [50].

Anti Reflective coating can be added to the surface of the panel to reduce the reflectivity, resulting in greater efficiency [51].

# 6. Risk Management

## 6.1 Risk Mitigation

*Table 16. Failure Modes and Effects Analysis*

| Process Step/Input | Potential Failure Mode | Potential Failure Effects | Severity (1-10) | Potential Causes | Occurrence (1-10) | Current Controls | Detection (1-10) | RPN | Action Recommended |
|---|---|---|---|---|---|---|---|---|---|
| **What is the process step, change or feature under investigation?** | In what ways could the step, change or feature go wrong? | What is the impact if this failure is not prevented or corrected? | | What causes the step, change or feature to go wrong? (How could it occur?) | | What controls exist that either prevent or detect the failure? | | | What are the recommended actions for reducing the occurrence of the cause or improving detection? |
| **Maintenance Health & Safety** | Weather conditions not suitable for maintenance crew safety | FPV would be out of commission/underperforming for too long | 4 | Waves creating unstable surface | 4 | Maintenance should be scheduled on days where the weather is good | 2 | 32 | New design for pontoons is much larger and therefore is more stable in poorer weather conditions. During extreme weather events maintenance should not occur |
| | Slippery pontoon walkways from sea spray | Maintenance would be delayed and potential injury to maintenance staff | 3 | Sea spray accumulating on surface of walkways | 7 | Take care when walking | 4 | 84 | Nonslip surface on walkways of pontoon to prevent slipping occurring |
| **Solar Panels** | Solar panel corrosion due to prolonged exposure to seawater. | Reduced efficiency of the solar panel, leading to a decrease in the power output of the system. | 6 | Exposure to high levels of saltwater or other corrosive | 3 | Use of high-quality materials that are highly | 3 | 54 | Conduct regular inspections of the solar panels to identify any signs of corrosion. |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | substances in the water | | resistant to corrosion | | | |
| | Inadequate maintenance or cleaning of the solar panel surface. | A decrease in power output and increased maintenance costs. | 3 | Lack of proper maintenance schedules | 7 | Regular maintenance schedules that include cleaning of the solar panel surfaces | 3 | 63 | Ensure personnel are properly trained and equipped with the selected solar panel cleaning solution and tools |
| | Hotspots on the solar panel due to faulty diodes or shading. | This can lead to damage to the solar cells and decreased efficiency of the panel, reducing the overall power output of the system. | 3 | Faulty or defective diodes | 4 | Quality control checks during maintenance and installation to identify faulty diodes | 2 | 24 | Conduct regular performance monitoring to identify power output mismatches between different modules and take corrective action |
| | Physical damage to the solar panel due to impacts from floating debris or collisions with other objects. | Reduced efficiency of the solar panel or complete failure of the panel, leading to a decrease in the power output of the system. | 5 | Poorly designed or installed floating structures that do not protect the solar panels from impacts | 2 | Use of materials that are impact-resistant for the floating structure | 7 | 70 | Maintenance schedule that includes provision for replacement of solar panels that are damaged. Clamps used allow for easy removal of solar panels |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Floating Structure** | Leaks in the floating structure due to inadequate sealing or manufacturing defects. | The water inside the floating structure can cause the buoyancy to reduce and therefore sink. | 10 | Inadequate sealing of the structures | 3 | Quality control checks during manufacturing and installation | 2 | 60 | During maintenance check for any signs of leaks occurring |
| | Uncontrolled movement or drifting of the floating solar panel due to severe weather conditions or improper anchoring. | Risk of collision with other objects or nearby boats, leading to physical damage to the solar panel or the system. | 8 | severe weather than may dislodge the floating structure. | 2 | high quality anchoring systems designed to withstand severe weather conditions | 6 | 108 | During maintenance check for signs of anchoring not being secure |
| | Degradation of the anchoring system due to prolonged exposure to water or corrosion. | The floating solar panel may become detached from its anchor, leading to uncontrolled movement. | 8 | Prolonged exposure to seawater, causing corrosion | 3 | High quality materials which withstand exposure to seawater | 3 | 72 | Conduct regular inspections of the anchoring system to identify any signs of corrosion |
| **Electrical System** | Malfunctioning of the electrical system due to defective components or improper installation. | Complete failure of the system, electrical hazards, or increased maintenance costs. | 8 | Improper installation of electrical components that compromises their function or causes damage to the system | 2 | Quality control checks during manufacturing and installation | 1 | 16 | Conduct regular inspections of the solar panels to identify any signs of wear or damage. Sensors which can monitor the systems |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Failure of the electrical connections between solar panels. | Reduced efficiency of the system or complete system failure, leading to a decrease in the power output of the system. | 8 | Inadequate installation | 2 | Implementation of installation guidelines to ensure the connections are properly made | 1 | 16 | Conduct regular performance monitoring to identify any faults or weaknesses in the electrical connections |
| **Racking System** | Inadequate corrosion protection of the support structure | Corrosion can lead to physical damage | 5 | Use of low-quality or inappropriate materials in the support structure | 4 | High quality stainless steel to be used ensuring high resistance to corrosion | 3 | 60 | Scheduled cleaning and inspections of the racking to prevent corrosion occurring |
| | Damage to the support structure due to severe weather conditions, such as high winds or waves. | Physical damage to the support structure or solar panel, leading to reduced efficiency or complete system failure. | 7 | Use of low-quality or inappropriate materials in the support structure | 1 | High quality stainless steel to be used which has been FEA and CFD tested | 2 | 14 | Conduct regular inspections to identify any signs of damage or wear |
| | Improper tilt angle or orientation | Lower energy output an inefficient collection | 6 | Lack of geographical locating data | 2 | Optimal angle for the latitude determined | 4 | 24 | Simulations to further research optimal tilt and orientation considering wind, sunlight hours, and optimal azimuth angle |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Marine Life** | Inadequate protection against wildlife or marine life. | Animals may cause physical damage to the solar panel or its support structure, leading to reduced efficiency or complete system failure. | 4 | Design does not account for wildlife and marine life | 8 | Installation of nets, wiring and acoustic deterrents after an assessment of the wildlife likely to be a problem | 3 | 128 | Conduct inspections to detect signs of damage caused by wildlife or marine life and implement contingencies within the maintenance schedule |
| **Supply Chain Management** | Delayed delivery of products | Delayed project delivery and monetary losses | 6 | Delays at shipping customs | 3 | Sourcing majority of parts from Australian companies | 4 | 72 | Establish clear protocols for resolving issues with international suppliers |
| **Finance** | Inaccurate financial forecasting | Reduced financial feasibility and performance | 10 | Inadequate research or expertise in financial management | 3 | Regular review of market trends | 3 | 90 | Hiring experienced financial managers who can analyse to market adequately |

## 6.2 Risk Evaluation

**Technical Evaluation:**

The wind speed used for calculations and the technical analysis was taken from the greatest wind speed recorded in the local area. This may lead to the overdesign of the panels as the strength required of the materials is not as great. As a result, a greater expense may have incurred paying for items that are not required.

Software used for simulations, such as FEA and CFD only produce simplified models and may not reflect the reality of the local conditions. There are other factors such as cyclic loading that have not been considered. Calculation and Equations used are also assumptions and do not reflect reality.

Furthermore, the results for PVsyst are based on historic data. Worldwide greenhouse gas emissions have increased which has contributed to global warming. This could change the local climate and possibly change wind speed and sun exposure, making the project unviable.

**Wider Implications:**

Approval of the project by the Victorian Government as well as the Federal Australian government has not currently been given and is required for proceeding with the plan. Concerning the laws, the local regulations may be subject to change. Amendments to laws or outright repealing of laws may lead to the project not being able to go ahead or be much more restricted in its design.

**Business Management:**

It is expected the stakeholders mentioned in Section 7.3 will be interested in funding the project. If the stakeholders and Australian government do not provide the adequate funding needed, then the project may have to cut costs and, certain costly items such as the bird nets, racking system and L-shaped brackets would have to be redesigned to be cheaper or bought using standard parts. This may affect the quality and durability of the final product.

Additionally, it has been assumed that the prices of the materials will not change due to supply chain issues. As a result, if this occurs, the costings of the product will need to be amended, and the overall project may end up costing more, depending on the severity of the issue.

# 7. Business Plan

## 7.1 Market Analysis

As previously stated, Australia is reliant on fossil fuels which induced the energy crisis as the recent Russia-Ukraine war led sanctions to the Russian produced oil [3]. Given the dearth of industrial land vacancy to install a PV farm in Australia [52], one of the apparent but untapped locations is to place solar panels on water bodies. The 20MWp Floating Photovoltaic (FPV) farm will help Australia transition away from the dependence of fossil fuels towards a more sustainable future with complete autonomy over its energy production. In conjunction with the Australian-government-led project Star of the South windfarm (to be commissioned in 2028), the FPV farm will aid the resilience of energy production during the intermittence of energy production often linked with renewable energy sources. This allows more affordable and competitive energy prices to be assigned. The maturity of ground mounted solar technology exhibits low costs and its ease to be customized for FPV purposes [5]. As the mass chain of suppliers are present for conventional PVs, the availability for sourcing components for FPVs is high, and the complexity of installation/assembly processes would also be reduced. Furthermore, installing an FPV farm provide additional job opportunities (to the already estimated 2,580 as a result of the Star of the South Project) and help boost the local economy since most, if not all, of the components will be sourced from Australia. Currently, only two small scale FPV farms for offshore application exist in the world, Ocean Sun (1 MWp) and Swimsol (400kWp) [5]. Nonetheless, the current FPV market status (mainly onshore applications) is showing progress with installation capacities surging every year [5]. In summary, this project will be targeted at the Australian government to aid their efforts in lowering emissions, safeguarding their energy security, and providing affordable energy prices to their citizens. Furthermore, this project will be pioneering, where three different technologies of solar, wind, and wave, will be working in tandem to provide up to 20% of Victoria's electricity. This will be an opportunity for the Australian government to mark their role as critical roles in the transition to renewable energy sources considering meeting their net zero emissions by 2050 [2].

## 7.2 Project Costing

**Outsourced Component Costs**

*Table 17. Product Sourcing Cost Analysis*

| Part | | Supplier | QTY/string | Total QTY | Price/QTY | Cost (£) |
|---|---|---|---|---|---|---|
| **Panel – Racking mounting components** | **Hex Bolt (M8 x 30mm)** | Accu | 104 | 175,136 | 2.80E-04 | 4.90E+01 |
| | **Hex Bolt (M8 x 110mm)** | Accu | 50 | 84,200 | 5.00E-04 | 4.21E-01 |
| | **Middle clamp (CL01)** | Custom | 50 | 84,200 | - | 3.28E+03 |
| | **T- Slot Nuts (M8, 40mm groove)** | RS | 154 | 259,336 | 3.38E-02 | 8.77E+03 |
| | **Washer (M8 R.D)** | Accu | 154 | 259,336 | 6.25E-06 | 1.62E+00 |
| | **Z clamp Short (CL03)** | Custom | 4 | 6,736 | - | 7.82E+03 |
| | **Z clamp Long (CL02)** | Custom | 100 | 168,400 | - | 9.66E+01 |
| **Racking – mounting components** | **Cable Ties (300mm x 7.0mm)** | RS | 50 | 84,200 | 6.77E-01 | 5.70E+04 |
| | **Hex Bolt (M10 x 20mm)** | Accu | 208 | 350,272 | 4.30E-04 | 1.51+E02 |
| | **Hex Bolt (M10 x 90mm)** | Accu | 100 | 168,400 | 9.10E-03 | 1.53+E03 |
| | **Hex Nut (M10)** | Accu | 308 | 518,672 | 1.00E-04 | 5.19+E01 |
| | **L Bracket** | RS | 104 | 175,136 | 1.64E+00 | 2.87+E05 |
| | **PVC End caps (25mm x 75mm)** | Vital Parts | 104 | 175,136 | 1.12E-04 | 1.96E+01 |
| | **PVC End caps (50mm x 50mm)** | Vital Parts | 104 | 175,136 | 1.24E-04 | 2.17E+01 |
| | **Racking extruded (RC01)** | Custom | 2 | 3,368 | - | 2.60E+06 |
| | **Racking truss (RC02)** | Custom | 26 | 437,784 | - | 5.72E+06 |
| | **Racking hollow (RC03)** | FH Brundle | 52 | 87,568 | 1.22E+01 | 1.07E+06 |
| | **Washer (M10 H.D)** | Accu | 308 | 518,672 | 7.50E-06 | 3.89E+00 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Pontoon – mounting components** | **Liebig anchor AB bolts (M10)** | Leibig | 52 | 87,568 | 8.33E-01 | 7.30E+04 |
| **PV Module (including frame customisation, junction box, bypass diodes, glass panel and backplate)** | | S. Khan, shereen.khan@stern-energy.com , 2/05/2023 | 25 per string | 42,100 | 0.33 euros/Wp (475 Wp/panel) | 5.77E+06 |
| **Thermal Pyranometer** | | Kipp and Zonen | N/A | 4 | £2,500 | 1.00E+04 |
| **Lightning Protection System** | | **Electrical group selection | <10 | - | - | - |
| **Bird Protection** | **Meshed Bird Netting** | Quatra | 2 per 25 panels | 3,380 | 7.00E+01 | 2.37E+05 |
| | **Nylon Cable Ties (292mm x 3.6mm)** | RS | 75 | 126,300 | 1.00E-01 | 1.27E+04 |
| | | | | | **Total Cost (£)** | **1.56E+07** |

**Process & Manufacturing Costs**

All custom parts are made from 316 stainless steel, which has a density of 7980 $\mathrm{kg/m^3}$. [53]. The volume of each part has been calculated from the dimensions given in the engineering drawings (A.1 Part Drawings and Assembly Drawings). With an average value of £0.88/kg, overall providing an estimate of £7.69E+06 for the manufacturing costs, excluding machining energy costs.

*Table 18. Product Manufacture Costs*

| Part Name (No.) | Total QTY | Part Volume ($m^3$) | Total Mass (kg) | Material Cost (£) |
|---|---|---|---|---|
| **Middle clamp- (CL01)** | 168,400 | 6.88E-05 | 4.53E+05 | 4.07E+04 |
| **Z clamp (Long)- (CL02)** | 3368 | 5.40E-05 | 7.12E+05 | 6.39E+04 |
| **Z clamp (Short)- (CL03)** | 175,136 | 5.85E-05 | 3.08E+04 | 2.77E+03 |
| **Racking Extruded- (RC01)** | 84,200 | 2.08E-01 | 5.49E+07 | 4.92E+06 |
| **Racking Truss- (RC02)** | 175,136 | 8.32E-03 | 2.85E+07 | 2.56E+06 |
| | | | **Total Cost (£)** | **7.59E+06** |

**Transport Costs**

Using the data provided in Section 5.3.1 the Eco-Audit outlines the transport energy requirement was 15.3 MJ for one solar string. If average land freight travels at 80 km/h [54] and cargo shipping speeds are 25 km/h [55], then the time taken to travel 10km in land followed by 10km would be 0.5 hours. Excluding any additional loading time, which would be expected. The current average energy cost in Victoria Australia is "54.340 AUD/MWh in March 2023" [56] Therefore the overall cost for transporting 130 string to the facility would be $1.24E+02 AUS, which converts to £1.60E+04.

**Maintenance Costs**

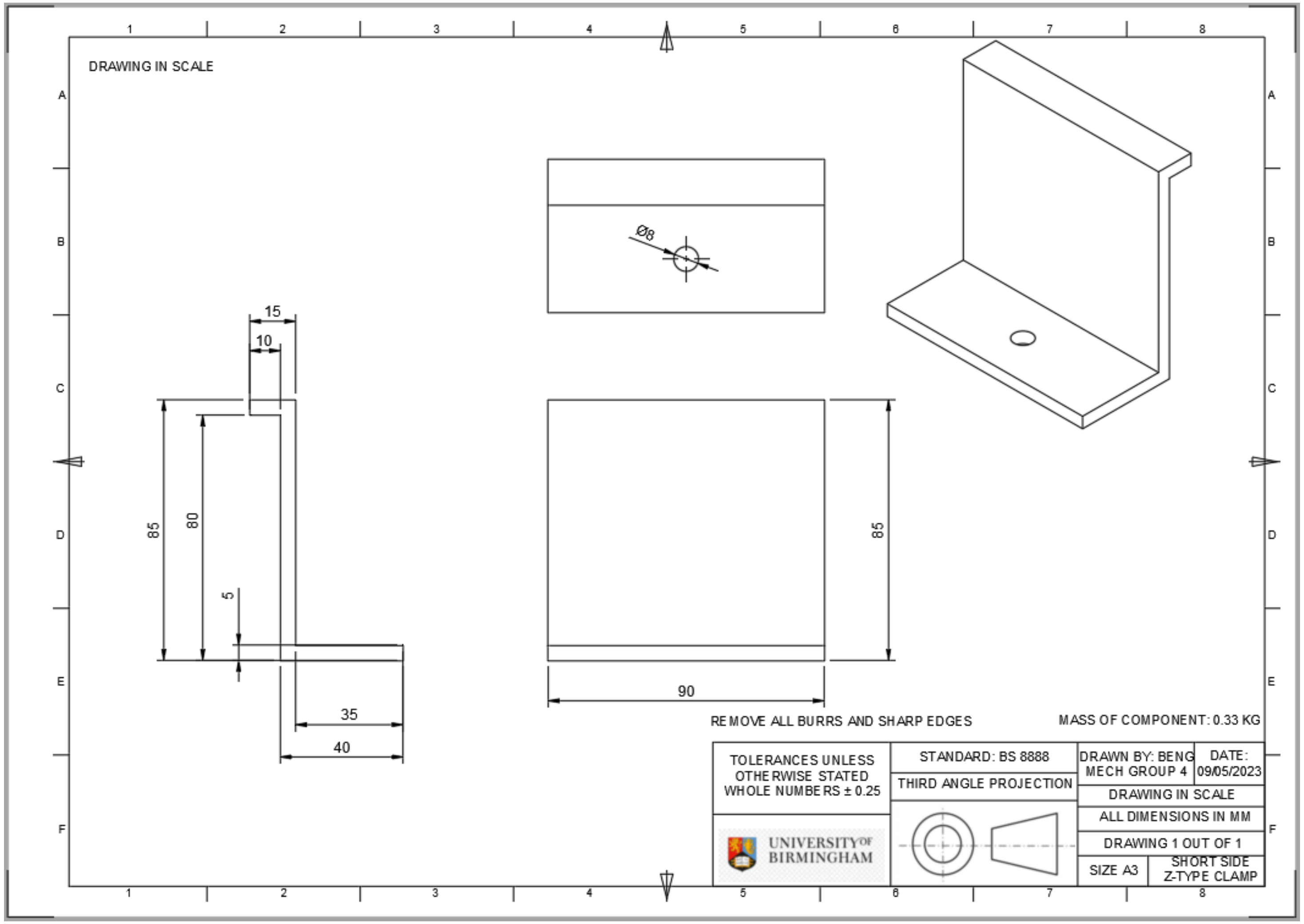
*Table 19. Product Maintenance Cost Analysis*

| Maintenance Procedure | Parts associated | Maintenance Type | | | Frequency | Completed on scheduled maintenance checks (Yes/No) | Cost (£) |
|---|---|---|---|---|---|---|---|
| | | Preventive | Corrective | Predictive | | | |
| Cleaning | Cleaning staff | X | | | Per annum | Yes | 4.80E+05 |
| | Water tanks | X | | | One off | Yes | 5.56E+03 |
| | Brushes | X | | | One off | Yes | 4.00E+03 |
| | Solution | X | | | Per annum | Yes | 4.52E+03 |
| Inspections | Maintenance Engineer Staff | | X | | Per annum (X) | Yes | 1.17E+05 |
| | Pyranometer | | | X | Every 10 years | Yes | 1.00E+04 |
| | Replacements | | X | | N/A | Yes | N/A |
| | | | | | | **Total Cost (£)** | **6.21E+05** |

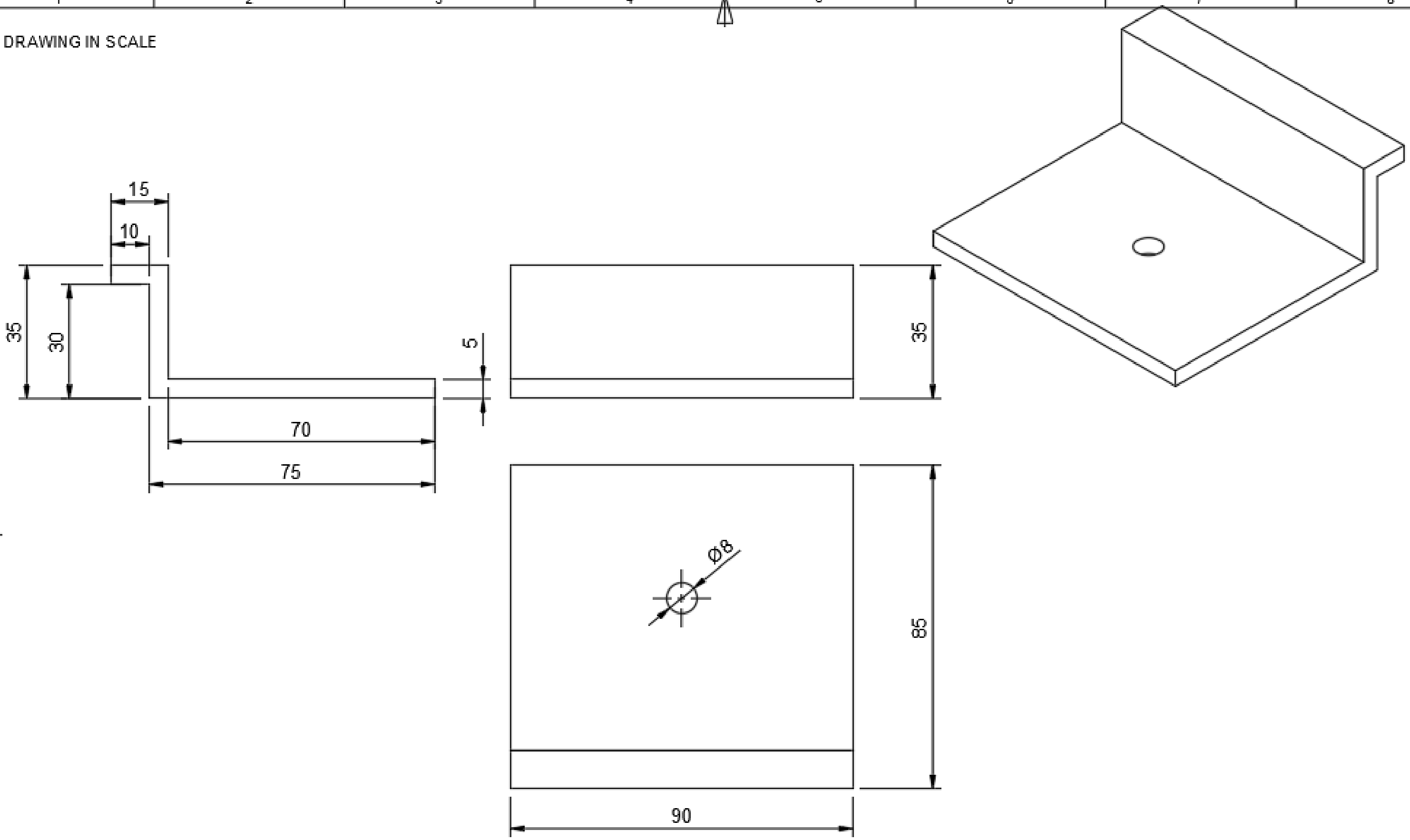
## 7.3 Stakeholders

A stakeholder analysis was conducted to ensure the accommodation of organisations that would be affected by the project. The Star of the South project would be interested as the project would aid the goal of providing 2.2 GW of renewable energy to Victoria [36]. The two major investment fund managers in the original project, Copenhagen Infrastructure Partners (CIP) and Cbus Super, specialise in investing in renewable energy, with the former having the goal of raising €100 billion to invest in renewable energy by 2030 [57]. Additionally, the Australian Federal Government's investment body, Clean Energy Finance Corporation, has a goal of reaching net zero carbon emissions by 2050, which the project would help to achieve. They have so far invested a total of A$11.7 billion since 2012 [58]. The State Government of Victoria would be a likely supporter of the addition of a solar farm to the project as they have a 95% renewable energy target by 2035 [59]. Certain environmental organisations, such as the Australian Marine Conservation Society, may object to the project, due to the potential impact on the local marine environment [60]. However, we have made sure to create the least environmental impact as possible as explained in Section 5 in the wider engineering implications.

# Appendix
## A.1 Part Drawings and Assembly Drawings



DRAWING IN SCALE

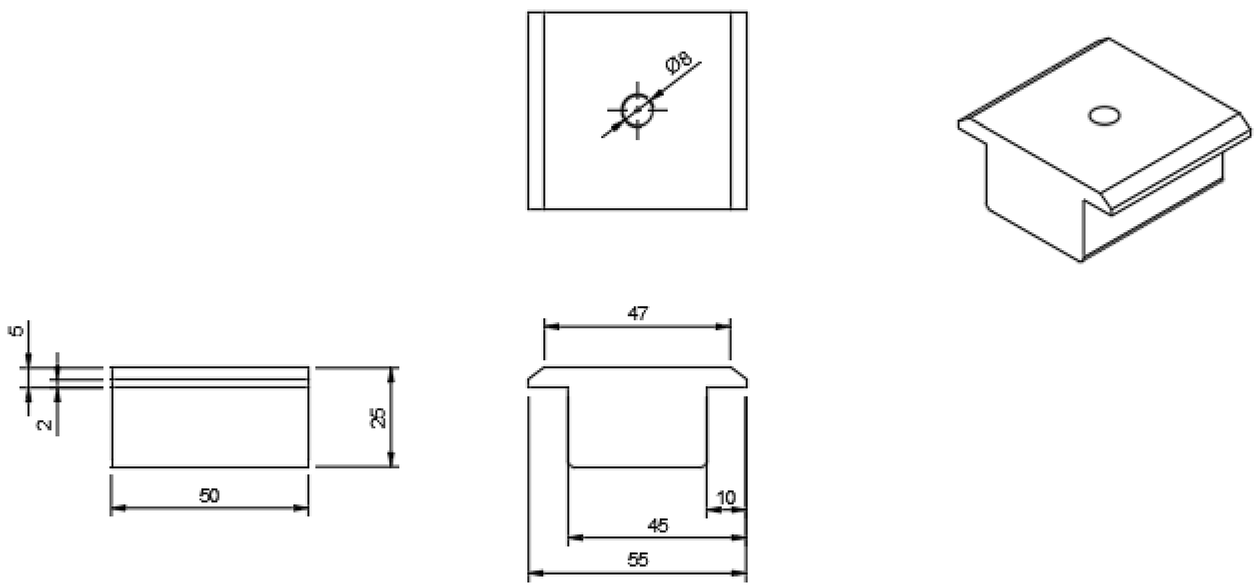



REMOVE ALL BURRS AND SHARP EDGES

MASS OF COMPONENT: 0.3KG

| | | | |
|---|---|---|---|
| TOLERANCES UNLESS OTHERWISE STATED WHOLE NUMBERS ± 0.25 | STANDARD: BS 8888 | DRAWN BY: BENG MECH GROUP 4 | DATE: 09/05/2023 |
| | THIRD ANGLE PROJECTION | DRAWING IN SCALE | |
| UNIVERSITY OF BIRMINGHAM | | ALL DIMENSIONS IN MM | |
| | | DRAWING 1 OUT OF 1 | |
| | | SIZE A3 | LONG SIDE Z-TYPE CLAMP |

DRAWING IN SCALE

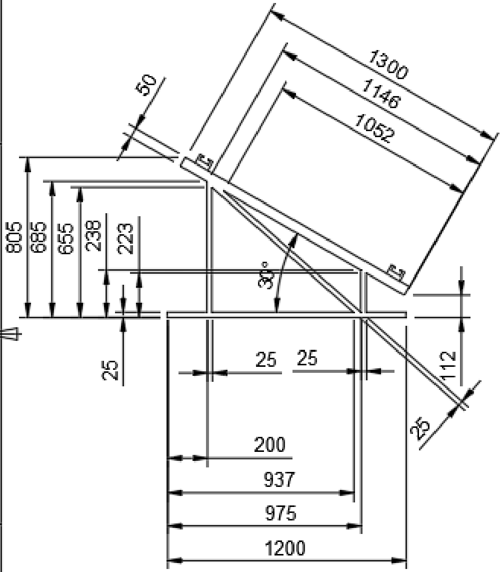


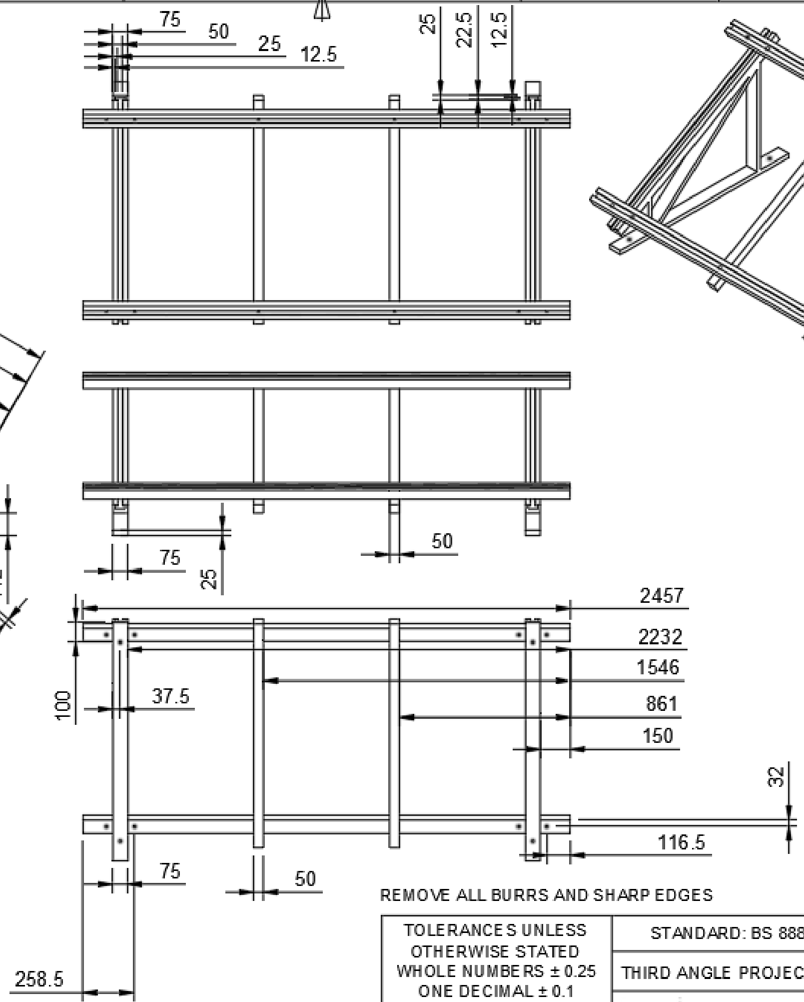

REMOVE ALL BURRS AND SHARP EDGES

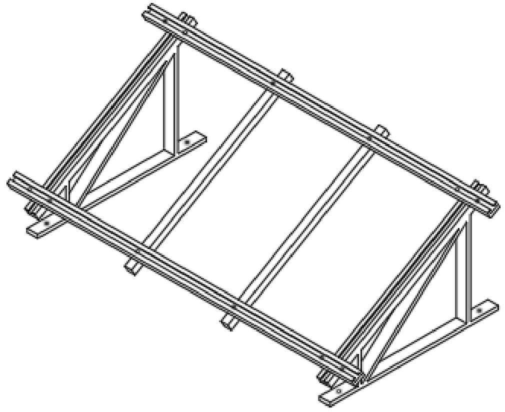
MASS OF COMPONENT: 0.37 KG

| | | | |
|---|---|---|---|
| TOLERANCES UNLESS OTHERWISE STATED WHOLE NUMBERS ±0.25 | STANDARD: BS 8888 | DRAWN BY: BENG MECH GROUP 4 | DATE: 09/05/2023 |
| | THIRD ANGLE PROJECTION | DRAWING IN SCALE | |
| UNIVERSITY OF BIRMINGHAM | | ALL DIMENSIONS IN MM | |
| | | DRAWING 1 OUT OF 1 | |
| | | SIZE A3 | MID CLAMP |

DO NOT SCALE



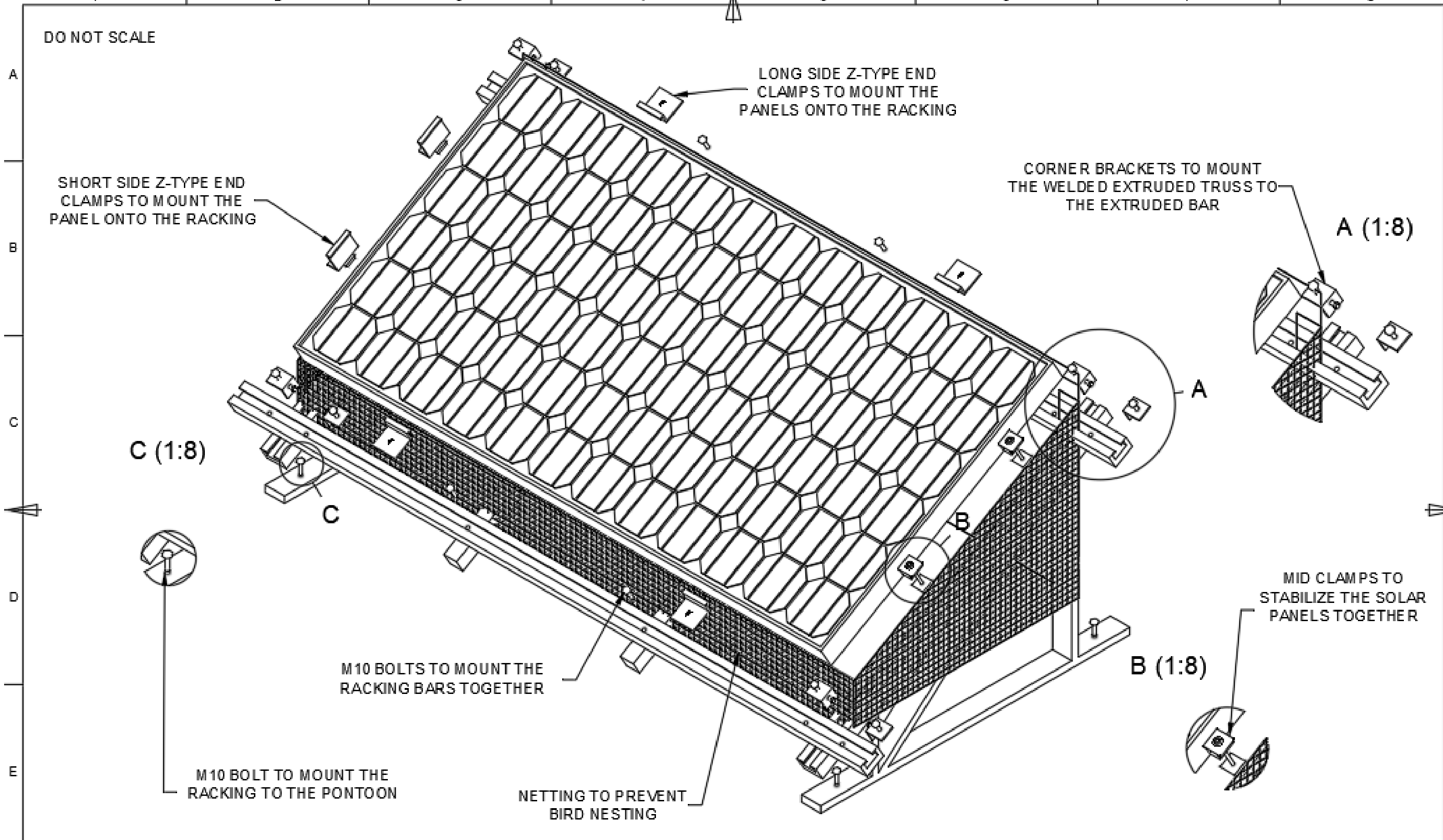
REMOVE ALL BURRS AND SHARP EDGES

NOTES:

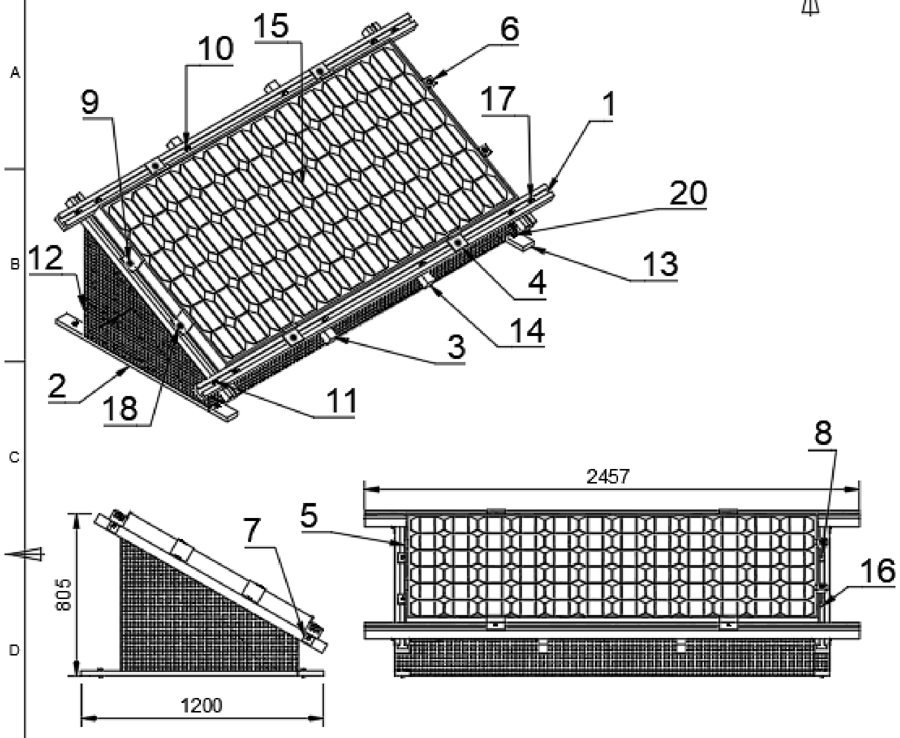
-ALL THE DEPICTED HOLES HAVE A DIAMETER OF 10MM UNLESS OTHERWISE STATED

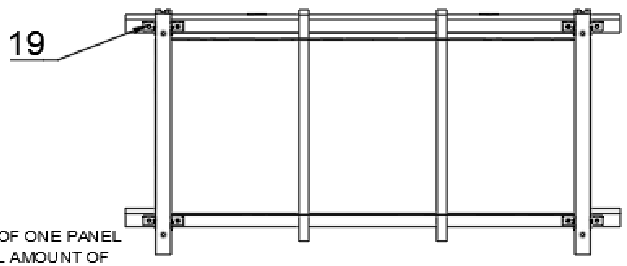
-WEIGHT OF THE COMPONENT: 55KG

| | | | |
|---|---|---|---|
| TOLERANCES UNLESS OTHERWISE STATED<br>WHOLE NUMBERS ± 0.25<br>ONE DECIMAL ± 0.1 | STANDARD: BS 8888 | DRAWN BY: BENG MECH GROUP 4 | DATE: 09/05/2023 |
| | THIRD ANGLE PROJECTION | SCALE 1:20 UNLESS OTHERWISE STATED | |
| UNIVERSITY OF BIRMINGHAM | | ALL DIMENSIONS IN MM | |
| | | DRAWING 1 OUT OF 1 | |
| | | SIZE A3 | RACKING |




| | | | |
|---|---|---|---|
| TOLERANCES UNLEES OTHERWISE STATED WHOLE NUMBERS ± 0.25 | STANDARD: BS 8888 | DRAWN BY: BENG MECH GROUP 4 | DATE: 09/05/2023 |
| | THIRD ANGLE PROJECTION | SCALE 1:10 UNLESS OTHERWISE STATED | |
| UNIVERSITY OF BIRMINGHAM | | ALL DIMENSIONS IN MM | |
| | | DRAWING 1 OUT OF 1 | |
| | | SIZE A3 | EXPLODED VIEW |




| Parts List | | |
|---|---|---|
| Item | Qty | Part Name |
| 1 | 2 | RC01-Racking Extruded |
| 2 | 2 | RC02-Racking Truss |
| 3 | 2 | RC03-Racking Hollow |
| 4 | 4 | Z-Type Clamp (Long) |
| 5 | 2 | Z-Type Clamp (Short) |
| 6 | 2 | Mid Clamp |
| 7 | 8 | L-Bracket (41mm x 57mm) |
| 8 | 2 | Full Thread Hex. Bolt (M8x 110mm) |
| 9 | 6 | Full Thread Hex. Bolt (M8x30mm) |
| 10 | 4 | Full Thread Hex. Bolt (M10x75) |
| 11 | 16 | Fulll Thread Hex. Bolt (M10x30mm) |
| 12 | 2 | Anti-Bird Mesh |
| 13 | 4 | PVC End Caps (25mm x 75mm) |
| 14 | 4 | PVC End Caps ( 50mm x 50mm) |
| 15 | 1 | Solar Panel |
| 16 | 8 | T-Slot Nuts |
| 17 | 20 | Washer (M10 Heavy Duty) |
| 18 | 8 | Washer (M8 Reduced Diameter) |
| 19 | 12 | Hexagon Nuts (M10) |
| 20 | 4 | LieBig Anchor AB Bolts (M10) |

WEIGHT OF ASSEMBLY: 78 KG

DO NOT SCALE

NOTES:
THIS IS AN ASSEMBLY OF ONE PANEL HOWEVER THE TOTAL AMOUNT OF PANELS IS 42100 SO THE QUANTITY OF ALL THE PARTS SHOULD BE MULTIPLIED BY THIS NUMBER REFER TO THE BOM IN APPENDIX A.2

| | | | |
|---|---|---|---|
| TOLERANCES UNLESS OTHERWISE STATED WHOLE NUMBERS ± 0.25 | STANDARD: BS 8888 | DRAWN BY: BENG MECH GROUP 4 | DATE: 09/05/2023 |
| | THIRD ANGLE PROJECTION | SCALE 1:20 UNLESS OTHERWISE STATED | |
| UNIVERSITY OF BIRMINGHAM | | ALL DIMENSIONS IN MM | |
| | | DRAWING 1 OUT OF 1 | |
| | | SIZE A3 | ASSEMBLY |

## A.2 Bill of Materials

The Bill of Materials below is scaled down for one assembled Solar string found described 'Routing sheet 2', which contains 25 solar modules. Overall, there are 130 pontoons each containing 13 solar strings in the entire facility. An exploded view with the main parts can be found in Appendix A1.

*Table 20. Bill of Materials*

| **Bill of Materials** | | | | | | |
|---|---|---|---|---|---|---|
| **Part No.** | **Part name (Dimensions)** | **Qty.** | **Material** | **Supplier** | **Product code** | **Standard** |
| 1 | Cable ties (292mm x 3.6mm) | 75 | Nylon (Black) | RS | 233-477 | IEC 62275: 2019 |
| 2 | Cable ties (300mm x 7.0mm) | 75 | 316 Stainless steel | RS | 121-624 | IEC 62275: 2019 |
| 3 | Full thread hexagon bolts (M10x 30mm) | 208 | Marine stainless steel (A4) | Accu | SEBF-M10-30-A4 | ISO 4017 (DIN 933) |
| 4 | Full thread hexagon bolts (M10x 75mm) | 100 | Marine stainless steel (A4) | Accu | SEBF-M10-75-A4 | ISO 4017 (DIN 933) |
| 5 | Full thread hexagon bolts (M8 x 30mm) | 104 | Marine stainless steel (A4) | Accu | SEBF-M8-30-A4 | ISO 4017 (DIN 933) |
| 6 | Full thread hexagon bolts (M8 x 110mm) | 50 | Marine stainless steel (A4) | Accu | SEBF-M8-110-A4 | ISO 4017 (DIN 933) |
| 7 | Hexagon nuts (M10) | 308 | Marine stainless steel (A4) | Accu | HPN-M10-A4 | ISO 898-2 (DIN 934) |
| 8 | Hexagonal anti- bird mesh (25m x 1.2m (19mm holes)) | 2 | High density polyethylene | Quatra | - | - |
| 9 | Junction box- Deltron 480 (IP68) | 25 | Die cast aluminium | RD | 769-6850 | BS EN 60529: 1992 |
| 10 | L- bracket (41mm x 57mm, 90 deg.) | 104 | Stainless steel (A2) | RS | 767-652 | ISO 10474: 2013 |
| 11 | Liebig anchor AB Bolts (M10) | 52 | Marine stainless steel (A4) | Liebig | AB1015070040A4 | - |
| 12 | Panel clamp- Z shape (Long) | 100 | Marine stainless steel (A4) | - | - | - |
| 13 | Panel clamp- Z shape (Short) | 4 | Marine stainless steel (A4) | - | - | - |
| 14 | Panel clamps- Middle | 50 | Marine stainless steel (A4) | - | - | - |
| 15 | PVC End caps (25mm x 75mm) | 104 | Polyvinyl chloride (PVC) | Vital Parts | REC121 | - |
| 16 | PVC End caps (50mm x 50mm) | 104 | Polyvinyl chloride (PVC) | Vital Parts | SQ061 | - |
| 17 | Pyranometer | 4 | - | - | - | - |
| 18 | RC01- Racking extruded | 2 | 316 Stainless steel | - | - | - |
| 19 | RC02- Racking truss | 26 | 316 Stainless steel | - | - | - |

| | | | | | | |
|---|---|---|---|---|---|---|
| 20 | RC03- Racking hollow | 52 | 316 Stainless steel | FH Brundle | 300550503 | - |
| 21 | Solar panels | 25 | - | Sun Power | Maxeon A6 (410-425W) | ISO 9001:2015<br>ISO14001:2015 |
| 22 | T- Slot nuts (M8, 40mm, 10mm groove) | 154 | Galvanised stainless steel | RS | 197-1359 | ISO 299 (DIN 508) |
| 23 | Washer (M10 Heavy duty) | 308 | Marine stainless steel (A4) | Accu | HRDW-M10-A4 | ISO 4762 (DIN 7349) |
| 24 | Washer (M8 Reduced Diameter) | 154 | Marine stainless steel (A4) | Accu | HRDW-M8-A4 | ISO 4762 (DIN 7349) |

## A.3 Routing sheets

The solar farm has been divided into two main sub-assemblies the ‘Racking system’ (Sheet 1) and the ‘Solar Assembly’ (Sheet 2). An in depth explanation of the assembly methods can be found in the Tables below, furthermore manufacture of inhouse components will be discussed in ‘Section 6.3- Operations list’.

**Assembly Routing Sheets**

*Table 21. Routing sheet for assembly of racking system*

<table>
<tr><th colspan="4">Routing Sheet 1</th></tr>
<tr><td colspan="2">Name of Assembly (Part No.)</td><td colspan="2">Racking system (RC01, RC02 and RC03)</td></tr>
<tr><td colspan="2">Quantity to be produced:</td><td colspan="2">1,684 units</td></tr>
<tr><td colspan="2">Planner:</td><td colspan="2">L. Stevenson</td></tr>
<tr><td>Date:</td><td>28/04/2023</td><td>Drawing No: A1 (Pg. 55)</td><td>Revision: 1</td></tr>
<tr><td>Op No.</td><td colspan="2">Description</td><td>Equipment/ Tooling</td></tr>
<tr><td>1</td><td colspan="2">Connect the horizontal extruded beams (RC01) to the main racking trusses (RC02). The extrusions on the RC01 will bolt four L shaped brackets to directly to the main truss of RC02. Two L brackets towards each end of the extruded beam.<br>Align the holes, insert the M10 bolts each along with a washer, then use the torque wrench to tighten to the outlined setting.</td><td>Full thread hexagon bolts (M10 x 20mm)<br>Hexagon nuts (M10)<br>Washer (M10 Heavy duty)<br>L- bracket (41mm x 57mm, 90 deg.)<br><br>Torque wrench (Set to 57.3 Nm) with M10 socket</td></tr>
<tr><td>2</td><td colspan="2">Orientate the two vertical 1.3m hollow beams (RC03), these will be in the same inclination/ direction as the main welded truss system (RC02). Now bolt the vertical beams onto the previously fixed extruded beams. Align the M10 bolts, along with washers, through the extruded beams and into the supporting RC02 beams hence the longer bolts. Once again tighten with torque wrench to outlined setting.</td><td>Full thread hexagon bolts (M10 x 90mm)<br>Hexagon nuts (M10)<br>Washer (M10 Heavy duty)<br><br>Torque wrench (Set to 57.3 Nm) with M10 socket</td></tr>
<tr><td>3</td><td colspan="2">Fit the PVC end caps to the bottom hollow base rails of the racking trusses (RC02), two each end so four in total. This will require a light force from a rubber mallet due to the interference fit, the end caps will prevent injury and debris build up.</td><td>PVC End caps (41mm x 41mm)<br><br>Rubber mallet</td></tr>
<tr><td>4</td><td colspan="2">Cleaning, quality testing and general inspection of finalised system.</td><td>97% Isopropyl alcohol and microfibre cloth<br>Ammeter (DC)</td></tr>
<tr><td colspan="4" align="right">Page 1 of 2</td></tr>
</table>

*Table 22. Routing sheet for solar assembly (solar panels to racking system)*

| Routing Sheet 2 | | | |
|---|---|---|---|
| **Name of Assembly (Part No.)** | | Solar Assembly (RC01, RC02, CL01, CL02 and CL03) | |
| **Quantity to be produced:** | | 1,684 units | |
| **Planner:** | | L. Stevenson | |
| **Date:** | **28/04/2023** | **Drawing No:** A1 (Pg. 56) | **Revision: 1** |
| **Op No.** | **Description** | | **Equipment/ Tooling** |
| **1** | The Maxeon 6 solar panels are standard from Sun Power (Sun Power, 2022), therefore these will arrive pre-constructed. Ensure panels are thoroughly cleaned before and after assembly process. | | 97% Isopropyl alcohol<br>Microfibre cloth |
| **2** | Assemble the racking system as described in assembly 'Routing Sheet 1'. Now attach the landscape orientated solar panels through the use of a variety of clamps. Evenly spaced long sided Z shaped clamps (CL02) will go at the top and bottom of each panel, 25 each side therefore 50 in total. Furthermore in between each panel should be a middle clamp (CL01). Finally on either end of the string system will be two short sided Z clamp (CL03) thus 4 total. Overall 154 in total assorted clamps. (Appendix A1 Pg. 56) presents the specific layout of the clamps).To fasten the clamps to the racking frame slide the T-slot nut through the extruded bar, then insert M8 socket head screws along with a washer. Ensure to use a torque wrench to not overtighten or damage the panels. | | Panel clamps (Middle and Z shaped)<br>Full thread hexagon bolts (M8 x 70mm)<br>T- Slot nuts (M8, 40mm with 10mm groove)<br>Washer (M8 Reduced diameter)<br><br>Torque wrench (Set to 28.8 Nm) with M8 socket |
| **3** | Secure the inverter using two adjustable metallic cable ties, to the bottom of the racking system frame. Connect the solar panel to the inverter by plugging in the electrical cable. Ensure the wiring is neatly cable tied to the racking support beams, with maximum of three nylon ties per panel. This reduces the risk of rubbing, damage or getting caught. | | Stainless steel 316 cable ties (300mm x 7.0mm)<br>Black nylon cable ties (292mm x 3.6mm) |
| **4** | Attach the entire solar panel system to the pontoon with Liebig Anchor bolts, the AB variant is with a hex nut. Therefore a torque wrench fitted with an M10 attachment. Careful not to overtighten, reducing risk of shearing or stripping the thread of the bolt. | | Liebig Anchor AB (A4) Bolts (M10 x 65mm)<br><br>Torque wrench (Set to 57.3 Nm) with M10 socket |
| **5** | Surround the full string with HDPE anti- bird mesh, cable tie for ease of adjustment and maintenance. | | HDPE High density polyethylene mesh<br>Black nylon cable ties (292mm x 3.6mm) |
| **6** | Cleaning, quality testing and general inspection of finalised system. Ensure 30 degree angle for the panel is achieved. | | 97% Isopropyl alcohol and Microfibre cloth<br>Ammeter (DC) |
| | | | **Page Number: 2 of 2** |

## A.4 Operations lists

The operations list defines the manufacturing processes required to make individual in-house components, this includes specified tooling and machine characteristics. In this case, only the racking system and clamps are manufactured, the design has been broken into sections due to size limitations of some machinery or raw materials. The remaining components such as solar panels, bolts and nuts are all outsourced which can be found in Appendix A.2- Bill of Materials. Overall to manufacture the custom parts will be approximately a year and a half (580 days).

*Table 23. Operations Sheet- Racking support (extruded beams)*

| **Operations List 1** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Name of Part (Part No.)** | Racking extruded (RC01) | | | | | | |
| **Quantity to be produced:** | 3368 units | | | | | **Planner:** | L. Stevenson |
| **Material(s) used:** | 316 Stainless steel coil | | | | | **Date:** | 28/04/2023 |
| **Op No.** | **Description** | **Machine Tool** | **Speed (rev/min)** | **Feed (m/min)** | **Set-up Time (min)** | **Op. Time (days:hr:min)** | **Remarks** |
| **1** | Steel coil is unwound during the roll forming process, once complete the final shape is known as a 'C profile' a outside channel width of 75mm by 50mm height, The internal dimensions are 50mm wide and 10mm height, allowing for the T-nut to sit inside. (As outlined in Appendix A1 Pg. 54) | Purlin Machine (PMA350) - Forming | - | 35 | 5 | 03:12:00 | Continuous process with no length limitation<br><br>Fitted with custom roll forming profile and dimensions |
| **2** | Predefine the Purlin machine settings to cut final profile down into two separate lengths of 54.22m and 1.3m. The longer extrusion is for across the two horizontal beams and the shorter beams are to be welded onto the racking truss (RC02) | Purlin Machine (PMA350) - Cutting | - | 35 | 5 | 03:12:00 and 01:04:00 | Continuous process with no length limitation |
| **3** | Only the 54.22m beams require holes as the 1.3m will be welded. Predefine the Purlin machine for drilling holes, this is with the integrated fly punching settings. The all of the holes will be in the centre of the 75mm wide extrusion. | Purlin Machine (PMA350) - Drilling | 720 (10mm) | 0.021 | 5 | 02:07:10 | Continuous process with no length limitation<br><br>10mm diameter solid carbide drill bit |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Drill 10mm diameter holes, located every 620mm, starting 150mm in from either end of the extruded beam. These holes are for locating extruded beam onto the with the racking truss. | | | | | | (Location fit, tolerance H7/g6) |
| **4** | Deburr and clean up sharp edges of material from beam | - | - | - | 1 | 00:01:30 | Use a deburring tool or woven abrasive disc attached to right angle grinder to remove excess. |
| **5** | Inspection and quality analysis | - | - | - | 0.5 | 00:00:30 | Manually or automated inspection |
| | | | | | | | **Page Number: 1 of 5** |

*Table 24. Operations Sheet- Racking main (truss beams)*

| **Operations List 2** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Name of Part (Part No.)** | Racking truss (RC02) | | | | | | |
| **Quantity to be produced:** | 437,784 units | | | | | **Planner:** | L. Stevenson |
| **Material(s) used:** | 316 Stainless steel sheet | | | | | **Date:** | 28/04/2023 |
| **Op No.** | **Description** | **Machine Tool** | **Speed (rev/min)** | **Feed (m/min)** | **Set-up Time (min)** | **Op. Time (days:hr:min)** | **Remarks** |
| **1** | Cut 1mm thick AISI 316 sheets down to size, which is 3m by 200mm in preparation for the shaping. | Punching machine (Amada EM 3612 M11 NT) | - | *500 | 5 | 00:14:35 | *Press per minute.<br><br>Maximum sheet size 3m x 1.5m.<br><br>(Location fit, tolerance H7/g6) |
| **2** | To bend sheet metal into shape use a panel bender, the first two bends use | Panel bending machine | - | - | 5 | 06:19:15 | Machine specification P4-4020 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | an internal punch leaving a 'U' shape, the final bend will require an external press to get a hollow rectangle profile, with external dimensions of 75mm wide by 25mm height, with 90 degree angles. | (Salvagnini P4Xe 3216 CNC Folder) | | | | | Maximum sheet size 4m x 1.5m |
| **3** | Cut the now hollow bar into the defined lengths, the final truss system consists of 4 hollow lengths and an extruded top beam.<br>The hollow trusses require angled cuts, hence the use cutting jigs. (Dimensions and angles found in Appendix A1 Pg. 54) | Circular saw (High speed machining) | 2500 | 55-65 | 5 | 03:09:35 | Attachment- 6.5 inch diameter, 50 teeth, carbide tipped blade<br><br>Angled jigs |
| **4** | Drill 10mm diameter through holes in the centre of the 'bottom beam', 100mm from each end using a solid carbide drill bit. These holes will be for locating the racking system with the pontoon. | HSS Drill (High speed steel) | 960 (8mm) | 0.016 | 2 | 04:16:45 | Castor oil is used for lubrication<br><br>10mm diameter solid carbide drill bit<br><br>(Location fit, tolerance H7/g6) |
| **5** | Prepare the weld sights with steel wool and acetone. Using an automated MIG welder, layout the 4 different trusses (RC02) within a custom jig and weld together. Repeat the process for the final extruded beam (RC01) across the top of the trusses, as seen in Appendix A1. | Tregaskiss Hercules automated welding system | - | - | 10 | 36:19:15 | Steel wool and acetone<br><br>5-10% Ferrite weld filler<br><br>ER314 MIG wire |
| **6** | Inspection and quality analysis | - | - | - | 0.5 | 02:00:00 | Visually check for incorrect angles, bad weld points or to areas of slag. |

*Table 25. Operations Sheet- Solar panel middle clamp*

| **Operations List 3** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Name of Part (Part No.)** | Panel middle clamp (CL01) | | | | | | |
| **Quantity to be produced:** | 84,200 units | | | | | **Planner:** | L. Stevenson |
| **Material(s) used:** | 316 Stainless steel billet | | | | | **Date:** | 28/04/2023 |
| **Op No.** | **Description** | **Machine Tool** | **Speed (rev/min)** | **Feed (m/min)** | **Set-up Time (min)** | **Op. Time (days:hr:min)** | **Remarks** |
| **1** | To directly extrude the 316 Stainless Steel billet, heat to 1200°C in furnace then feed through an extruder. The die forms a final 'T' shaped profile, an overall 55mm width and height 25mm<br><br>(Full profile dimensions seen in Appendix A1 Pg. 55) | Halton Crest HC4000 extruder | 3200 | 0.9 | 60 | 233:19:15 | *kg/hr<br><br>Fitted with custom die profile and dimensions<br><br>Extrusion ratio= 40:1 |
| **2** | Once cool, every 25mm drill a 12mm hole halfway through the extruded bar. Followed by a 8mm through hole in the centre of the previously drilled hole, these are for the bolt head to sit flush and allow for tooling clearance.<br><br>The holes are to fix the clamps into the T nuts, securing the panels. | HSS Drill (High speed steel) | 500 (12mm)<br>960 (8mm) | 0.026<br>0.016 | 5 | 11:14:55<br>and<br>17:12:25 | Castor oil is used for lubrication<br><br>12mm and 8mm diameter solid carbide drill bits.<br><br>(Location fit, tolerance H7/g6) |
| **3** | Firstly using an automated circular saw ensure to end-off the bar, due to damage incurred as a result of during extrusion. Furthermore cut down to 50mm long individual clamps.<br><br>(Full profile dimensions seen in Appendix A1 Pg. 55) | Circular saw (High speed machining) | 2500 | 55-65 | 5 | 05:19:15 | Attachment- 6.5 inch diameter, 50 teeth, carbide tipped blade |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **4** | Deburr and clean up sharp edges of material from beam. | - | - | - | 1 | 01:12:00 | Use a deburring tool or woven abrasive disc attached to right angle grinder to remove excess. |
| **5** | Inspection and quality analysis | - | - | - | 0.5 | 01:00:00 | Visually check for incorrect angles, weld points or to areas of slag. |
| | | | | | | | **Page Number: 3 of 5** |

*Table 26. Operations Sheet- Solar panel Z- clamp (Long)*

| **Operations List 4** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Name of Part (Part No.)** | Panel Z shaped clamp Long (CL02) | | | | | | |
| **Quantity to be produced:** | 168,400 units | | | | | **Planner:** | L. Stevenson |
| **Material(s) used:** | 316 Stainless steel coil | | | | | **Date:** | 28/04/2023 |
| **Op No.** | **Description** | **Machine Tool** | **Speed (rev/min)** | **Feed (m/min)** | **Set-up Time (min)** | **Op. Time (days:hr:min)** | **Remarks** |
| **1** | Steel coil (5mm thick) is unwound during the roll forming process, predefine the Purlin machine for drilling holes, this is with the integrated fly punching settings. The through holes will be 8mm diameter, found 35mm from the bottom edge.<br><br>The holes are to fix the clamps into the T nuts, securing the panels. | Purlin Machine (PMA350) - Drilling | 960 (8mm) | 0.016 | 5 | 58:00:00 | Continuous process with no length limitation<br><br>8mm diameter solid carbide drill bit<br><br>(Location fit, tolerance H7/g6) |
| **2** | The unwound coil is subject to roll forming, the final shape is known as a ‘Z profile’ as outlined in Appendix A1 Pg 53. | Purlin Machine (PMA350) - Forming | - | 35 | 5 | 175:09:30 | Continuous process with no length limitation |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | The top bend being 10mm from the end, the middle section being 25mm long and then in the reversed bend direction, which is 70mm from bottom. | | | | | | Fitted with custom roll forming profile and dimensions |
| **3** | Predefine the Purlin machine settings to cut final profile down into lengths of 90mm. These will be individual lengths of the long sided clamps. | Purlin Machine (PMA350) - Cutting | - | 35 | 5 | 00:07:15 | Continuous process with no length limitation |
| **4** | Deburr and clean up sharp edges of material from beam. | - | - | - | 1 | 02:00:00 | Use a deburring tool or woven abrasive disc attached to right angle grinder to remove excess. |
| **5** | Inspection and quality analysis | - | - | - | 0.5 | 01:00:00 | Visually check for incorrect angles, weld points or to areas of slag. |
| | | | | | | | **Page Number: 4 of 5** |

*Table 27. Operations Sheet- Solar panel Z- clamp (short)*

| **Operations List 5** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Name of Part (Part No.)** | | Panel Z shaped clamp short (CL03) | | | | | |
| **Quantity to be produced:** | | 6736 units | | | | **Planner:** | L. Stevenson |
| **Material(s) used:** | | 316 Stainless steel coil | | | | **Date:** | 28/04/2023 |
| **Op No.** | **Description** | **Machine Tool** | **Speed (rev/min)** | **Feed (m/min)** | **Set-up Time (min)** | **Op. Time (days:hr:min)** | **Remarks** |
| **1** | Steel coil (5mm thick) is unwound during the roll forming process, predefine the Purlin machine for drilling holes, this is with the integrated fly punching settings. The through holes will be 8mm diameter, found 17.5mm from the bottom edge. | Purlin Machine (PMA350) - Drilling | 960 (8mm) | 0.016 | 5 | 02:07:15 | Continuous process with no length limitation<br><br>8mm diameter solid carbide drill bit |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | The holes are to fix the clamps into the T nuts, securing the panels. | | | | | | (Location fit, tolerance H7/g6) |
| **2** | The unwound coil is subject to roll forming, the final shape is known as a 'Z profile' as outlined in Appendix A1 Pg 52.<br><br>The top bend being 10mm from the end, the middle section being 75mm long and then in the reversed bend direction, which is 35mm from bottom. | Purlin Machine (PMA350) - Forming | - | 35 | 5 | 07:02:30 | Continuous process with no length limitation<br><br>Fitted with custom roll forming profile and dimensions |
| **3** | Predefine the Purlin machine settings to cut final profile down into lengths of 90mm. These will be individual lengths of the short sided clamps. | Purlin Machine (PMA350) - Cutting | - | 35 | 5 | 04:14:45 | Continuous process with no length limitation |
| **4** | Deburr and clean up sharp edges of material from beam. | - | - | - | 1 | 00:03:00 | Use a deburring tool or woven abrasive disc attached to right angle grinder to remove excess. |
| **5** | Inspection and quality analysis | - | - | - | 0.5 | 01:00:00 | Visually check for incorrect angles, weld points or to areas of slag. |

## A.5 Summary of minutes

| No. | Date | Absent | Actions completed: | Actions to be taken: |
|---|---|---|---|---|
| 1 | 03/02/2023 Friday | - | >Set up communication channels (WhatsApp + MS Teams)<br>>Decided on meeting times (twice a week but could be more if need be)<br>>Belbin & Myers Briggs personality tests, | >Rank challenges<br>>Familiarise ourselves with solutions in past reports from previous students |
| 2 | 09/02/2023 Thursday | - | >Brainstormed solution ideas at a group level during workshop in regard to the challenge (Sustainable Offshore Energy Island)<br>>Group leader feedback to the group of potential solution as discussed at a team level | >Input timeline into Gantt chart<br>>As a group, upload main questions that need addressing, to the team level word document – this will allow for the team to make a more informed decision on the solution |
| 3 | 10/02/2023 Friday | - | >We took on the energy requirements work package from the team level document | >Research into the energy requirements – i.e., required energy output from island, Scotland's energy demand |
| 4 | 15/02/2023 Wednesday | Afshin | >Relayed to the group, information pertaining to potential solution (Wave Energy Converter (WEC)) for Mech Eng, as discussed in the group leader meeting<br>>Set out reading assignment on a relevant scientific paper (Wave energy) | >Summarise information from research paper on assigned reading pages |
| 5 | 17/02/2023 Friday | - | >Met up with the supervisor (Dr. Mehdi Jangi) and discussed current progress<br>>Following discussion with supervisor, we realised that the group, did not have plausible justification as to why we wanted to do Wave energy as opposed to solar | >Research and prepare material highlighting pros and cons of the different renewable energies (Wave, PV Solar, CSP + Heat storage, Hydrogen fuel production) |
| 6 | 20/02/2023 Monday | Afshin, Lois | >Discussed the research on the different renewable energies - their pros and cons<br>>Decided to focus on Solar energy technology | >Obtain information from the group leaders on what the solution is, so as to identify interfaces<br>>Start looking into the different technologies of harnessing solar energy |
| 7 | 21/02/2023 Tuesday | Lois | >Relayed information from group leader meeting in regards to what is required of us to progress the project (i.e., create PDS, task breakdown at group level to | >Further research on solar technology (for Thursday) to consolidate understanding and to inform the decision making |

| | | | | |
|---|---|---|---|---|
| | | | identify overlap with other groups, identify critical tasks) | on what type of solar technology is viable (i.e., CSP, PV, or combined CSP and PV)<br>>Continue adding details into the Gannt Chart |
| 8 | 23/02/2023 Thursday | - | >Decided on PV technology and dedicated research on different PV solar energy subsystems to each member to be ready for Monday | >Summarise research on assigned task in regards to solar subsystems (tracking system, racking, PV module material choice etc) |
| 9 | 24/02/2023 Friday | - | >Met with the supervisor to discuss progress (this mainly included providing justification for the choice of PV system)<br>>Discussed with the supervisor about the desire for the potential relocation of the offshore island since Hull (UK) was not the best location for solar energy<br>>Discussed with the team about the concerns about Hull not being a good location for solar energy which prompted the selection of Star of the South wind farm (Australia) | >Continue research on the solar systems for Monday<br>>As a group leader, keep record of justifications for why approaches (in regards to type of technology etc) were taken or disregarded |
| 10 | 27/02/2023 Monday | - | >Discussed everyone's research so that everyone understands the overall (possible) group solution to the challenge<br>>Provided feedback by asking questions which brought about further research for the person responsible (peer review)<br>>Performed task breakdown which was filled into the Gantt Chart, identifying critical tasks for the presentation stage | >Finalise research on solar technology for Wednesday<br>>Begin thinking about concept designs |
| 11 | 01/03/2023 Wednesday | - | >Started to brainstorm concept ideas and identified pertinent subsystems (i.e., design against wind, design to maximise yield, cost effective designs etc)<br>>Identified the team level interfaces with the group project (e.g. inverter requirement from electrical group) | >Further research into the specific system subsystems and how they work in order to closely identify interfaces with the other groups |
| 12 | 02/03/2023 Thursday | - | >Started laying down concept sketches | >Finalise concept sketches ready to input into the presentation<br>> Perform Pugh’s matrix on concept designs and finalise high level concept |

| | | | | |
|---|---|---|---|---|
| | | | | idea (CAD) ready for the presentation |
| 13 | 03/03/2023 Friday | Lois | **>**Met up with the supervisor for advice on presentation style<br>**>**As a group, went over the presentation mark scheme and highlighted the deliverables | **>**Start creating presentation |
| 14 | 04/03/2023 Saturday | Lois, Afshin | **>**Worked on presentation following the template provided by the MEng group to ensure consistency throughout team presentation | **>**Start creating presentation script<br>**>**Decide on how many people should present<br>**>**Finalise the presentation |
| 15 | 15/03/2023 Wednesday | - | **>**Looked at factors affecting force calculation for the PV mounting structure i.e. wind gusts, as factors affecting maintenance schedules i.e. bird migration and rainfall frequency | **>**Summarise and perform further research on assigned chapters within the PV handbook (provides best practices) |
| 16 | 21/03/2023 Tuesday | - | **>**Presented research we undertook on the assigned PV handbook chapters so everyone has an overall understanding of the PV system | **>**Start report writing + compile interfaces required with the other groups in a single document<br>**>**Familiarise ourselves with PVsyst Software as well as PV*SOL and perform simulations<br>**>**Perform CFD analysis + FEA |
| 17 | 29/03/2023 Wednesday | - | **>**Had an MS Teams meeting where we summarised the respective assigned tasks so as to see if we are on track | **>**Continue exploring with the different software + report writing, ready for Tuesday in order to have more focused discussions |
| 18 | 04/04/2023 Tuesday | Lois | **>**Had an MS Teams meeting to check whether everyone is on track (i.e., encountered difficulties and findings) + keep everyone in the loop | **>**Allocated new work packages to Afshin and Lois (FMEA, wider engineering implications, health & risk + routing and operations list)<br>**>**Continue exploring with the different software + report writing, ready for Monday |
| 19 | 11/04/2023 Monday | Alex, Cameron, Lois | **>**Had an MS Teams meeting to peer review everyone's work | **>**Finalise Calculations, Simulations after which we start report writing |
| 20 | 17/04/2023 | - | **>**Discussed the group's current progress | **>**Dedicate most of the work force on report writing<br>>Perform project costing + look into stakeholders |
| 21 | 02/05/2023 | - | >Discussed progress of report | **>**Complete report write up |

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## Software

- ABAQUS
- Ansys CFX Workbench R2021
- CES Edupack, Granta Design 2021
- Fusion 360, Autodesk
- FTool
- Microsoft ‘Word’, ‘PowerPoint’, ‘Teams’
- PVSyst
- SkyCiv
- Vortex interface

**University of Birmingham**

School of Engineering

# Integrated Design Project 3

## FINAL GROUP REPORT

## Mechanical Engineering

## MSc

| | |
|---|---|
| **Team Number** | 3 |
| **Group Number** | MSc 2 |



| **Student Names** | **ID Numbers** |
|---|---|
| Benjamin Richards | 2025922 |
| Ryan Ennis | 1909845 |
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| Yicheng Chen | 2420422 |
| Jiyao He | 2444706 |
| Zeyu Sun | 2457482 |

| Feedback (Compulsory Section) | | |
|---|---|---|
| Reflecting on the feedback that we have received on previous assessments, the following issues/topics have been identified as areas for improvement: | 1 | More obvious and appropriate figures/tables |
| | 2 | Unify structure throughout document |
| | 3 | Unify equation format throughout document |
| In this assignment, we have attempted to act on previous feedback in the following ways: | 1 | Having no text wrapped around figures/tables |
| | 2 | Utilise navigation tools on word |
| | 3 | Utilise equation function on word |
| Feedback on the following aspects of this assignment (i.e. content/style/approach) would be particularly helpful to us: | 1 | Does the group structure work in your opinion? And is a team role test really necessary? |
| | 2 | Are the style of the tables too informal? |
| | 3 | Does the structure of the report run fluidly? |

# Contents

# i. Executive Summary

The development of an offshore energy island is an infant technology, with definite possibility to provide some of the capacity of national energy demands. However, in the case of point absorbing wave energy converters (PAWEC), the average energy output of a single unit is much smaller when compared to that of an offshore wind turbine and other wave energy converter (WEC) technologies. PAWEC technologies must be scaled to generate enough power to have any impact. Nonetheless, the overwhelming advantages of PAWEC lie within the compatibility of low frequency generation, low impact on marine life, suitability for climate change and opportunity for learning and improvement.

MSc 2 provide a solution to a scalable PAWEC + Hydraulic Motor system for a floating offshore wind farm located within existing offshore wind farms, minimising the impact on marine life (as location is already considered suitable) and maximising the energy density of the offshore wind farm, shown in Figure 1. Combined with the two other proposed forms of sustainable energy production in this report, the PAWEC systems will help to maintain sufficient output energy levels of offshore wind farms by bolstering low output conditions with low frequency wave energy generation. This will minimise the reliance on unrenewable hydrocarbon sources such as gas and oil which have a damaging effect to the climate.

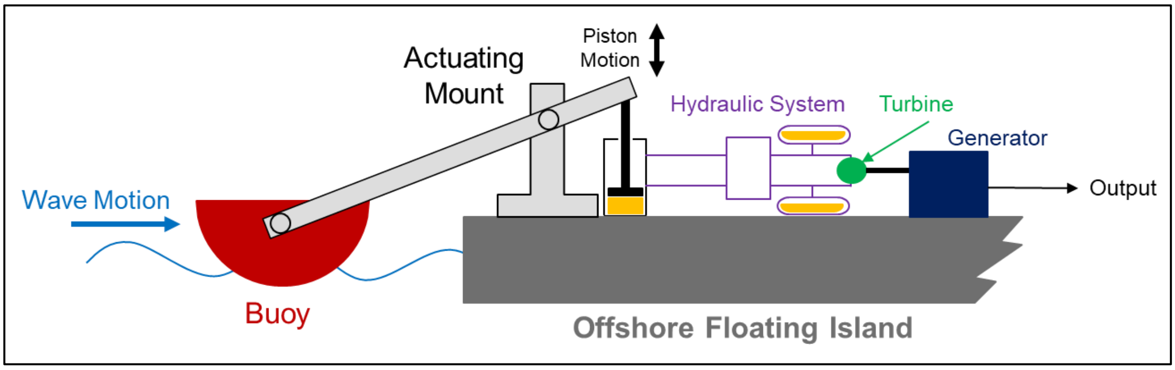



*Figure 1- Simple PAWEC Schematic*

The PAWEC uses an innovative piston hydraulic system connected to a turbine to generate an AC output that can be supplied to a distribution network such as a national grid. The actuating mount acts to convert the vertical displacement of the buoy, due to the wave amplitudes, into a piston which turns the turbine due to closed hydraulic action- allowing generation in positive and negative piston displacement scenarios. The PAWEC system is divided into the following sub-systems:

- Buoy
- Piston
- Actuating Mount
- Hydraulic System
- Turbine
- Generator

Theoretically, one PAWEC unit can produce an average output of 10kW. Scaled across the entire 190 systems of the offshore energy island gives the possibility to provide 1.9GW on average per platform. The main issues with the system are found within maintenance of the hydraulics and the piston end-stop problem which are discussed within the maintenance and technical evaluation sections respectively.

## ii. Project Management

The PAWEC system was split into 6 sub-systems, providing 6 main work packages as shown below in Figure 2. A primary and secondary role structure was established, which aimed to provide support to members with larger primary workloads as well as aiding in the collaboration and integration of the sub-systems. The hydraulic system was immediately identified as a system which needed closer attention and therefore 3 members of the team had a focus on this. The major roles of the project manager was to oversee the interfacing between the sub-systems and other groups, compile the report and prototype generation- while providing support for individual tasks.

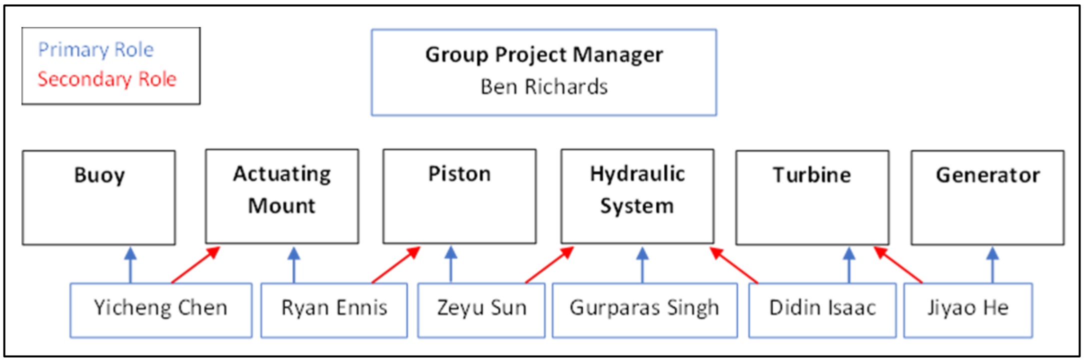



*Figure 2- Group Role Structure*

Roles were decided primarily on personal preference and where members justified their technical abilities lay. Nonetheless, a free online team role analysis was undertaken by every group member to provide a qualitive decision to any conflicting preferences. Figure 3 below shows the results of this analysis.

The group met weekly to discuss personal progress and complete any group wide decisions/work (mostly in the concept development stages). An online Microsoft Teams page was established on a team level, utilising the channels feature to split file sharing per groups and allow group specific chat feeds. An informal chat location was also created on a group level to allow an agile style of management, simple questions, alterations of meeting timings, attendance updates etc. A summary of meeting minutes can be found in Appendix E and a copy of the group level Gantt chart in Appendix D. Alongside these, in Appendix C, there is a breakdown of the final individual contribution.

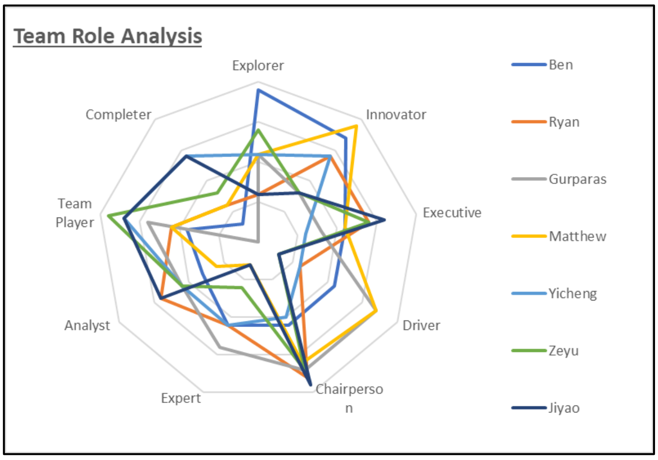



*Figure 3- Team Role Analysis Results*

# 1. Product Design Specification

| Ref | Requirement | Acceptance Criteria | Comment |
|---|---|---|---|
| 1.0 General | | | |
| 1.1 | Compatible with a floating island | - System can oscillate as a separate body from the island. | - Island assumed fixed |
| 1.2 | Minimise setup cost | - <£100,000 | - Costing vs Victoria wind-farm funding. [1] |
| 1.3 | Ease of maintenance | - Use of stock parts where possible<br>- Minimise submerged systems. | |
| 1.4 | Scalability | - Can be used on a 'cluster' scale. | |
| 1.5 | Minimise weight | - <5000kg | |
| 1.6 | Maximise lifespan | - >20years | - Typical wind farm lifespan. |
| 2.0 Performance | | | |
| 2.1 | Maximise Efficiency | - Production = 10,000 Watts | |
| 2.2 | Low frequency compatibility | - Works with minimum amplitude waves | |
| 2.3 | Maximise Energy density | - Minimise size of device | |
| 2.4 | Bi-directionality | - System can generate electricity on both the upwards and downwards stroke of the piston. | |
| 2.5 | Sustainability | - No Scope 2 emissions. | |
| 3.0 Environmental | | | |
| 3.1 | Adaptable to climate change | - Adaptable to sea level rise<br>- Robust enough for harsher weather conditions. | - Confirm with FEA on actuating arm<br>- *turn-off switch* |
| 3.2 | Low impact on marine life | - Only effect already effected/ approved areas. | |
| 3.3 | Bio-compatible materials | - Only use non-toxic materials for sea life. | - Especially hydraulic fluid |
| 4.0 Manufacturing | | | |
| 4.1 | Material Availability | - Use readily available material for the location. | |
| 4.2 | Corrosion resistance | - Use of a corrosion resistant material due to environment. | |
| 4.3 | Minimise Scope 1 emissions | - Where possible, use sustainable manufacturing processes. | |
| 5.0 Business Case | | | |
| 5.1 | Maximise ROI | - ROI > 4.47% | - [2] |
| 5.2 | Possibility for improvement | - Minimise bespoke parts/sizes | |
| 5.3 | EOL | - Use recyclable materials<br>- Minimise use of thermosetting plastics<br>- Minimise Scope 3 emissions | |

# 2. Concept Selection

## 1.1. PTO System

In order to harvest energy from waves, the WEC must be combined with a power take-off (PTO) method to allow the conversion of kinetic energy from the waves into a useful electrical output. Table 1, below, shows the analysis of the 5 PTO systems compatible with the PAWEC system chosen on a team level. Piezoelectric technology was also discussed on a team level as an innovative method of power generation. However, this was found to be impractical as the energy density of piezoelectric materials are too low for power generation of this scale. Criteria were selected based on the 10 most influential factors from the PDS and weighted accordingly in a selection matrix. This allowed a quantitative result for the most suitable PTO system.

*Table 1- PTO Concept Selection Matrix*

| Selection Criteria | Weighting (%) | Triboelectric | | Hydraulic Motor | | Pneumatic Turbine | | Electrical Drive | | Direct Mechanical | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | score/10 | weight | score/10 | weight | score/10 | weight | score/10 | weight | score/10 | weight |
| Floating Island Compatibility | 15 | 7 | 1.05 | 8 | 1.2 | 8 | 1.2 | 1 | 0.15 | 8 | 1.2 |
| Efficiency | 15 | 9 | 1.35 | 9 | 1.35 | 5 | 0.75 | 10 | 1.5 | 9 | 1.35 |
| Low Frequency Compatibility | 10 | 10 | 1 | 8 | 0.8 | 5 | 0.5 | 3 | 0.3 | 8 | 0.8 |
| Impact on Marine Life | 10 | 5 | 0.5 | 4 | 0.4 | 2 | 0.2 | 8 | 0.8 | 6 | 0.6 |
| Scalability | 10 | 2 | 0.2 | 8 | 0.8 | 8 | 0.8 | 7 | 0.7 | 8 | 0.8 |
| Climate Change Adaption | 10 | 8 | 0.8 | 6 | 0.6 | 6 | 0.6 | 2 | 0.2 | 6 | 0.6 |
| Ease of Maintenance | 10 | 1 | 0.1 | 3 | 0.3 | 2 | 0.2 | 6 | 0.6 | 2 | 0.2 |
| Energy Density | 10 | 5 | 0.5 | 8 | 0.8 | 6 | 0.6 | 4 | 0.4 | 8 | 0.8 |
| Setup Cost | 5 | 8 | 0.4 | 9 | 0.45 | 3 | 0.15 | 2 | 0.1 | 3 | 0.15 |
| Opportunity for improvement | 5 | 9 | 0.45 | 6 | 0.3 | 2 | 0.1 | 2 | 0.1 | 3 | 0.15 |
| Total | 100 | 64 | 6.35 | 69 | 7 | 47 | 5.1 | 45 | 4.85 | 61 | 6.65 |

As can be seen, the 'Hydraulic Motor' system was deemed most appropriate, which converts the kinetic energy into electrical by the use of a hydraulic motor. Nevertheless, this bought rise to challenges in hydraulic fluid impact on marine life and maintenance, as well as the end-stop issue, which are discussed later in the technical evaluation.

## 1.2. PAWEC Configuration

Physical implementation and fixation of a PAWEC and hydraulic PTO to the main body of the platform can be configured in various methods. Challenges arose when considering fixation to an island that was floating and not fixed, due to most current research considering only a fixed island. 4 methods of fixation were considered, Appendix F, and selection was made based on 4 main criteria:

1. Complexity of floating island integration
2. Limiting submerged components (to limit corrosion and submerged hydraulics)
3. Ease of access for maintenance
4. Preventing end stop problem.

From this, a group-wide decision was made to proceed with configuration 4. Figure 4 below gives a basic schematic of the WEC + PTO system and its fixation method.

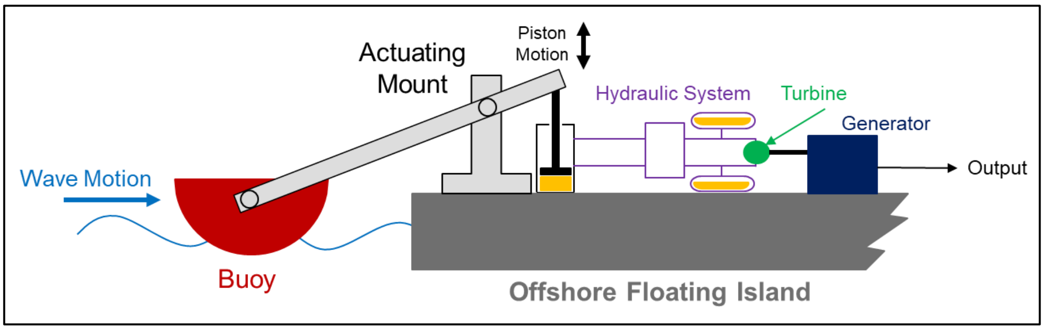



*Figure 4-Basic PAWEC Schematic*

# 3. Technical Evaluation & Validation

## 3.1. Assumptions

The following section outlines and justifies the assumptions made in order to model the proposed PAWEC solution. Unless stated otherwise, the assumptions are as below:

- Rigid platforms: in order to calculate the fluctuations in the PAWEC system relative to the platforms- the assumption that the platforms were stationary and rigid was made. This was deemed justifiable due to the high weight of the platforms making their vertical displacement oscillate very little in low wave amplitude conditions that the PAWEC will operate in.
- Constant Buoyancy: in order to calculate the power output of the buoy, the buoy was assumed to be submerged at a constant volume through the wave phase. In reality this would not be the case. However, the mathematics to calculate this variation was deemed outside the scope of this project.
- Isentropic Generator: The thermodynamic changes between the generator are assumed to be isentropic which is a realistic condition based on the system's cycle time [3]
- Waves are sinusoidal in nature.
- Masses act out of COM for stress calculations.

## 3.2. Buoy Shape

Buoyancy is the ability of an object to float in a fluid- saltwater in this case. In the maritime industry, buoys are heavily relied upon to navigate hazards, define safe areas such as shipping lanes and provide reference points. Although this use case is for the conversion of energy, the shape of buoys has been heavily [4] [5] [6] [7] [8]and will be used to justify design decisions.

Two buoy shapes have been considered against their respective wave power absorption properties:

- Conical (120° apex)
- Hemispherical

As shown In Figure 5 below, there is no significant difference in the energy absorption capacity of the two shapes. However, the conical buoy provides slightly better performance than the hemispherical buoy. Therefore, the conical shape is chosen.

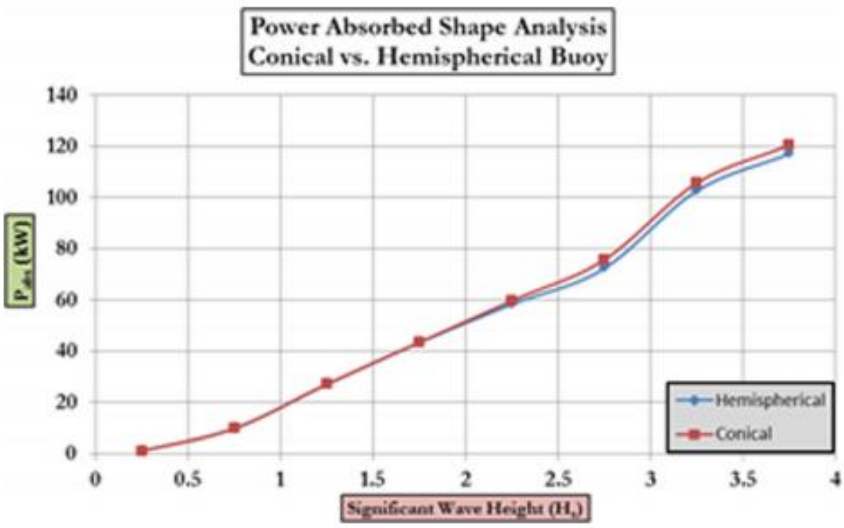



*Figure 5- Conical vs Hemisphere Buoy Power [5]*

The conical shape was then investigated against varying drafts. Results were obtained for drafts of 2, 2.5 and 3m, shown in Figure 6.

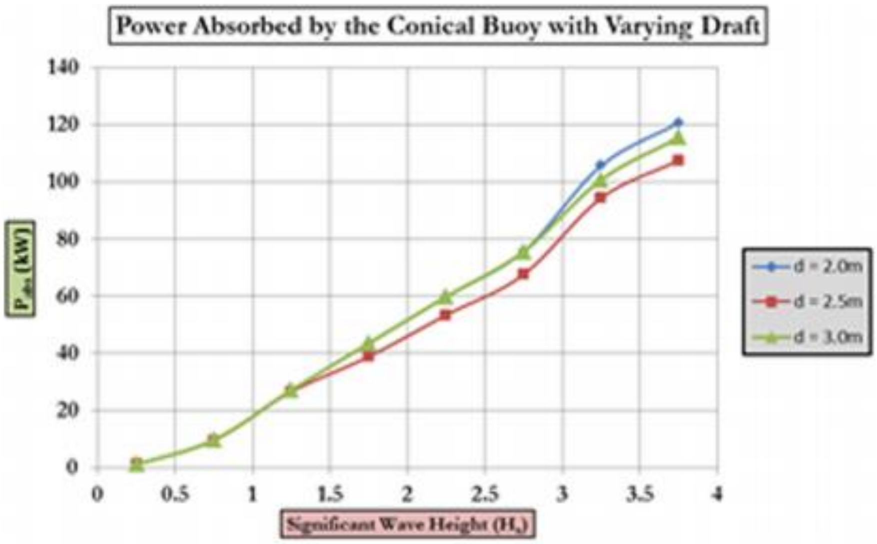



*Figure 6- Conical Buoy Draft Size vs Power Absorbed [5]*

Approximately, the buoy drafts had very little effect on the absorption of power, especially with drafts of 2 and 2.5m up to significant wave heights of 3m. However, due to the slight advantage of 2m drafts at higher significant wave heights, this draft was chosen.

Finally, the buoy diameter was investigated, ranging from 1.5m to 6.5m, shown in Figure 7.

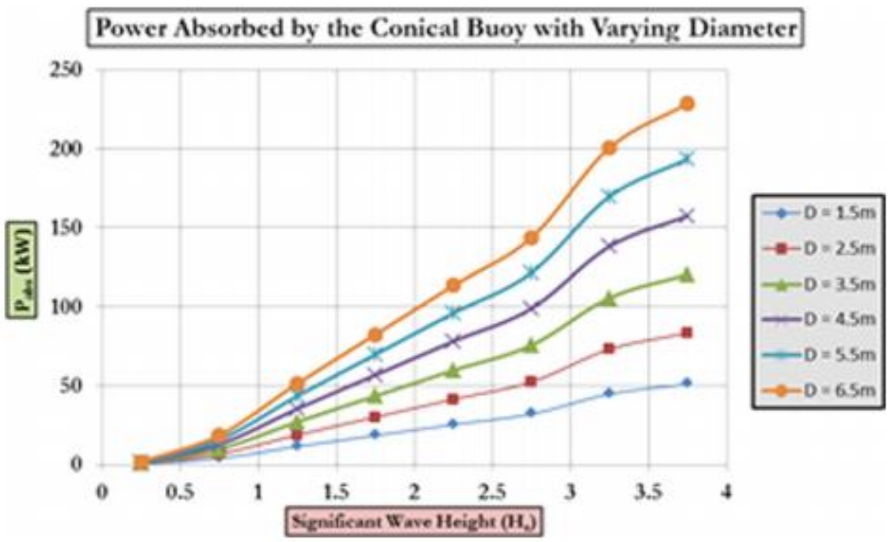



*Figure 7- Conical Buoy Diameter vs Power Absorbed [5]*

Although the max diameter was set at 6.5m, with the diameter and power absorption increasing proportionally, it was felt that a diameter over 3.5m was difficult to implement in this use case. This is due to large buoys being difficult to manufacture, expensive to manufacture and unsuitable for a floating platform.

Therefore, the initial geometry of the chosen buoy is presented below in Figure 8. This shape and size is also justified by a similar design choice in [7].

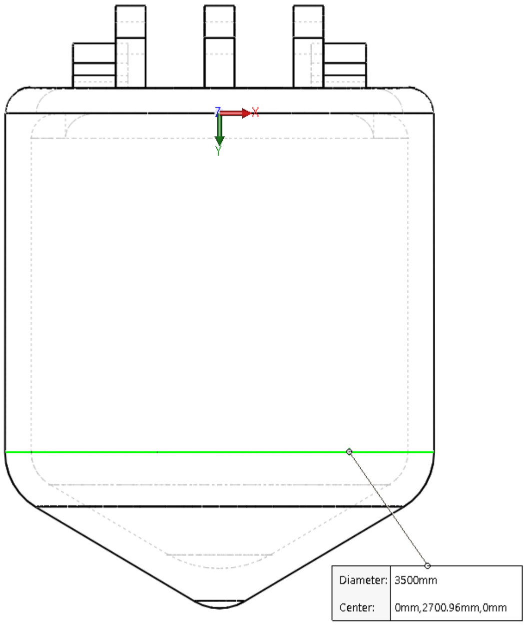



*Figure 8- Initial Conical Buoy Cross Section*

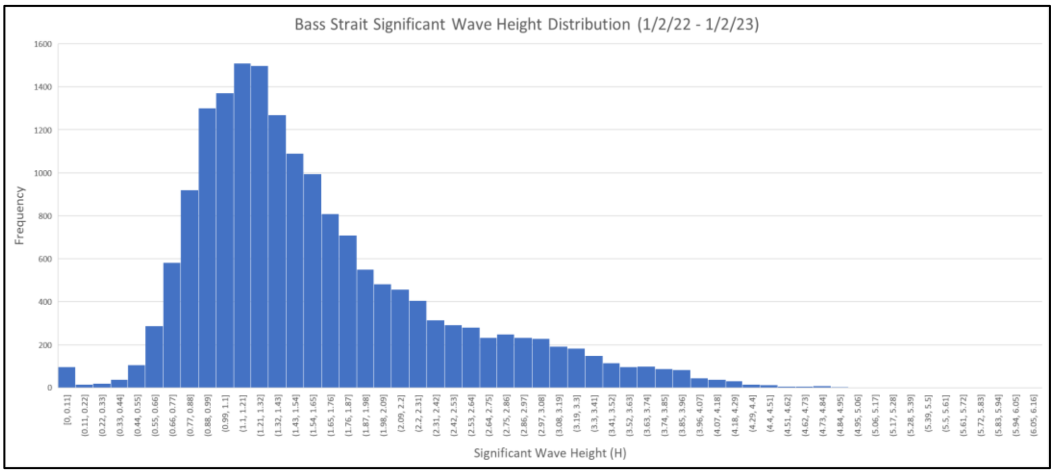
### 3.3. Actuating Mount

The Actuating Mount, Figure 11, consists of 3 main parts:

- Columns
- Arms
- Locking mechanism.

This configuration is effective in keeping key components out of the water thus preventing corrosion and limiting impact to marine life. Additionally, this configuration enables climate change adaptation as the components will not be subjected to changes in ocean acidification and increased ocean temperatures.

Wave data from the bass strait region between 1/2/22 – 1/2/23 was obtained [9] [10] and analysed. The histogram in Figure 9 shows the frequency of different significant wave heights, defined as the average height of the highest 1/3 of waves in a given time period, with the average significant wave height being 1.6m. The significant wave height can be used to approximate the most frequent and maximum expected wave heights by halving or doubling it respectively [11] [12]. Since the maximum wave height can occur up to 3 times every 24 hours [11] it was selected as the minimum vertical displacement design criteria (with a safety factor of 1.72).



### 3.3.1. Design Methodology

The maximum vertical distance travelled by the buoy is half the maximum wave height (1.6m in this instance). After considering the safety factor, the buoy is designed to travel a maximum vertical distance of 2.75m via the actuating mount rotating through an angle of 45 degrees. The arm length is calculated as 5m with the pivot point at 3.9m relative to the buoy as shown in Figure 10. From this, a minimum cylinder stroke length of 0.78m during operation is required.

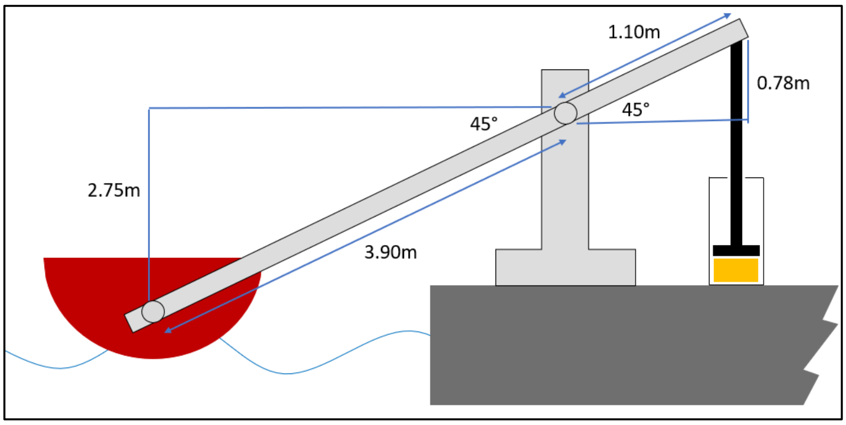



*Figure 10- Actuating Mount Problem Diagram*

#### 3.3.1.1. Columns

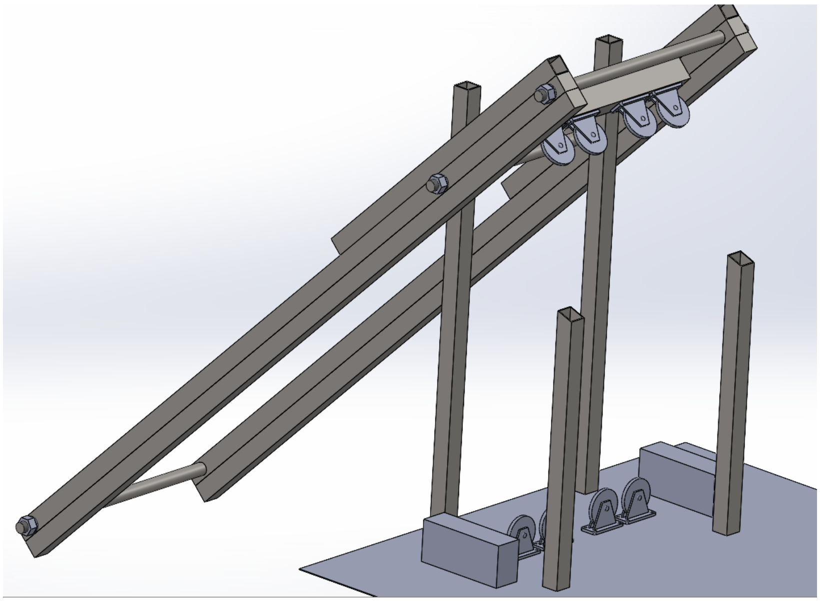
The height of the column's and the pivot point are influenced by the maximum vertical travel of the buoy, the depth of the floating island above sea level (1m, Meng Civil) and clearance for the piston. The columns will be welded to the floating island via 5mm steel plates lining the surface of the island, as informed. Figure 11 shows the column design.

#### 3.3.1.2. Arms

Each arm consists of a 100mm square bar and two reinforcement bars welded above and below. It connects to the PAWEH system through either rods or square bars as shown in Figure 11and secured with M60 nuts or by welding, dependant on the joint.

#### 3.3.1.3. Locking Mechanism

The locking mechanism uses two winches and series of pulleys to pull the arms down thus lifting the buoy up as shown in Figure 11. This is useful in preventing damage of the system by avoiding waves of heights up to 4.8m (which accounts for almost all of the wave height distributions in Figure 9) and is useful during maintenance. The winch brake is then activated to hold the arms in place. Supporting pillars either side of the arms provide support and prevent the arms from over rotating. The locking mechanism increases the minimum required piston stroke length to 1.15m.



*F*

### 3.3.2. Material Selection

EduPack (Level 3) was used to select the most suitable materials for the actuating mount components. Table 2 outlines the selected material criteria. Fatigue strength and water durability are seen as the most important criteria, due to the cyclic loading and wet nature of the use case. Additionally, weldability was important as the design incorporates several welded components.

*Table 2- Actuating Mount Material Selection Criteria*

| Criteria | Min Requirement |
|---|---|
| Material Family | Metal (ferrous or non-ferrous) |
| Youngs Modulus (GPa) | 100 |
| Yield Strength (MPa) | 400 |
| Fatigue Strength (at $10^7$ cycles) | 200 |
| Weldability | Good, Excellent |
| Water Durability (fresh & salt) | Excellent |

As shown in Figure 12, stainless steel is far superior to other materials due to its high fatigue strength at a low cost, whilst meeting the other required criteria.

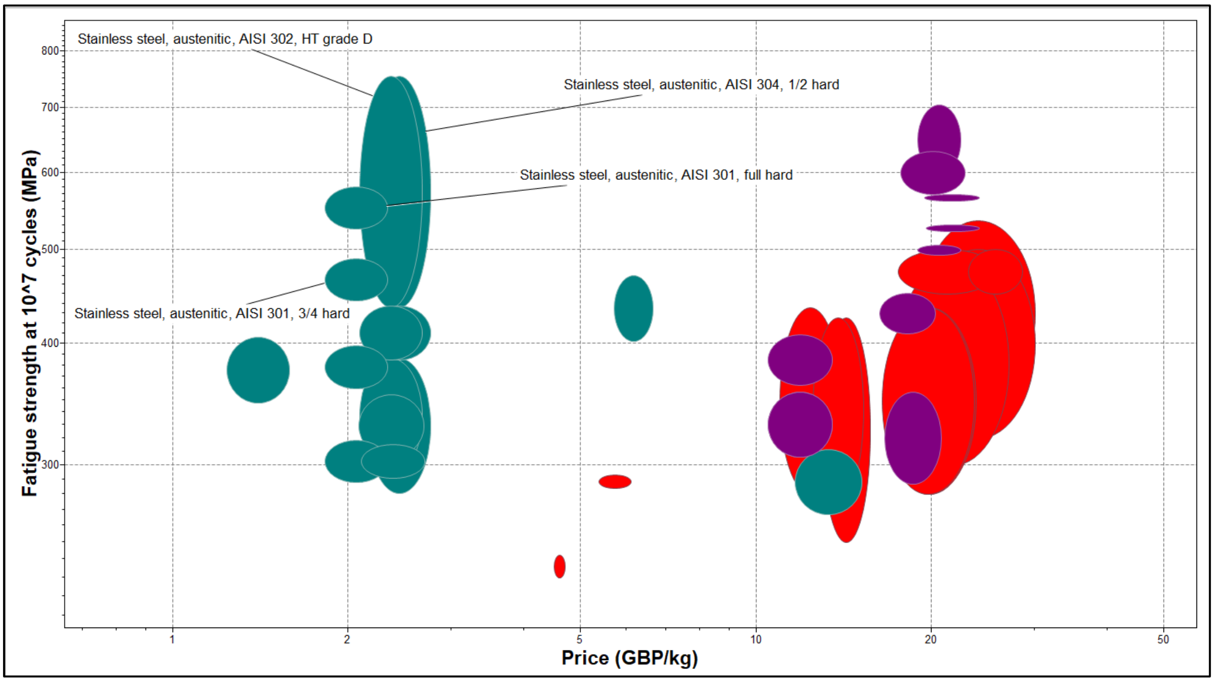



*Figure 11- EduPack Material Selection Ashby Plot*

Stainless Steel 304 was selected due to its common use and wide availability and will be used for all key components of the actuating mount. Table 3 outlines the key properties of the material.

*Table 3- Stainless Steel 304 Properties*

| Mechanical Property | Value |
|---|---|
| Density ($kg/m^3$) | 8000 |
| Youngs Modulus (GPa) | 193 |
| Yield Strength (MPa) | 207 |
| Fatigue Strength (at $10^7$ cycles) (MPa) | 436-753 |

### 3.3.3. Calculations

#### 3.3.3.1. Winch

Figure 13 shows the free body diagram (FBD) for the arm when the winch locking mechanism is activated. As a minimum, the winch is required to support the mass of the buoy and the arms. Taking moments about the pivot point P with the parameters outlined in Table 4 give a minimum force of 157.6kN.

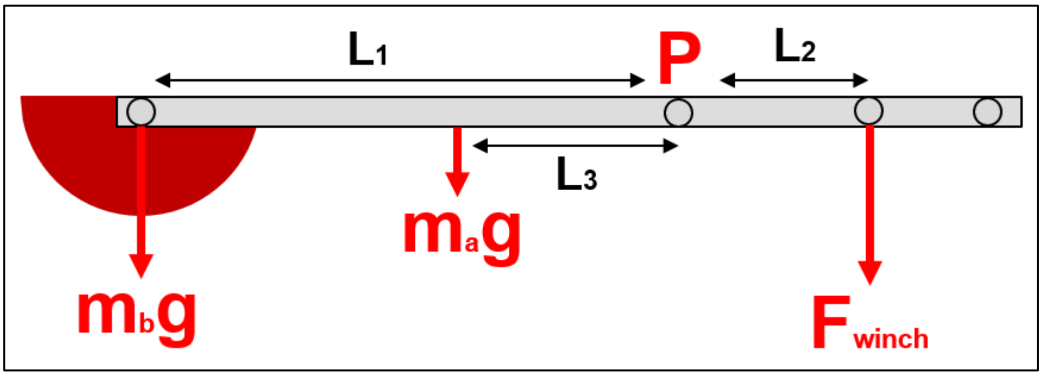



*Figure 12- Winch Calculations FBD*

*Table 4- Winch Calculation Parameters*

| Parameter | Value |
|---|---|
| $m_b$ | 2000kg |
| $m_a$ (2 arms) | 1600kg |
| $L_1$ | 3.9m |
| $L_2$ | 0.6m |
| $L_3$ | 1.23m |

Splitting the load across two winches and using a series of 4 pulleys reduces the required winch force to 19.7kN. Kartt 9500lbs 42.3kN 12v Electric Winch with Synthetic Rope [13] was selected due to its high maximum pulling force of 42.3kN providing a safety factor of 2.14. Additionally, the winch can be operated either wired or wirelessly.

#### 3.3.3.2. Structural: Column

Equation 1 can be used to calculate the critical load on the columns which would induce buckling. With the calculated critical load being 319kN and the maximum force exerted on the column is 198kN (according to the forces in Figure 13), the factor of safety is 1.61 deeming the column safe from buckling.

$$Equation\ 1:\ \ P_{Critical} = \frac{\pi^2 EI}{4L^2} = \frac{\pi^2 * 193E09 * 4.18E-06}{4 * 2.5^2} = 319kN$$

#### 3.3.3.3. Structural: Bending Deflection

The bar and rod connecting to the locking mechanism and buoy respectively were anaylsed to assess the bending deflection where Figure 14 represents the FBD for both.

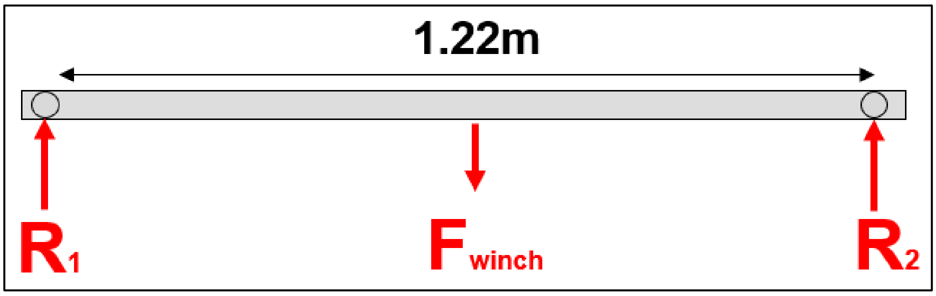



*Figure 13- Bending Deflection FBD*

Equation 2 shows the bending moment equation for the locking mechanism bar.

$$Equation\ 2:\ \ M = R_1 x - F_{winch}[x - 0.61]$$

Integrating Equation 3 twice gives Equation 3x which can be used to find the maximum deflection of the beam (where A is a constant obtained from the integration).

$$Equation\ 3:\ \ EI\frac{d^2v}{dx^2} = -M$$

$$Equation\ 3x:\ \ v = \frac{-1/6 * R_1 x^3 + Ax}{EI} = \frac{-1/6 * 78.8E03 * 0.61^3 + 14.7E03 * 0.61}{193E09 * 3.02E-05}$$
$$= 0.97mm$$

Repeating this for the buoy rod with the force of the buoy gives a deflection of 1.63mm. Although larger, as a rule of thumb, the maximum acceptable deflection for beams of this length is 3.75mm therefore making both acceptable [14].

#### 3.3.3.4. Structural: Bending Stress

Using Equation 2, the maximum bending moment experienced by the winch bar and buoy rod are 48.1kNm and 5.98kNm respectively, Figure 15.

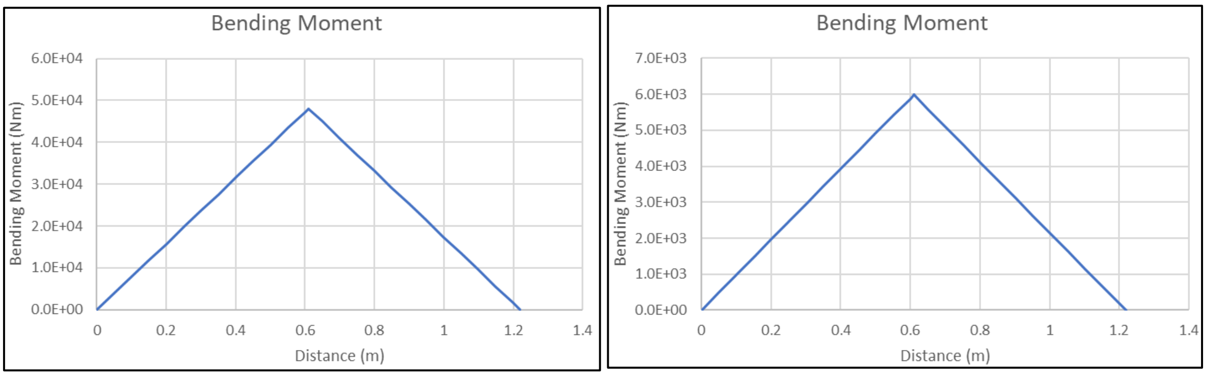



*Figure 14- Bending Moment Results*

Equation 4 can be used to calculate the maximum bending stresses in both where M is the maximum bending moment, y is the distance to the neutral axis, and I is the second moment of area. With a yield strength of 207MPa, this gives safety factors of 1.97 and 2.33 respectively.

$$Equation\ 4:\ \ \sigma = \frac{My}{I}$$

$$\boldsymbol{\sigma = \frac{48.1E03 * 0.07}{3.20E-05}}$$
$$\boldsymbol{\sigma = 150.1MPa}$$

$$\boldsymbol{\sigma = \frac{5.98E03 * 0.07}{2.36E-06}}$$
$$\sigma = 88.85MPa$$

#### 3.3.3.5. Piston Force

A FBD of the forces acting on the beam at its maximum operating condition is shown in Figure 16. Where: $F_w$ = Wave force, $F_b$ = Buoyancy force, $m_bg$ = Weight of buoy, $m_ag$ = weight of arms, $F_p$ = Force acting on piston.

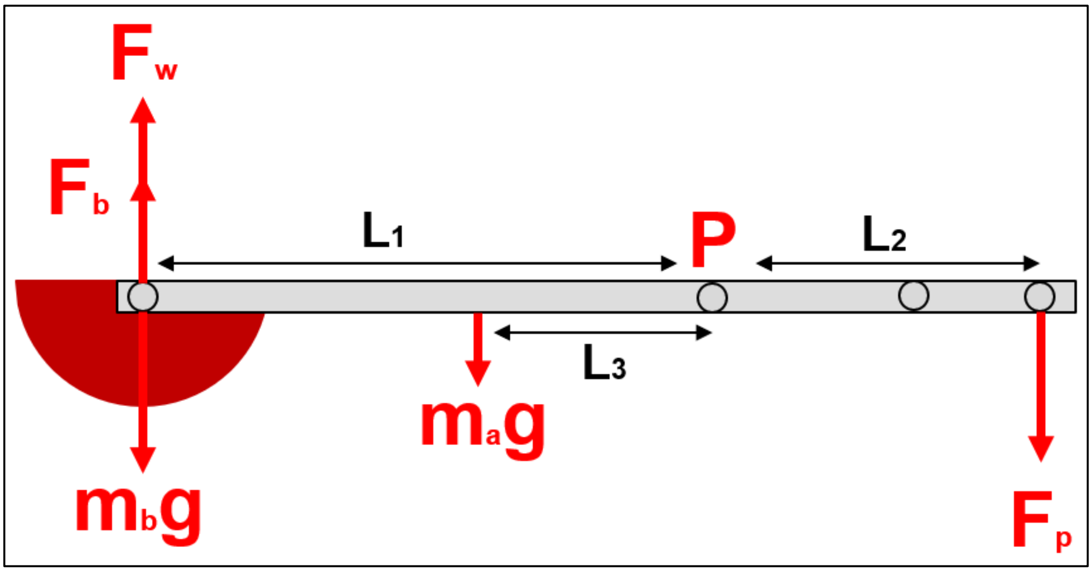



*Figure 15- FBD for Resolving for $F_p$*

Due to the complicated nature of modelling ocean wave behaviour, several assumptions have been made to simplify the problem as summarised in Table 5.

*Table 5- Assumptions in Force Calculations*

| Assumptions |
|---|
| All wave energy is transferred to the PAWEH system at the buoy |
| Wave force is equally distributed between each arm |
| Negligible friction losses in the system |

Equation 5 can be used to calculate the energy of a wave [15] [16], which considers the potential and kinetic energy of the wave, where: g is the acceleration due to gravity, ρ is the density of seawater, a=amplitude of the wave (half the wave height assuming sinusoidal wave) and A is the area of the wave (or area of the buoy in contact with the water).

$$Equation\ 5\colon\ \ E_w = \frac{1}{2} g\rho a^2 A\ (J)$$

Since the wave is doing work on the buoy, the force of the wave can be calculated by work= force*distance. Substituting and rearranging gives Equation 6 for the wave force.

$$Equation\ 6\colon\ \ F_{w,max} = \frac{1}{2} g\rho aA = \frac{1}{2} * 9.81 * 1025 * 1.6 * 9.62 = 77.4kN$$

Assuming the buoy always contacts the water, it can also be assumed that the buoyant force ($F_b$) is equal and opposite to the weight of the buoy. Thus, the force acting on the piston ($F_p$) can be calculated according to Equation 7(when including the mass of the arms).

$$Equation\ 7:\ \ F_{P,max} = F_{w,max}\left(\frac{L_1}{L_2}\right) - F_a\left(\frac{L_3}{L_2}\right) = 77.4E4 * \left(\frac{3.9}{1.1}\right) - 1600 * \left(\frac{1.4}{1.1}\right) = 272kN$$

This system acts to multiply the wave force approximately 3.5 times. A summary of the actuating mount specification can be seen in Table 6, below.

*Table 6- Actuating Mount Parameters*

| Characteristic | Value |
|---|---|
| Typical Force Output (kN) | 66.7 |
| Maximum Force Output (kN) | 272 |
| Force Multiplier | 3.5 |
| Total System Mass (t) | 2.16 |
| Operating Range (degrees) | 45 |
| Required winch force (per winch) (kN) | 157.6 |

### 3.3.4. Validation

ANSYS Workbench was used to calculate the maximum deflection and equivalent Von Mises stress of each arm when loading was maximum. The boundary conditions were applied as per Figure 16 and Table 7, outlines the loads used.

*Table 7- FEA Load Conditions*

| Load | Value |
|---|---|
| Force of buoy (N) | 19620 |
| Force of winch (N) | 157614 |

Figure 18 shows there is a maximum deflection of 11mm. According to [14] the maximum allowable deflection is 15.4mm therefore making this acceptable. Figure 17 shows the Von Mises stress plot. Despite the stress concentration, the overall maximum stress experienced is lower than yield strength thus giving a safety factor of 1.3. Since the locking mechanism will not be used frequently, this is not of concern.

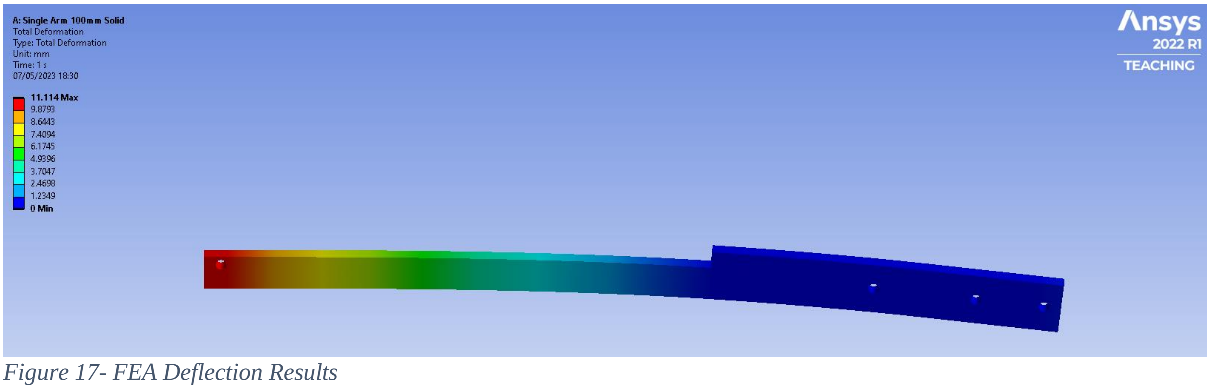



*Figure 17- FEA Deflection Results*

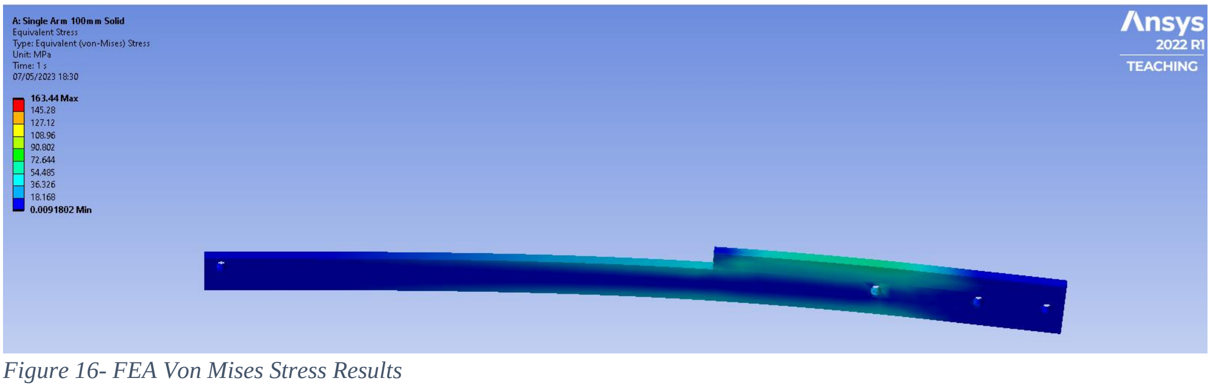



*Figure 16- FEA Von Mises Stress Results*

### 3.4. Piston Selection

For our project, we plan to use a double acting hydraulic cylinder. As shown in Figure 19, this is a 3D image of our model. The model mainly consists of 7 parts:

1. Cylinder tub
2. Piston
3. Rod
4. Fluid nozzle
5. Sealing cap
6. Connector
7. Pedestal

The piston shall be outsourced via Ramko [17], with the Connector bespoke manufactured.


*Figure 18- Piston CAD with Labelled Parts*

#### 3.4.1 Interfaces

The hydraulic cylinder is connected to the actuating mount through the connector.
The piston divides the cylinder tube into two chambers, and it is equipped with a seal to draw the fluid from one chamber to the other.
The rod is attached to the piston, and it transmits the force from the actuating mount to the piston that move the fluid.
The sealing cap can prevent the fluid from leaking out of the cylinder and remove dust and dirt from the rod.
The pedestal can support and fix the cylinder.

#### 3.4.2 Mechanism

When the piston moves downwards, the fluid will flow into the upper chamber from the upper nozzle, while the fluid in the lower chamber will flow out from the lower nozzle under the compression of the piston. When the piston moves upwards, the situation is opposite.

Compared with the single acting hydraulic cylinders, the double acting hydraulic cylinders undoubtedly have higher work efficiency. Thanks to the design of the upper and lower fluid nozzles, the fluid can be in circulation flow when the piston moves up and down, making energy output more continuous and stable. However, they have a larger volume, which means that more money needs to be spent on manufacturing and maintenance [18] .

#### 3.4.3 Material Selection

Due to literature review, Aluminium alloy A380 was chosen as the material for the hydraulic cylinder. It has the following advantages [19] [20] [21]:

- Lightweight: it is a lightweight alloy, which makes it an ideal material for applications where weight is a concern.

- Good Strength-to-Weight Ratio: it has a high strength-to-weight ratio, which means it can handle heavy loads without adding unnecessary weight to the overall structure.
- Excellent Machinability: it is easy to machine and can be shaped into a variety of complex shapes, making it an excellent choice for casting applications.
- Corrosion Resistance: it is highly resistant to corrosion, making it ideal for applications where the material will be exposed to harsh environments or chemicals.
- Good Thermal Conductivity: it has good thermal conductivity, which makes it an excellent choice for applications that require efficient heat transfer.
- Cost-effective: Compared to other materials such as steel, it is relatively inexpensive, making it an attractive option for budget-conscious applications.
- Recyclable: it is a recyclable material, which means that it can be reused, reducing the environmental impact of its production and use.
-

The parameters of the chosen A380 Aluminium alloy are shown below in Table 8 [22]. These parameters were taken from EduPack and used to form the piston calculations.

*Table 8- Aluminium Alloy A380 Parameters*

| Parameter | Value |
|---|---|
| Cost | 1.59~1.84 GBP/kg |
| Density | (2.71~2.77) *10^3 kg/m^3 |
| Young’s modulus | 69.6~72.4 GPa |
| Yield strength | 152~168 MPa |
| Tensile strength | 324~356 MPa |
| Compressive strength | 152~168 MPa |
| Poisson’s ratio | 0.322~0.338 |
| Thermal conductivity | 104~113 W/(m*K) |

### 3.4.4 Model Calculation

Figure 20 below shows a cross-section of the piston to be used as reference for the calculations below.

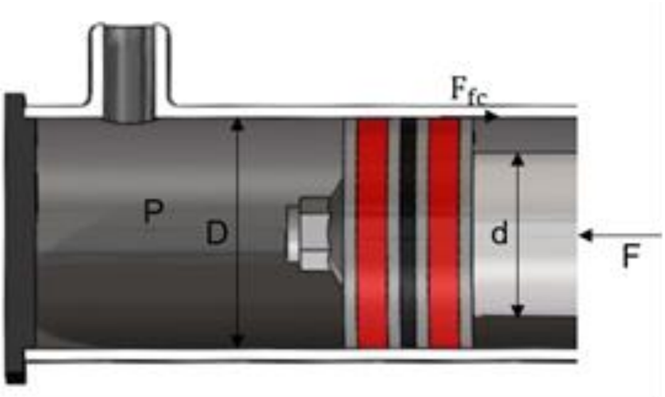



*Figure 19- Piston Reference Geometry/Forces*

[18]

Equation 8, below, is used to calculate the required diameter of the piston. Where, $F_{fc}$ = friction force (N) between the cylinder and piston.

$$Equation\ 8:\ \frac{\pi * D^2}{4} * P = F - F_{fc}$$

Since the exact value of friction force is not easy to obtain, the mechanical efficiency of hydraulic cylinder is often used to estimate the friction force as shown below. Where, $\eta$m = mechanical efficiency.

$$Equation\ 9:\ F_{fc} = F * (1 - \eta_m)$$

Generally, $\eta$m=0.9-97. Therefore, for our project, P=350 bar, F = 272 kN, $\eta$m = 0.95, so D can be calculated from a rearrangement of Equation 8 [23]:

$$Equation\ 10:\ D = \sqrt{\frac{4 * (F - F_{fc})}{\pi * P}} = \sqrt{\frac{4 * 272 * 10^3 * 0.95}{3.1416 * 350 * 10^5}} = 96.95\ mm \approx 100\ mm$$

The relationship between D and d is expressed below in Equation 11, for when the maximum pressure exceeds 7 MPa [24],

$$Equation\ 11:\ d = \frac{7 * D}{10} = 70mm$$

Concerning the cylinder wall thickness, usually 5% of the piston diameter is taken as the wall thickness = 5 mm [25].

The stroke length is determined by the maximum vertical displacement of the actuating mount. As seen in section 3.4.3, we know that the maximum displacement of actuating mount is 1150mm. Therefore, the stroke length should be selected as 1200mm, in order to comply with ISO standards [24].

In the interest of verifying the strength of the rod, Equation 12 is used [26]. Where, $d_{min}$ is the minimum diameter of the rod, F is the force from actuating mount, n is a safety coefficient and $\sigma_s$ is the yield strength of material. From the previously established Aluminium alloy A380 values, $\sigma_s$ =160Mpa. The safety coefficient is usually around 1.6 to 2.5, we take the n = 2.

$$Equation\ 12:\ d_{min} = 2 * \sqrt{\frac{F * n}{\pi * \sigma_s}} = 2 * \sqrt{\frac{272 * 10^3 * 2}{\pi * 160 * 10^6}} = 65.79\ mm$$

Therefore, d = 70mm > $d_{min}$ = 65.79mm, so the strength of the rod is enough, with a safety factor of 2.

## 3.5. Hydraulic System

### 3.5.1. Components

The hydraulic system comprises various components that are designed to distribute and effectively control the flow of the hydraulic fluid throughout the system. The main components include:

1. double acting equal area hydraulic piston
2. check valves
3. hydraulic displacement motors

4. generator
5. pressure accumulators (ensure smooth flow of hydraulic fluid throughout the system)

### 3.5.2. Mechanism

The repetitive heave motion of the buoy drives the double acting piston within a cylinder to pump the hydraulic fluid through a rectification circuit to provide a unidirectional flow through a hydraulic motor. The fluid is pumped through a set of four check valves to ensure that it consistently flows through the hydraulic motor in the same direction, regardless of the buoy's motion direction. A high pressure accumulator is positioned at the hydraulic motor's inlet while a low pressure is installed near the outlet [27]. The pressure difference between the two accumulators propels a turbine which is linked to a generator. The accumulators also store energy in a way that a flywheel might so that in conditions of low amplitude/frequency wave conditions when the sea is calm, the power remains consistent. An additional accumulator is added to maintain a minimum pressure of about 10bar and avoid cylinder cavitation. Pressure relief valves are placed to safeguard the hydraulic components.

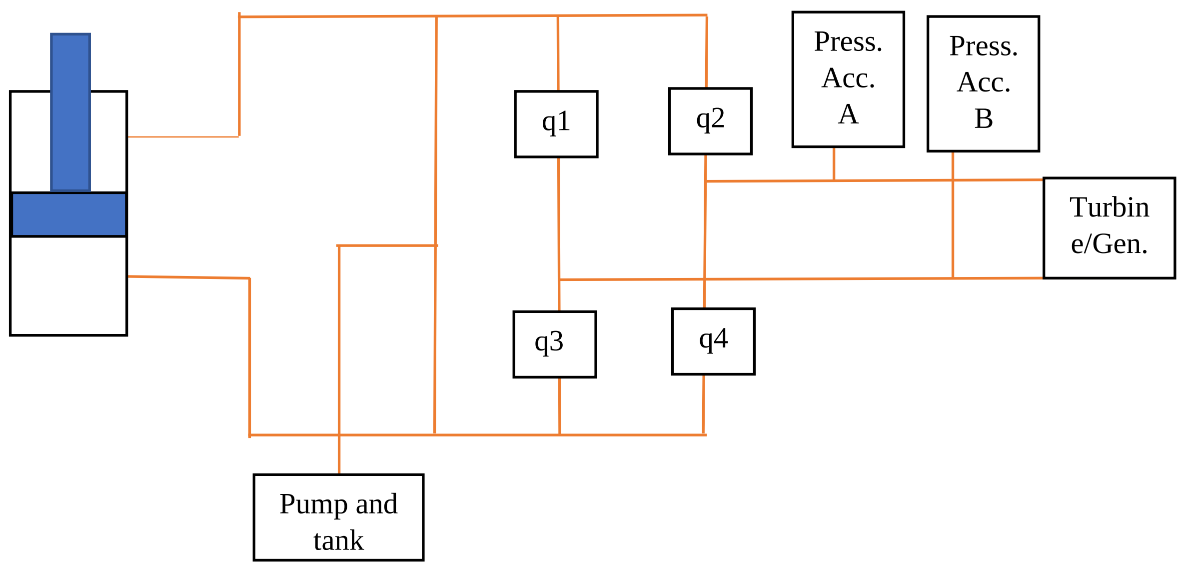



*Figure 20- Basic Hydraulic System Schematic*

### 3.5.3. Governing Equations

For simulating the conditions of the buoy, the below governing equation was used:

$$Equation\ 13:\ \ m\ddot{x} = f_h(t) + {}_{\varphi}(t)$$

Where, m is the mass of the buoy, $f_h$ is the wave force and φ is the mechanical force function.

The wave force $f_h$ is given in Equation 14 as the sum of the incident wave force, radiation force and the hydrostatic buoyancy force.

$$Equation\ 14:\ \ f_h = R_e(F_e e^{\omega t}) + (-A\omega\ddot{x} - B\omega\dot{x}) + \rho g\pi r^2 x$$

Where, A is the added mass coefficient and B is the damping coefficient.
The pressures in the two piston chambers were given by:

$$Equation\ 15:\ \ \int A_p\dot{x} - q_1 - q_2 = \int \frac{V_1}{B_0}\frac{dp_1}{dt}$$

$$Equation\ 16:\ \ \int A_p\dot{x} - q_3 - q_4 = \int \frac{V_2}{B_0}\frac{dp_2}{dt}$$

Where, V is the volume of the chamber and B is the Bulk modulus of the fluid and $q_1$, $q_2$, $q_3$ and $q_4$ are the flows at the 4 different check valves in the circuit [28].

The flow rates are in turn given by the following 4 equations,

$$Equation\ 17:\ \ q_1 = \begin{cases} 0, & P_1 > P_B \\ -K\sqrt{P_B - P_1}, & P_B \geq P_1 \end{cases}$$

$$Equation\ 18:\ \ q_2 = \begin{cases} 0, & P_A > P_1 \\ K\sqrt{P_1 - P_A}, & P_1 \geq P_A \end{cases}$$

$$Equation\ 19:\ \ q_3 = \begin{cases} 0, & P_2 > P_B \\ -K\sqrt{P_B - P_2}, & P_B \geq P_2 \end{cases}$$

$$Equation\ 20:\ \ q_4 = \begin{cases} 0, & P_A > P_2 \\ K\sqrt{P_2 - P_A}, & P_2 \geq P_A \end{cases}$$

Where $P_x$ denotes the pressure in accumulator A, B and the piston chamber 1 and 2 respectively. These equations were then used to model the waves and the flow through the hydraulic pipes.

### 3.5.4. Simulink Model

#### 3.5.4.1. Model Setup

The hydraulic circuit was then modelled in Simulink® [29], to simulate the wave pattern and the flow inside the pipes [30].

A schematic of the hydraulic circuit set-up for the system can be seen in Figure 22 below. The wave input was given to the ideal force block which was then dampened with a resistance and a mass to simulate the friction or the inconsistencies in the input. Some of the fluid might leak out and hence cause problems in the cylinder and cause cavitation. To prevent this, a boost pump is added to keep adding the fluid back into the circuit.

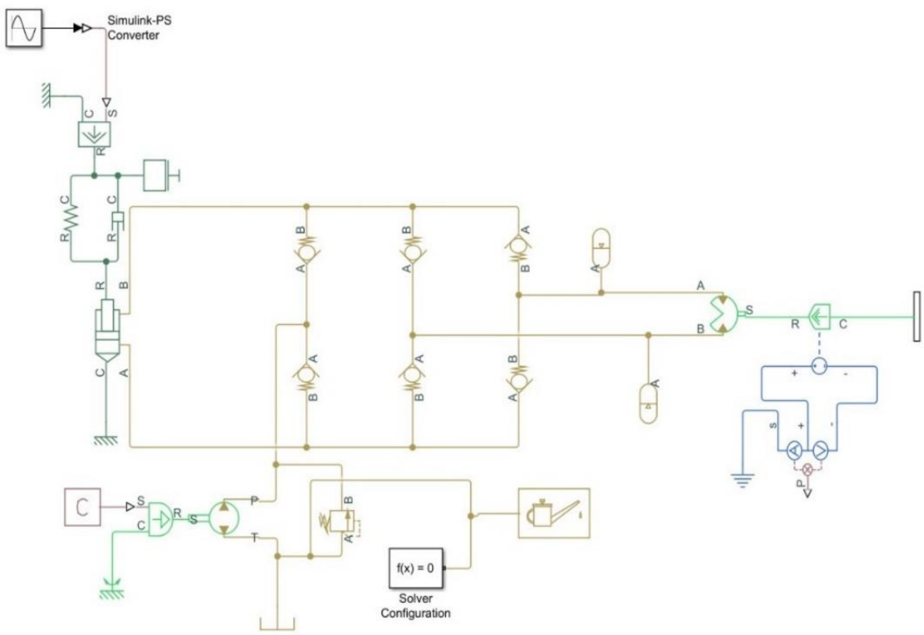



*Figure 21- Hydraulic System Simulink Model*

*Table 9- Simulink Model Parameters*

| Parameter | Value |
|---|---|
| Max. Amplitude of the actuating force | 227kN (from section 3.3.3.5) |
| Avg. actuating force | 66.7kN (from section 3.3.3.5) |
| Max pressure of the system | 350 bar |
| Fluid Viscosity | 50cSt |
| Fluid density | 847kg/m3 |
| Pre charge Pressure of Accumulator A | 30 bar [28] [27] |
| Pre charge Pressure of Accumulator B | 10 bar (minimum system pressure) |
| Relief Valve Max | 350 bar |
| Pipe diameter | 40mm [31] |

### 3.5.4.2. Wave Modelling

The hydraulic model takes in the data from a waveform generator and moves the piston accordingly. Thusly, wave modelling was done to replicate the motion of the waves and simulate the conditions of the movement of the cylinder.

The motion of the buoy, as governed by Equation 13, requires a wave force parameter. The wave force was calculated and modelled based on the average wave time period of about 5 seconds and an average and a maximum amplitude of the waves about 0.4 metres [9] [10]. The inertia of the buoy and the floating island was taken into account and a damping value of 1250kN/(m/s) was added.

Figure 23 shows the excitation force provided to the island by the waves and Figure 24 represents the normalised response function as a result of that excitation. As we can see that the response function tend towards zero, this data can be validated to be correct replication of the waveforms[6].

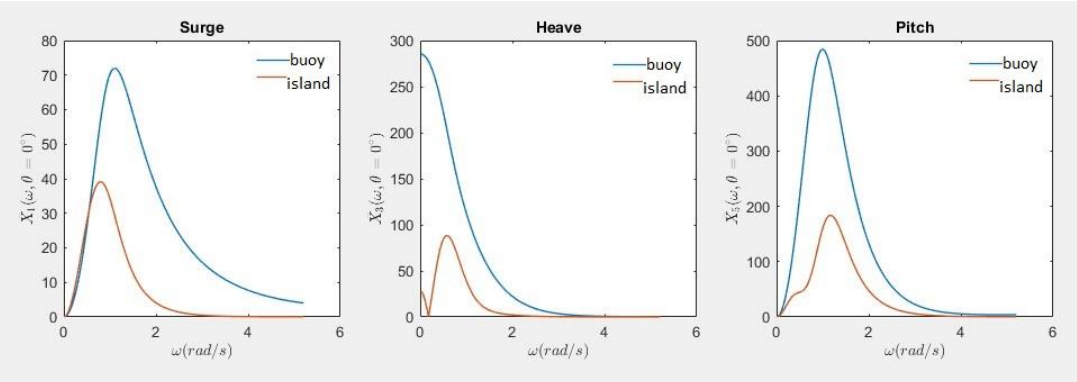



*Figure 22- Excitation Force Plots*

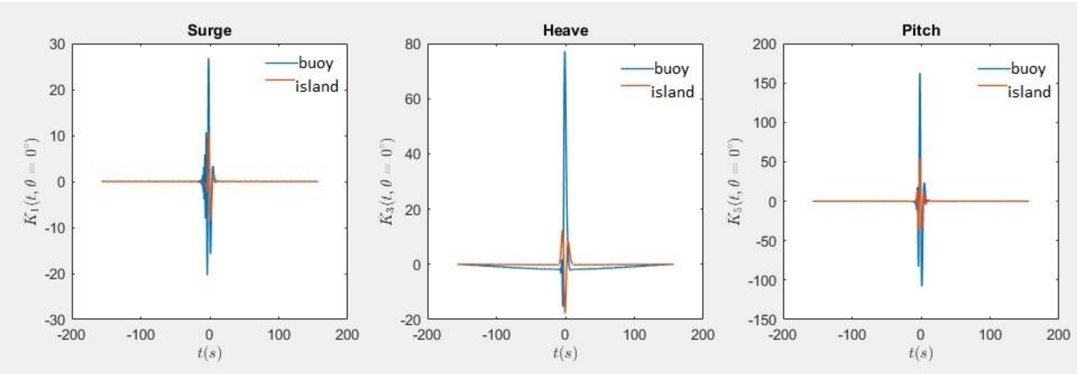



*Figure 23- Normalised Response Function*

### 3.5.4.3. Simulation Results

The below figures represent the hydraulic power output of the system and the total power output of the system taking in account the mechanical losses, hydraulic leakages, and the other losses. All said and done, we get a hydraulic system that is nearly 70% efficient in transferring the hydraulic power to the electrical power output. Although, this does not consider the power transmission losses in its electrical form.

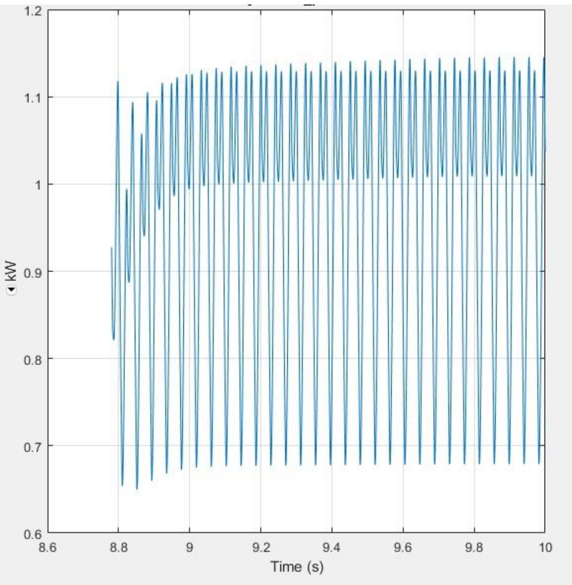



*Figure 25- Hydraulic Power Output*

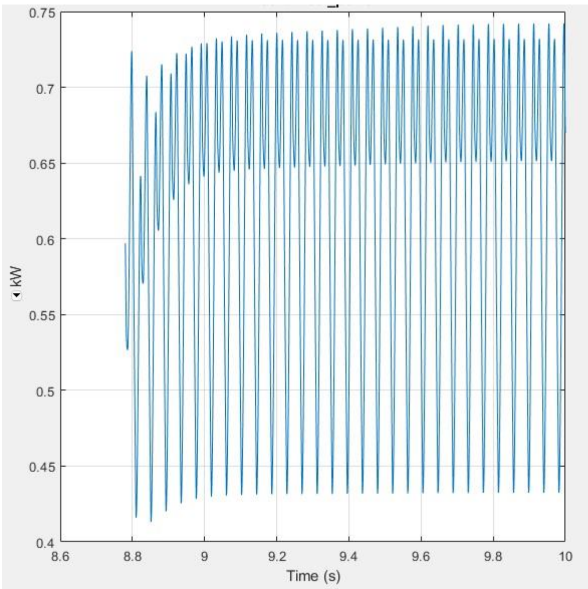



*Figure 24- Total Power Output*

The pressure difference in the hydraulic system takes a more repetitive form after the initial stages, mainly because of the repetitive nature of the input and also because the circuit is supposed to stabilise the pressure difference.

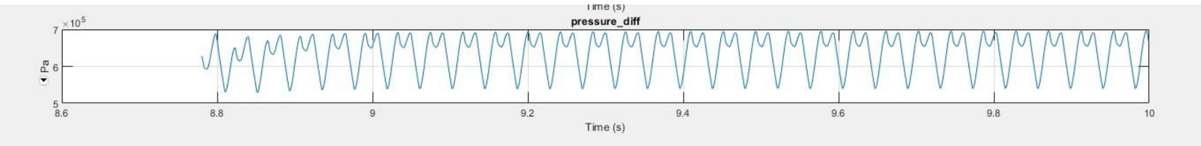



*Figure 26- Pressure Response Results*

*Table 10- Simulink Model Results*

| Parameter | Value |
|---|---|
| Flow rate at check valve 1 (q1) | 18.33*10e-4 m^3/s |
| Flow rate at check valve 2 (q2) | 2.26*10e-3 m^3/s |
| Flow rate at check valve 3 (q3) | 2.84*10e-3 m^3/s |
| Flow rate at check valve 4 (q4) | 3.033*10e-3 m^3/s |
| Flow rate at Double acting Rotary turbine | 1.54*10e-3 m^3/s |
| Avg. mass flow Leakage | 7.2*10e-5 kg/s |
| Avg. internal leakage | 8.5*10e-7 m^3/s |
| Hydraulic Power | 1.1 kW |
| Total Power | 0.74kW |
| ω Angular Velocity of Double acting Rotary turbine | 842 rad/s |
| Avg. Pressure at accumulator B | 10.3 bar |
| Avg. Pressure at accumulator A | 19.4 bar |

## 3.6. Turbine Selection

A turbine is a device that transforms mechanical energy from a flowing fluid, such as water, steam, or gas [32]. A variety of turbine types could be employed in offshore hydraulic systems. However, for the purpose of the PAWEC, reaction turbines were considered. Reaction turbines, are utilised in low head situations where fluid passes through the rotor's blades and creates a differential in pressure that propels the rotor's rotation.

The Kaplan turbine is a somewhat propeller reaction turbine, frequently employed in low-head, high-flow applications like hydroelectric power plants and tidal power systems. Similar conditions to the hydraulic system proposed by the PAWEC. Although these turbines are not the most efficient, they have several benefits applicable to our use case [33]:

- Operate at low head and high flow rates
- Adapt to shifting fluid conditions
- Small shape makes it simple to deploy

However there are some disadvantages on factors such as Kaplan turbines being expensive to manufacture and install which in-turn leads to higher maintenance costs [34]. Another turbine that was considered is consolidated below:

- For less than 1m-head, recently researched cross-flow type turbines are available. However, efficiency has to be compromised compared to Kaplan turbine and further studies are still taking place.

### 3.6.1. Calculations

A minimal set of conditions must be satisfied for a Kaplan turbine to begin operating, such as the requirement of a minimum water flow to initiate the turbine's spinning. Both the static head and the frictional losses inside the turbine should be able to be overcome by the flow rate. To enable the turbine to begin rotating, the blades must be correctly positioned with respect to the direction of the water flow. The turbine may stall if the blade angle is too high or too shallow [35].

The following sets of equations and calculations are worked out to find the appropriate specifications of turbine.

#### 3.6.1.1. Flow Velocity

EquationX below is used to find the cross sectional area of the flow as a prerequisite to fluid flow velocity. Where radius of pipe, r = 0.04m:

$$Equation\ 21{:}\ \ A\ =\ \pi r2\ =\ 5.026\ x\ 10-3m^2$$

Equation 22 below is then used to determine the velocity of the fluid flow. Where, flow rate, Q = 1.49x10-8 m3/s (from section 3.5).

$$Equation\ 22{:}\ \ V\ =\frac{Q}{A}=\ \mathbf{2.964x10^{-6}m/s}$$

#### 3.6.1.2. Turbine Head

By using the Bernoulli's Equation (Equation 24) below we can calculate the head of the turbine [36] [37]. Where the notations a and b represents inlet and outlet, respectively.

$$Equation\ 24{:}\ \ \frac{P_A}{\gamma}+\frac{V_A^2}{2g}+Z_A+h_{pump}=\frac{P_b}{\gamma}+\frac{V_B^2}{2g}+Z_B+h_{turb}+h_f$$

Where,

- Max pressure, $P_A = P_B$ = 350bar (Since flowing inside closed system)
- Density, $\gamma = 850kg/m^3$
- Velocity at Inlet, $V_A = 0$ (standstill condition)
- Velocity at Outlet, $V_B = 2.964x10^6$m/s (3.6.1.1)
- Head Pump, $h_{pump}$ = 0 (As there is no pump)
- Elevation at Inlet, $Z_A$ = 0.08m (diameter of pipe)
- Elevation at Outlet, $Z_B$ = 0 (datum)
- Total Frictional Loss, $h_L = 1.241x10^{-5}$ (from section 3.5)

By Using Darcy–Weisbach equation(Equation 25), we find the head loss due to friction in the pipe [38].

$$Equation\ 25:\ \ h_f\ =\ \frac{4fLv^2}{2gd}$$

Where,

- Length of pipe, L = 20m
- Diameter of pipe, d = 0.08m
- Flow Velocity = 2.964 x 10-6m/s

Friction factor, f, is calculated using Reynold Equation (Equation 26). Since we are using Oil 10-w, flow is laminar[22].

$$Equation\ 26:\ \ f\ =\ \frac{64}{Re}$$

Reynold's Number can be found from Equation 27 [39]:

$$Equation\ 27:\ \ Re\ =\ \frac{Vd}{v}$$

Where,

- Kinematic viscosity, v = 141.98 mm2/s = 0.00014198 m2/s [40]

Therefore, through back-substituting:
Equation 25, $h_f = 1.717x10^{-5}$.
Equation 27, Re = $1.67x\ 10^{-3}$
Equation 26, f = 38300 (3sf)
Equation 24, $h_{turb}$ = 0.08m

#### 3.6.1.3. RPM

Finally, Equation 28 is used to calculate RPM [40] from outsourced selection (section 3.6.3):

$$Equation\ 28:\ \ N_s\ =\ \frac{N\sqrt{P}}{{h_{turb}}^{5/4}} = 1200RPM\ (3sf)$$

Where,

- $h_{turb}$ = 0.08m
- Power output, P = 10KW
- Runner speed, N = 900rpm (From manufacturer).

Generator may be directly coupled to the turbine runner and rotate at the same speed to get maximum efficiency.

### 3.6.2. Selection

Table 11 below shows the selection of the turbine based upon the parameters calculated in section 3.6.1 above.

*Table 11- Turbine Selection Parameters*

| Low Head 10KW Micro Kaplan Hydro Generator Turbine [41] | |
|---|---|
| Parameter | Value |
| Cost (£) | 1342.51 |
| Head Range (m) | 2-30 |
| Efficiency (%) | 85-93 |
| Runner Diameter (m) | 0.2-0.4 |
| Rated Power (kW) | 10-40 |
| Rated Voltage (V) | 400 |

## 3.7. Generator Selection

A three-phase hydraulic motor-driven generator was chosen for integration with the PAWEC system. The advantages of hydraulic generators in comparison to other generators are as shown below:

- Compact
- Quiet
- Reliable
- AC or DC power supply
- Easy/variable integration

The general advantages of three phase generators in comparison to single-phase are presented below:

- Smaller volume
- Lighter weight
- Incredibly common
- Higher voltage output
- Higher efficiency
- Lower maintenance costs

The generator choice was parametrised through the calculations in sections 3.5 and 3.6 and the Dynaset Hydraulic Generator [42] was chosen. Compared to engine generators of the same power, the hydraulic generator is only a fraction of the size which means it takes up a minimal footprint on the offshore island. The generator parameters are presented below in Table 12.

*Table 12- Generator Selection Parameters*

| Parameter | Value |
|---|---|
| Maximum Output Power | 10kVA |
| Voltage | 400V / 415V |
| Nominal Current | 14.4 Amps for 400V |
| Frequency | 50 Hz |
| Frequency Control | FLC2 |
| IP (Waterproof Rating) | 23 |
| Voltage Regulator | Compound |
| Sockets Quantity | 1 for 400V |
| Weight | 57kg |
| Dimensions | 568 x 212 x 326mm (L x W x H) |
| Viscosity Range | 10-200cSt |

| | |
|---|---|
| Maximum Pressure | 210 bar |
| Cost | £ 2,994.99 |

# 4. Wider Engineering Implications

## 4.1. Hydraulic Fluid

Traditional hydraulic fluids contain a range of chemical compounds, including detergents, anti-wear agents, and corrosion inhibitors, which can be harmful to marine life if they come into contact with them. They can damage the gills of fish, interfere with their ability to reproduce, and in some cases, lead to death. Furthermore, the chemicals can have toxic effects on other sea life, including crustaceans, and other marine organisms.

Additionally, hydraulic fluid can also have physical effects on marine environments, such as reducing the amount of oxygen in the water or altering the pH levels, which can further harm marine ecosystems. Therefore, it is critical to take appropriate measures to prevent hydraulic fluid from entering the ocean to minimize the impact on marine life [43].

Many manufacturers like Total Energies, Midland lubricants, Premier lubricants offer services wherein they provide the environmentally friendly hydraulic fluid for any specific set of characteristics of fluid. This would makes the system more sustainable such that even when there are leakages the damage to the environment is kept to a minimum.

## 4.2. Ethical & Social

*Table 13- Ethics & Social Review [44]*

| Principle | Definition | Examples in context of project |
|---|---|---|
| Honest & Integrity | Duty to uphold the highest standards of professional conduct including openness, fairness, honesty and integrity. | The Project aims to provide an infrastructure to replace the fossil fuels as a source of energy. Our project also aims to make the energy generated by the offshore windfarms more reliable, consistent, and sustainable in so much as attempting to eliminate the requirement of non-renewable sources of energy altogether. |
| Respect for Life, Law and the Public Good | Duty to obey all applicable laws<br><br>and regulations and give due weight to facts, published standards and guidance and the wider public interest. | The offshore wind farms currently in place are dependant on the weather conditions for their consistency in energy production and our project intends to take an innovative and more creative approach to capture the already existing energy in hopes of smoothing out the inconsistencies of the energy production. |
| Accuracy & Rigour | Duty to acquire and use wisely the understanding, knowledge and skills needed to perform their role. | Given the rate at which polar ice caps are melting, the global temperature is rising, it is absolutely critical that we figure out ways to battle the climate change and our project does that by moving the energy production infrastructure away from non-renewable energy sources to a more sustainable approach. |
| Leadership & Communication | Duty to abide by and promote high standards of leadership and communication | Marine sources are one of the largest sources of renewable sources at the hands of our society. Given the infinite potential, our project aspires to make use of said resources for the sustainable development of our society towards a net zero world. |

## 4.3. Sustainability

In the interest of sustainable design and practices, a review was undertaken at a team level to determine which of the United Nations (UN) sustainability goals were applicable to the project. As a result of the review, 9 sustainability goals were identified as being directly relevant.

On a group level, in the context of the PAWEC system, 4 of the 9 identified goals were reviewed as being directly relevant. Table 14 below gives information on the SDGs identified and impacts/mitigating controls.

*Table 14- Sustainability Review [45]*

| SDG | Definition | Examples in context of project |
|---|---|---|
| 7 | Ensure access to affordable, reliable, sustainable and modern energy for all | In our project we aspire to be as truthful and honest as our conscious allows, we intend to make this project a representation of our integral beliefs by doing the work intended of us truthfully, honestly and with an attitude of camaraderie. |
| 9 | Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation | In our project as a team and as a group we adhere to certain laws and ethics and take rational, logical carefully thought out decisions that are not only in accordance to the laws of society we live in but also the general good of our race as a whole and the planet that we inhabit. |
| 13 | Take urgent action to combat climate change and its impacts | We aim to be accurate and precise in our decisions and to ascertain the different facts by validating the sources said data is taken from, all the while understanding the fact that the main purpose of this entire exercise is to provide us with an opportunity to learn and acquire knowledge and skills. |
| 14 | Conserve and sustainably use the oceans, seas and marine resources for sustainable development | Throughout the course of this module and the duration of the project we must lift each other up, communicate and help each other at every instance we feel our team needs us to step up. |

## 4.4. Risk Evaluation

The determination of risk is defined by the Risk Priority Number (RPN) which is calculated using Equation 29 below.

$$\text{Equation 29:} \quad RPN = O \times S \times D$$

Where O = occurrence, S = severity and D = detection. All are scored out of 10- with 10 being inevitable, hazardous, and absolute uncertainty, respectively.

*Table 15- FMEA [46]*

| Process/ Feature | Potential Failure Mode | Potential Failure Effects | Severity | Potential Causes | Occurrence | Current Controls | Detection | RPN | Action Recommended |
|---|---|---|---|---|---|---|---|---|---|
| What is the process/ feature under investigation? | In what ways could this feature go wrong? | What are the possible impacts of this failure? | | What changes could cause this failure? | | What preventative measures are in place? | | | Recommendations for improving the RPN number? |
| Buoy | Puncture to the HDPE material | - Water filling the hollow structure<br>- Hole propagation | 8 | - rogue sea-life<br>- harsh weather<br>- harsh swells<br>- drift objects<br>-impact force | 1 | - winch and locking mechanism | 5 | 40 | - incorporate a pressure sensor in the buoy.<br>- incorporate a stress sensor in the arms |
| | Failure at the actuating mount interface | - Excessive forces on the actuating arm<br>- Loss of the buoy | 10 | - harsh weather<br>- impact force<br>- improper maintenance | 1 | - winch and locking mechanism<br>- FEA | 1 | 10 | - perform life-cycle testing |
| | Bio-fouling | - increased drag<br>- corrosion<br>- local spread of invasive species<br>- interference with sensors/ instrumentation | 1 | - likely build-up over time due to being submerged | 10 | - cleaning<br>- sufficient maintenance | 1 | 10 | - explore with antifouling paints, silicone-based coatings, Copper-based coatings, UV light-activated coatings [47] |
| | Wave damage | - concaved sections of the buoy leading to less efficiency<br>- increased stress on actuating mount | 5 | - harsh weather | 5 | - winch and locking mechanism | 3 | 75 | - accurate weather forecasting |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Actuating mount | Fatigue failure/ deflection of the arms | - Loss of the buoy and arm(s)<br>- sharp metal exposed to rest of system<br>- loss of efficiency | 10 | - harsh weather<br>- impact force<br>- increased temperature/ humidity<br>- improper maintenance | 1 | - winch and locking mechanism<br>- FEA | 2 | 20 | - investigate surface finishing techniques to reduce initiation of propagating cracks |
| | Fatigue failure / deflection of the columns | - Loss of the buoy, arm(s) and columns<br>- sharp metal exposed to rest of system<br>- loss of efficiency | 10 | - harsh weather<br>- impact force<br>- increased temperature/ humidity<br>- improper maintenance | 1 | - winch and locking mechanism<br>- FEA | 2 | 20 | - investigate surface finishing techniques to reduce initiation of propagating cracks |
| | Bearing fatigue/ failure | - loss of efficiency<br>- damage to rest of system<br>- excessive vibrations | 8 | - overloading<br>- misalignment<br>- contamination<br>- increased temperature/ humidity<br>- improper maintenance<br>- improper assembly | 3 | - sufficient maintenance | 7 | 168 | - Investigation into lubrication needed |
| | Shearing of the welded joints | - increased stress on arms<br>- loss of arms<br>- loss of entire system | 10 | - harsh weather<br>- impact force<br>- improper maintenance | 1 | - winch and locking mechanism | 2 | 20 | - apply best practice welding methods |
| Piston | Rod fractures | - fluid leakages<br>- impact on sea-life<br>- increased stresses<br>- de-pressurisation | 9 | - material defects in manufacturing<br>- improper alignment<br>- loosening of fittings<br>- scuffing<br>- improper maintenance | 2 | - sufficient maintenance | 4 | 72 | - investigate surface finishing techniques to reduce initiation of propagating cracks |
| | Scuffing | - fractures<br>- reduced efficiency | 3 | - partial blockages in the cylinder<br>- improper maintenance | 2 | - sufficient maintenance | 7 | 35 | - follow manufacturers recommended break-in procedure<br>- temperature sensors to avoid overheating |
| | Sealing cap failure | - damaged rods<br>- fluid leakages<br>- impact on sea-life<br>- increased stresses<br>- de-pressurisation | 9 | - Increase in pressure<br>- impact force<br>- improper maintenance<br>- improper assembly | 1 | - pressure accumulators | 3 | 27 | - pressure/ temperature sensor network |
| | Mounting failure | - misalignment<br>- damage to actuating mount<br>- loss of efficiency | 7 | - increase in vibration<br>-harsh weather<br>- torsional load<br>- improper assembly<br>- improper maintenance | 1 | - winch and locking mechanism<br>- sufficient maintenance | 2 | 14 | - undergo FEA on mounting methods |
| Hydraulic System & Turbine | Fluid contamination | - damage to hydraulic system<br>- damage to turbine<br>- loss of efficiency<br>- turbulent flow<br>- clog filters<br>- cause corrosion | 5 | - corrosion<br>- improper maintenance<br>- entry of foreign particles in the fluid | 6 | - sufficient maintenance | 8 | 240 | - research into appropriate filter |
| | Discharge / Explosion | - harm to sea-life<br>- damage to rest of system<br>- damage to other team wide systems<br>- harm to workers | 10 | - increase in internal pressure<br>- blockage | 1 | - location is pre-approved (low marine life impact)<br>- sufficient maintenance | 1 | 10 | - pressure/ temperature sensor network |
| | Overheating | - increase in pressure<br>- hydraulic fluid brake down | 3 | - insufficient cooling<br>- increase in ambient temperatures<br>- increase in internal pressure | 5 | - Hydraulic fluid rated for increased temperatures<br>- maintenance schedule | 7 | 105 | - pressure/ temperature sensor network |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Internal erosion | - loss of efficiency<br>- decrease in pressure<br>- fluid contamination<br>- fatigue of system parts | 2 | - improper maintenance<br>- increase in fluid velocity<br>- increase in internal pressure | 10 | - pressure accumulators<br>- using verified market parts<br>- sufficient maintenance | 9 | 180 | - undergo material selection process + optimise flow rate |
| | Air pockets | - system inefficiencies<br>- reduced performance | 1 | - low fluid levels<br>- leaks in the system<br>- faults components | 8 | - sufficient maintenance | 9 | 72 | - regular venting procedure |
| | Misalignment to generator | - excessive vibration<br>- loss of efficiency<br>- increased wear | 5 | - harsh weather conditions<br>- improper assembly | 3 | - winch and locking mechanism | 3 | 45 | - incorporate poka-yoke system |
| | Cavitation | - Damage turbine blades | 1 | - bubbles forming and imploding due to drops in pressure | 2 | - pressure accumulators | 8 | 16 | - pressure/ temperature sensor network |
| Generator | Dust accumulation | - poor ventilation<br>- erosion contaminants | 1 | - blockages<br>- improper maintenance<br>- harsh weather | 9 | - sufficient maintenance | 1 | 9 | - research into appropriate filter |
| | Bearing fatigue/ failure | - overheating<br>- excessive vibration<br>-misfunctioning rotation | 8 | overloading<br>- misalignment<br>- contamination<br>- increased temperature/ humidity<br>- improper maintenance<br>- improper assembly | 3 | - sufficient maintenance | 7 | 168 | - Investigation into lubrication needed |
| | Stator core damage | - Short-circuits<br>- Winding damage | 3 | - overheating<br>- excessive vibrations<br>- moisture<br>- impact force | 7 | - Waterproofing<br>- sensor system (BEng EESE) | 8 | 168 | - incorporate live analysis of vibrations, current signature and magnetic flux [48] |
| General | Saltwater corrosion | - degradation of system components<br>- rusting<br>- create accidental conductive paths<br>- build-up of scale and deposits<br>- promote growth of organisms | 4 | - likely build-up over time due to being submerged<br>- harsh weather | 10 | - Waterproofing<br>- Cleaning | 2 | 80 | - exploring with anti-corrosion coatings such as epoxy, zinc, polyurethane, ceramic and Anodizing [49] |
| | Material degradation | - discolouration<br>- cracking/ brittleness<br>- loss of strength<br>- reduced flexibility | 2 | - likely build-up over time due to being outdoors<br>- harsh weather | 10 | - EduPack validation<br>- use of stock parts and market components | 1 | 20 | - explore with UV light activated coatings [49] |
| | Electrical failure | - reduced efficiency<br>- complete failure<br>- overheating | 6 | - harsh weather<br>- moisture build-up<br>- overloading<br>- power surges / short circuits<br>- age/ wear | 4 | - sensor system (BEng EESE) | 3 | 72 | - surge protection (BEng EESE)<br>- incorporate a training course |
| | Loss of communication | - unable to control system remotely<br>- damages if weather is bad/ waves are high | 10 | - harsh weather<br>- impact force<br>- electrical failure | 5 | - sensor system (BEng EESE) | 1 | 50 | - establish a back-up system<br>- incorporate a training course |
| | Loose fittings and components | - excessive vibrations<br>- misalignment<br>- increased stresses | 4 | - harsh weather<br>- excessive vibrations<br>- torsional loads | 7 | - winch and locking mechanism<br>- sufficient maintenance | 2 | 56 | - use tightening gauge and proper joining practices |

# 5. Manufacture

## 5.1. Outsourced Components

The PAWEC system utilises the benefits of outsourced components across its sub-systems in order to minimise costs and use stock sizing to simplify maintenance. Table 16, below, collates each of these components. Actuating mount components in separate bill of materials (BOM) due to large quantity of parts (Table 17).

*Table 16- Outsourced Components*

| Component Picture | Product Code / Model Number/ SKU | Quantity | Cost |
|---|---|---|---|
| Kartt 9500lbs 42.3kN 12v Electric Winch with Synthetic Rope [13] [13] | | | |
|   | WK95012S | 2 | £675.00 |
| Hydraulic Cylinder 100mm Bore 50mm Rod 1200mm Stroke [17] | | | |
|  | 100501200 | 1 | £327.50 |
| Low Head 10KW Micro Kaplan Hydro Generator Turbine [41] [41] | | | |
|  | ZD760-LM-40 | 1 | £1,342.51 |
| Dynaset Hydraulic Generator 10kVA 400V [42] [42] | | | |
|   | HG10E-E400ST23-49-VF | 1 | £ 2,994.99 |
| Schedule 40S 316/L Stainless Steel Pipe (2m) | | | |

| | | | |
|---|---|---|---|
|  | SSWP-406 | 10 | £23.70 |
| Hydraulic Check Valve, 250 L/MIN, 1 1/4" BSP [50] | | | |
|  | V0631 | 4 | £53.50 |
| HYDAC SB40-100A1/112U-40A (Pressure Accumulator) [51] | | | |
|  | 2127514 | 2 | £150.00 |

### 5.2. Buoy

Manufactured using HDPE injection moulding [52].

1. High-density polyethylene particles are commonly used as raw materials to make large objects. The particles are first heated and melted in a hopper or extruder.
2. Moulding: Melted high-density polyethylene is then injected into a mould usually made of metal. Moulds are designed to give objects the desired shape and size.
3. Cooling: The object is then allowed to cool and solidify in the mould.

### 5.3. Actuating Mount

Table 17 Below shows the BOM for the manufacture and assembly of the actuating mount.

*Table 17- Actuating Mount Bill of Materials*

| Part Number | Component | Size | Quantity | Cost (£) |
|---|---|---|---|---|
| 001 | Column (100mm) | 2.5m | 2 | 1802.92 |
| 002 | Main Arm (100mm) | 5m | 2 | 9556.18 |
| 003 | Reinforcement Arm (long) - 100mm | 5m | 2 | 9556.18 |
| 004 | Reinforcement Arm (short) - 100mm | 2m | 2 | 462.02 |
| 005 | Bearings | M60 | 2 | 21.29 |
| 006 | Winch Bar - 140mm | 1.3m | 1 | 2535.35 |
| 007 | Rods - 70mm | 1.6m | 3 | 1248.87 |
| 008 | Nuts | M60 | 6 | 47.94 |
| 009 | Washers (pack of 5) | M60 | 2 | 58.99 |
| 010 | M16 Bolts | M16 | 32 | 49.45 |
| 011 | Pulley | / | 8 | 440.00 |
| 012 | Winch | / | 2 | 1350.00 |
| 013 | Supporting Pillars | 1.6m | 2 | 370.72 |
| | | | Total Cost | 27499.91 |

### 5.4. Piston Connector

From Solidworks, we know the mass of connector is 4.655 kg.
As shown in Figure 29, from EduPack [22], the price of A380 aluminium alloy is around 20.9~21.2 GBP/kg. So the maximum cost for producing a 4.655 kg connector is £98.70.

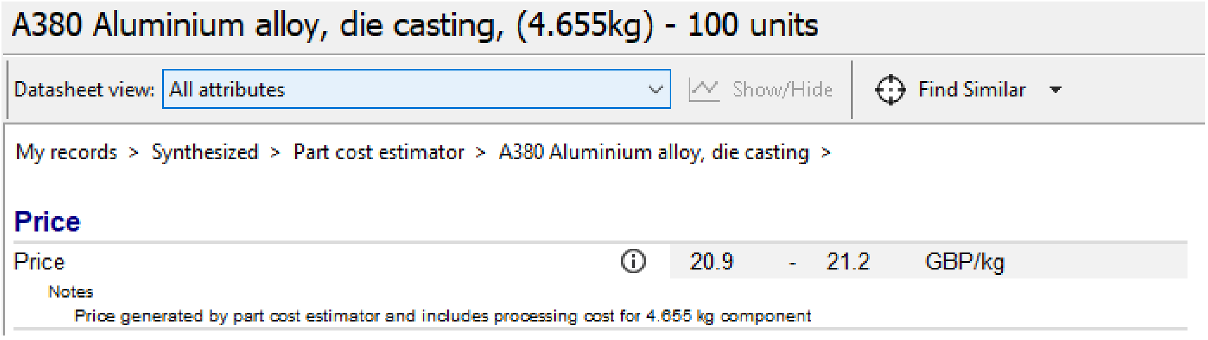



*Figure 27- EduPack Analysis of Die Casting For Piston Connector*

# 6. Business Plan

### 6.1. Product Description

3.5m diameter buoy, actuating mount, piston, hydraulic system, turbine and generator comprise to the PAWEC assembly to be implemented into a sustainable offshore energy island interconnected to Victoria, Australia's new offshore wind farm. The actuating mount will also incorporate a rudimentary winch/ pulley system for removing the buoy from the water during harsh weather conditions and/or maintenance.

### 6.2. The Market

#### 6.2.1. Customer

Initially targeting the state of Victoria, Australia due to the promise of 2GW of offshore energy by 2023 [1]. However, the modular design of the PAWEC system allows energy generation in any location with consistent waves. Other countries leading the way in offshore energy consist of: UK, China, US, Taiwan, Japan, South Korea and Denmark. Government bodies will be the main target.

#### 6.2.2. Current Competitors

*Table 18- Competitor Analysis*

| Name & Company | Product | Price | Strengths | Weaknesses |
|---|---|---|---|---|
| CETO 6, Carnegie, [53] | PTO Intellectual property first launched in 2013, US patent (6 November 2017) | Still in development | 1. Fully submerged = no visual impact<br>2. Developed & Proven<br>3. Flexible swells and depths<br>4. Storm survivability mitigation system<br>5. Scalable<br>6. Clean energy | 1. Has to be moored<br>2. Submerged = higher impact on marine life<br>3. Low energy production per device (has to be scaled) |
| WaveRoller, AW-Energy [54] | Near-shore, anchored wave energy PTO device. | N/A | 1. 350kw to 1000 kW rating<br>2. Scalable (as farms)<br>3. Hermetic structure for hydraulic system | 1. Limited to depths of 8-20m, 0.3-2km from shore<br>2. Has to be anchored to the seabed with large footprint, high impact on marine life |

| | | | | |
|---|---|---|---|---|
| PB3 PowerBuoy®, Ocean Power Technologies [55] | Moored direct drive generator device/ Uninterrupted Power Supply (UPS) | >US$1.9m | 1. Operate in depths of 20-3000m<br>2. Can supply power while moored (UPS)<br>3. Can provide real-time data transfer<br>4. Three year maintenance intervals<br>5. Very robust (rigorously sea tested) | 1. Very large in size and heavy<br>2. Highly Expensive<br>3. Has to be anchored, impact on marine life |
| Marmok-A5, IDOM [56] | Near shore hydraulic pump/generator WEC | Still in prototype stage | 1. Tried and testing (currently in operation)<br>2. Capacity = 30kW<br>3. Survived 3 winters already.<br>4. Provides enormous amounts of data | 1. Massive in size (L=42m)<br>2. Has to be anchored or moored, high impact on marine life<br>3. Large visual impact |

### 6.3. Strategy

The product to market strategy will follow the Technology Readiness Levels (TRLs), originally proposed by NASA, to define 9 stages of the product [57]. Table 19, below, describes each stage.

*Table 19- Product to Market Strategy [57]*

| TRL | Description | Objectives in Context |
|---|---|---|
| 1 | Basic principles observed and recorded | PTO concept selection.<br>WEC concept selection. |
| 2 | Technology concept and/or application formulated | Sub-systems defined.<br>Initial PDS proposed. |
| 3 | Analytical and experimental critical function and/or characteristic proof-of-concept | Culmination of concept report including the optimising on the buoy shape, modelling of the hydraulic system, the FEA of the actuating mount, material selection and the selection of components based on calculations.<br>Initial prototype development. |
| 4 | Component and/or breadboard validation in laboratory environment | Scaled prototype testing in indoor laboratory tank with sinusoidal wave generator. |
| 5 | Component and/or breadboard validation in relevant environment | Scaled prototype testing in low frequency, low amplitude coastal environment. |
| 6 | System/ sub-system model or prototype demonstration in a relevant environment | Fully functional prototype, generating an electrical output with no emissions and transmitting valuable data for continued optimisation in low frequency, low amplitude coastal environment. |
| 7 | System prototype demonstrated in an operational environment | Fully functional prototype, generating an electrical output with no emissions and transmitting valuable data for continued optimisation on an offshore energy island. |
| 8 | Actual system completed and ‘flight qualified’ through test and demonstration | Fully functional system, generating an electrical output with no emissions, that is supplying some demand from the grid in response to low outputs from its unified offshore wind farm, transmitting valuable data for continued optimisation on an offshore energy island. |
| 9 | Actual system ‘flight proven’ by successful mission operations | Fully functional system, generating an electrical output with no emissions, that is supplying some demand from the grid in response to low outputs from its unified offshore wind farm, transmitting valuable data for continued optimisation on an offshore energy island.<br>Life span >5years, demonstrating the ability of the system to handle harsh weather conditions without fail. |

# 7. Appendices

## 7.1. Appendix A: CAD Drawings

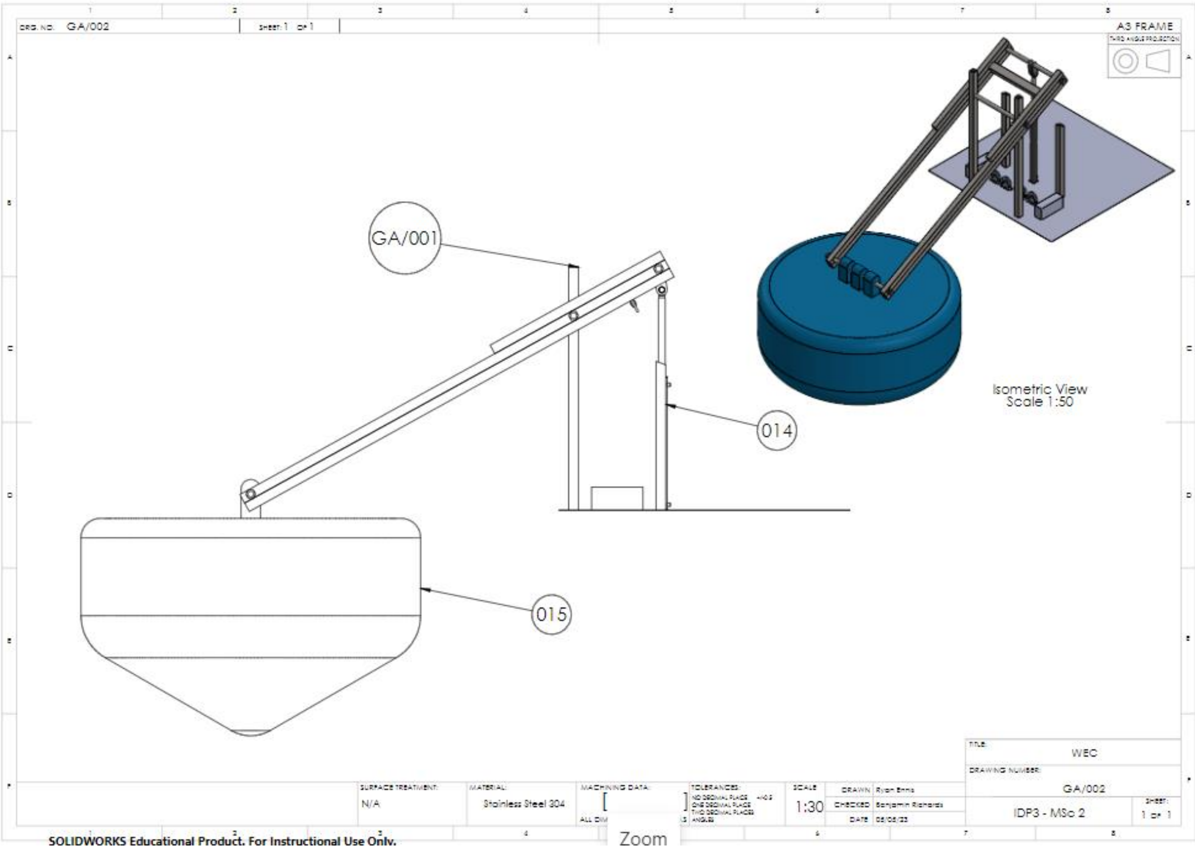



*Figure 27- WEC Assembly CAD Drawing*

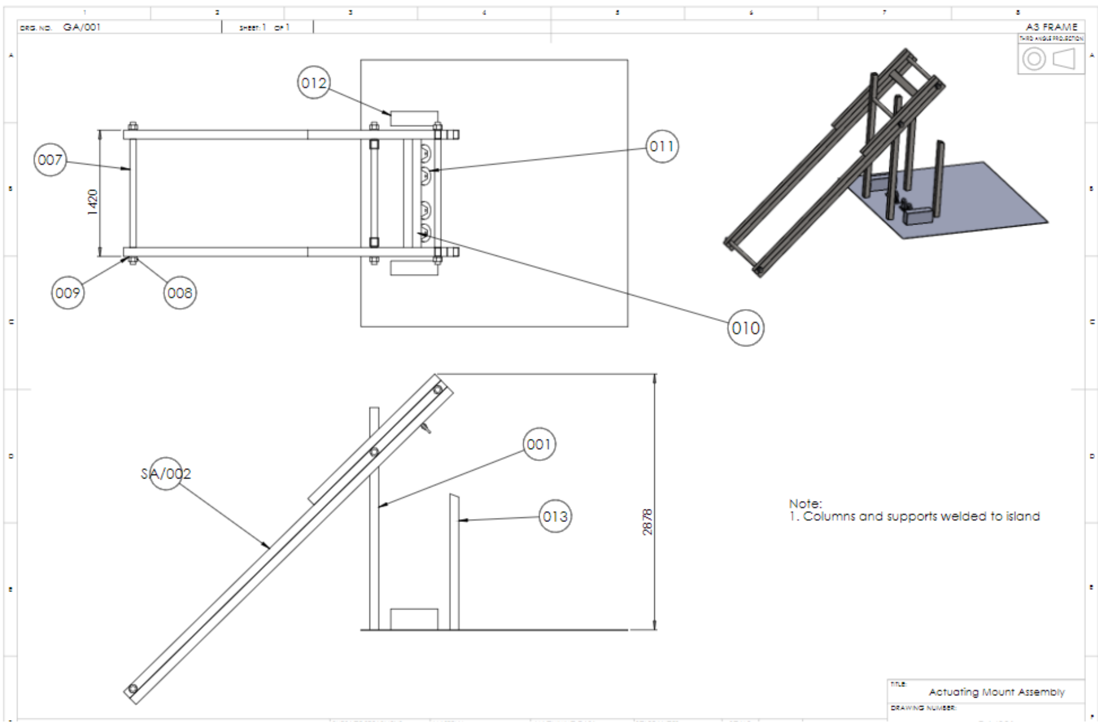



*Figure 28- Actuating Mount CAD Drawing*

SOLIDWORKS Educational Product. For Instructional Use Only.

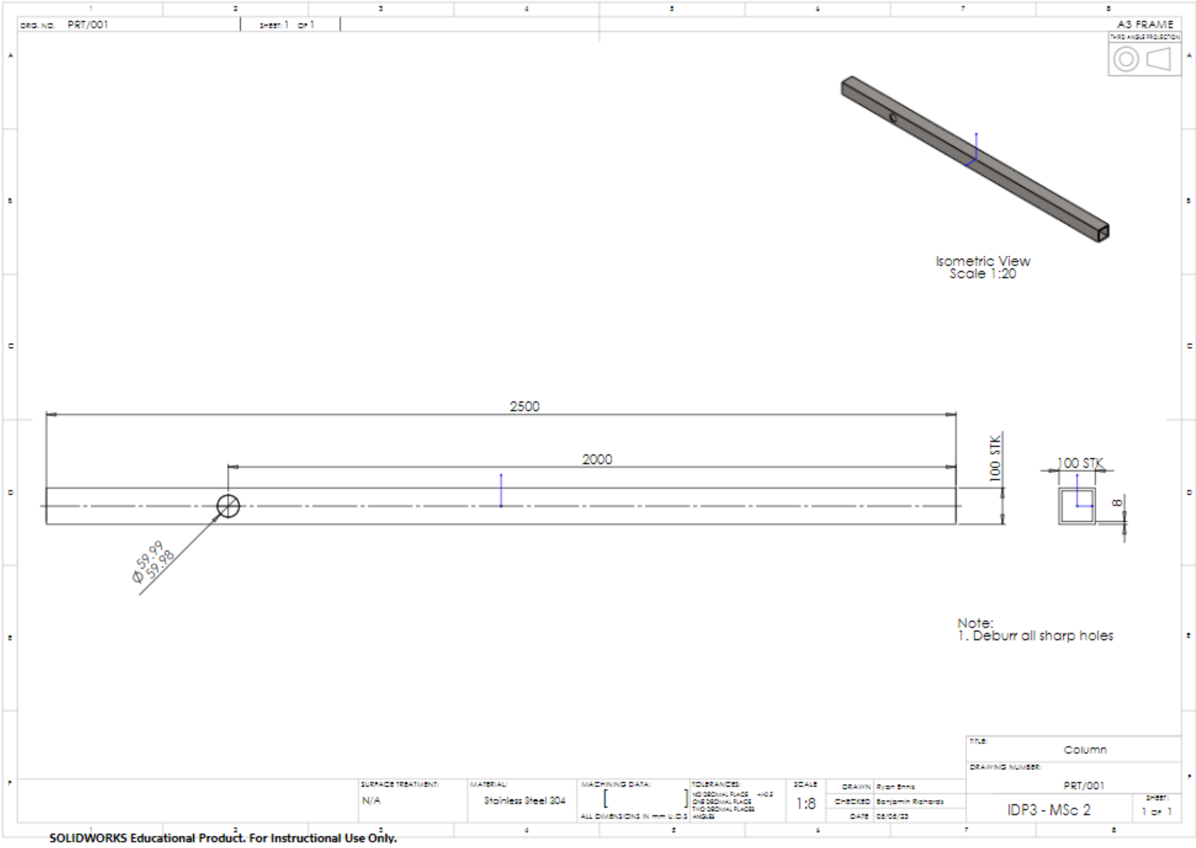



*Figure 29- Column CAD Drawing*

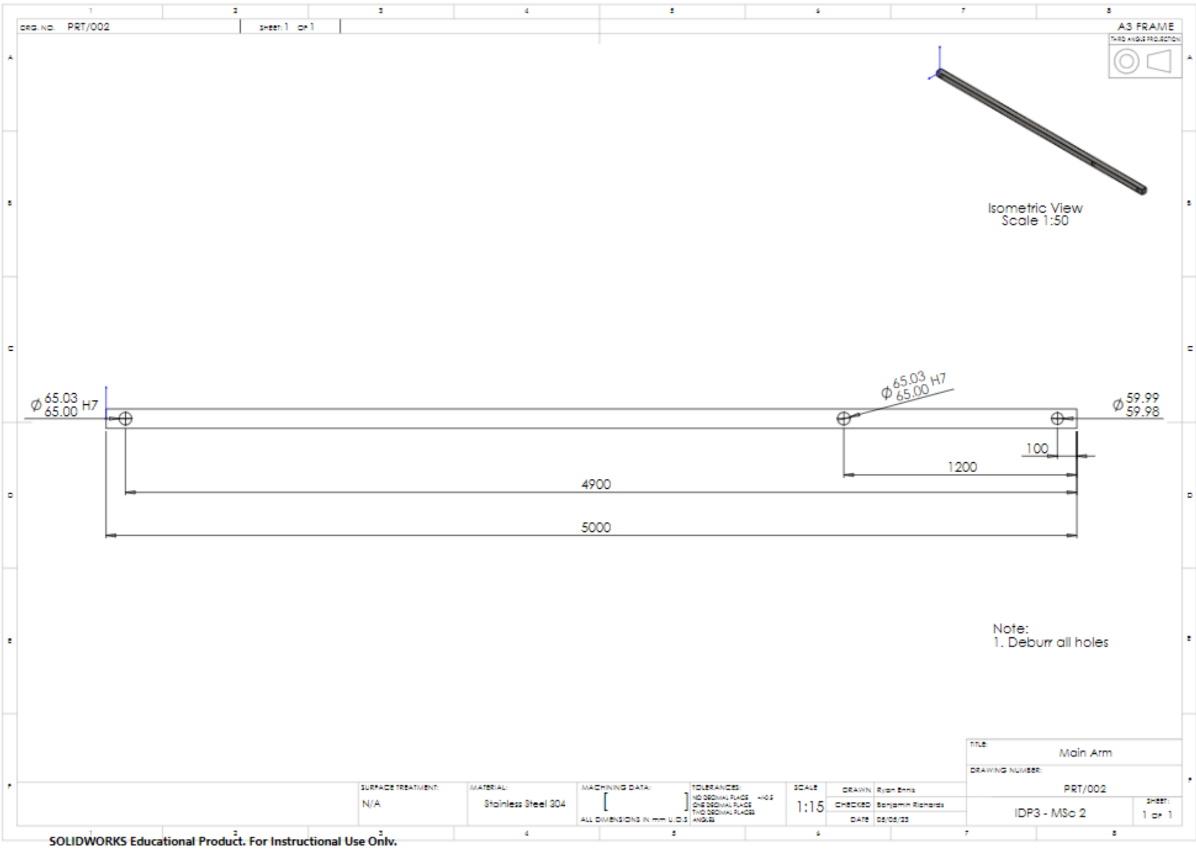



*Figure 30- Main Arm CAD Drawing*

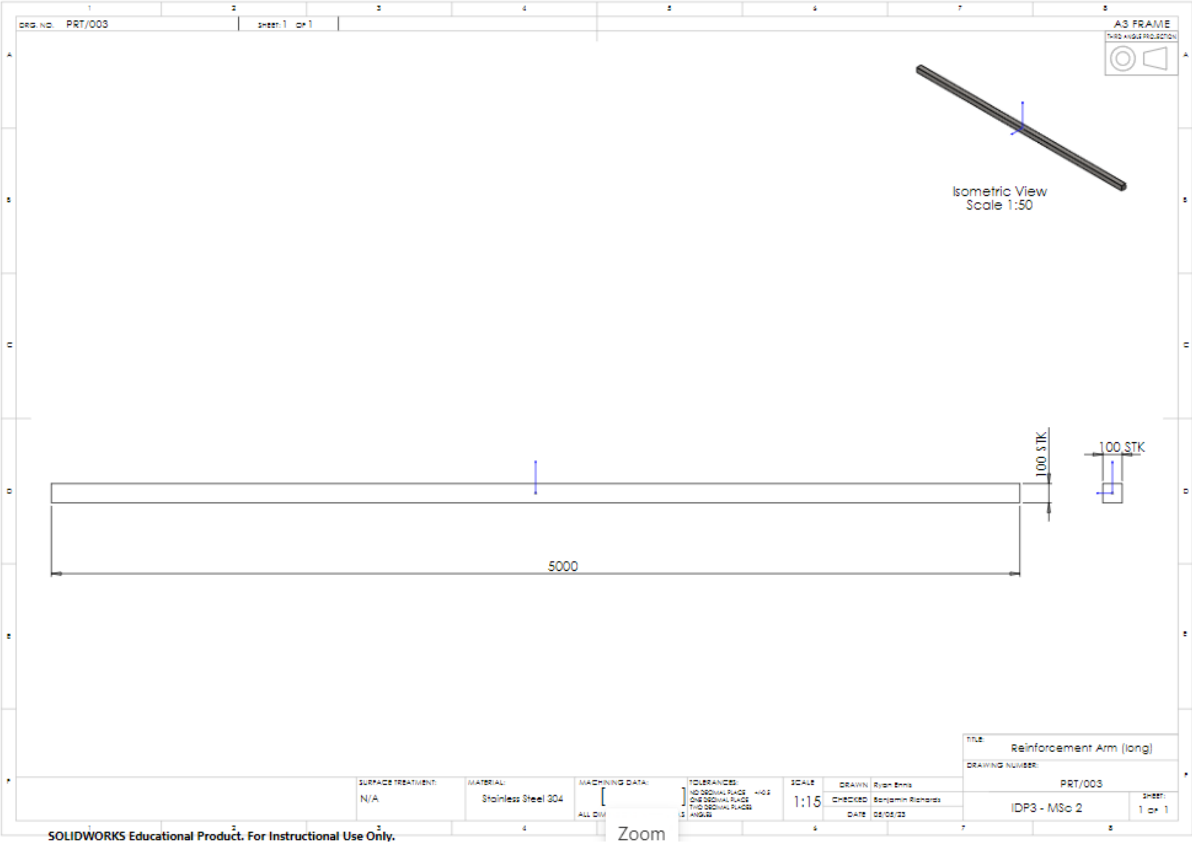



*Figure 31- Long Reinforcement Arm CAD Drawing*

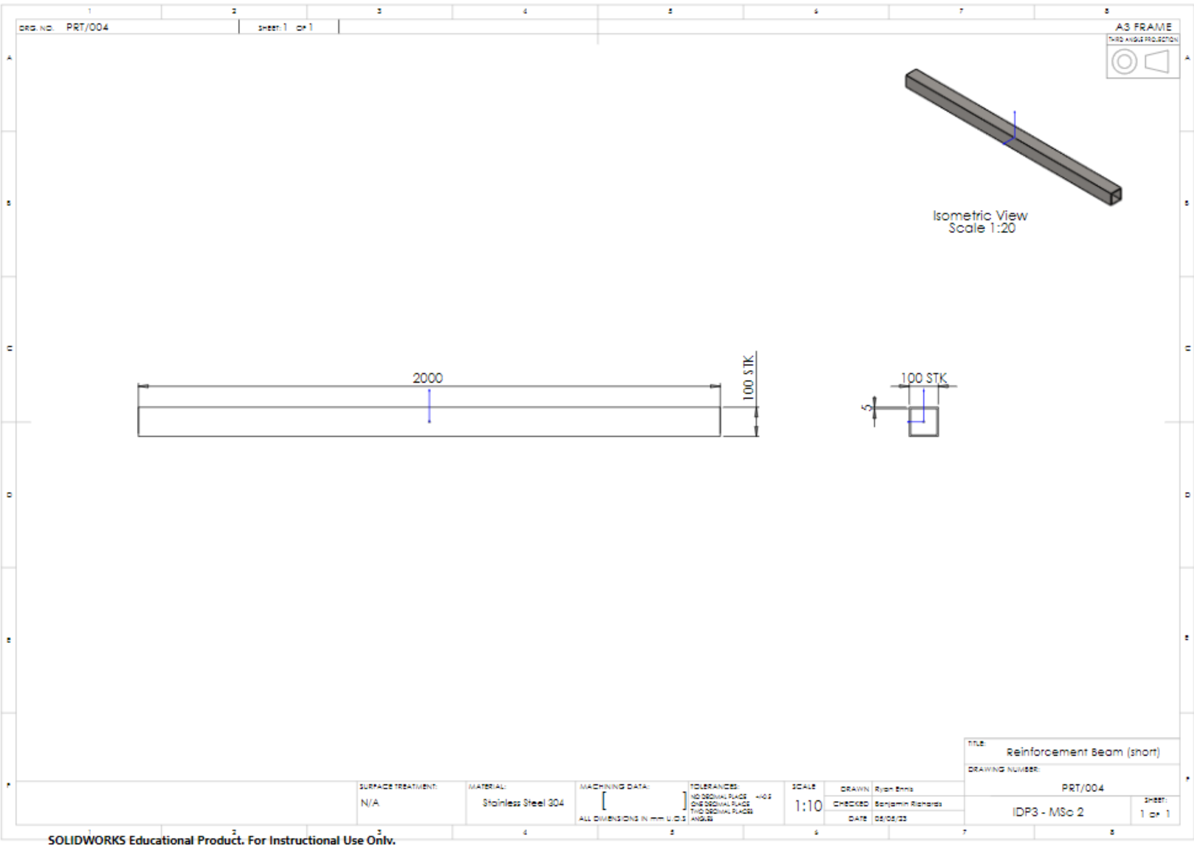



*Figure 32- Short Reinforcement Arm CAD Drawing*

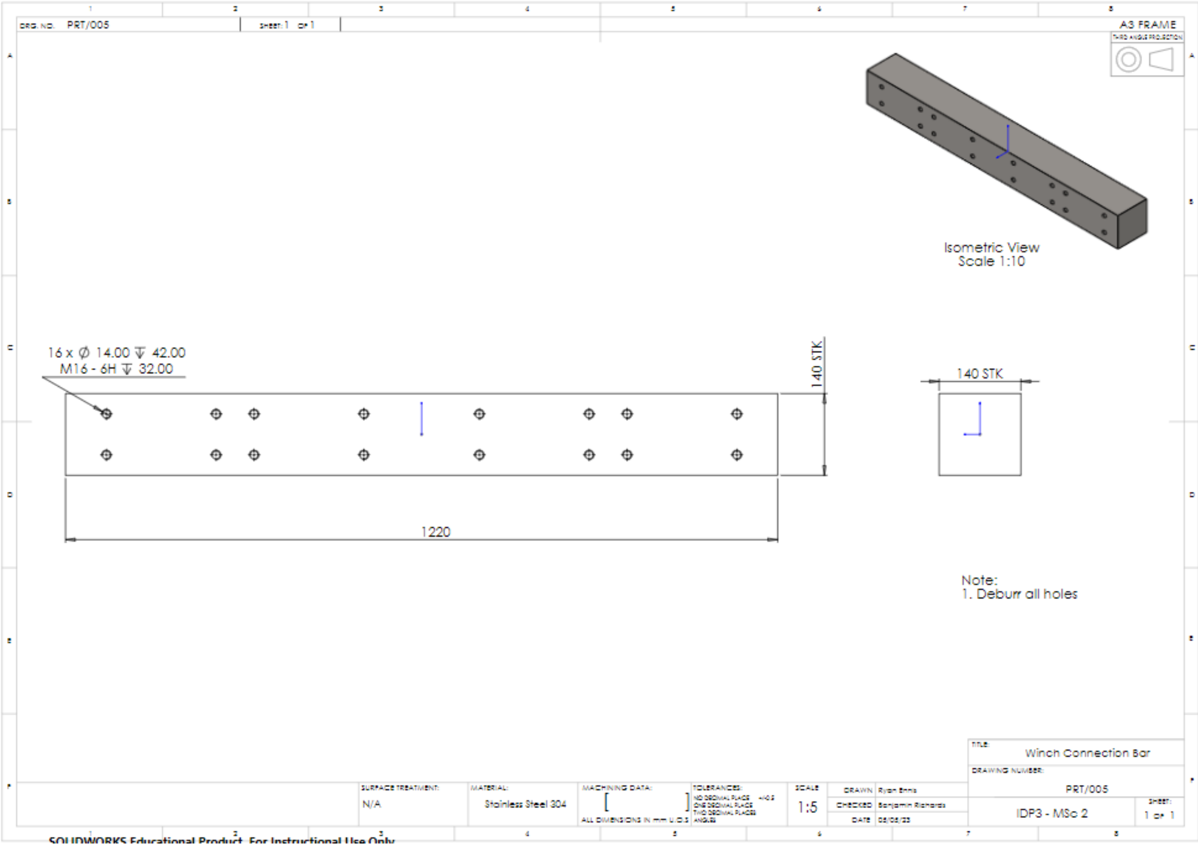



*Figure 33- Winch Connection CAD Drawing*

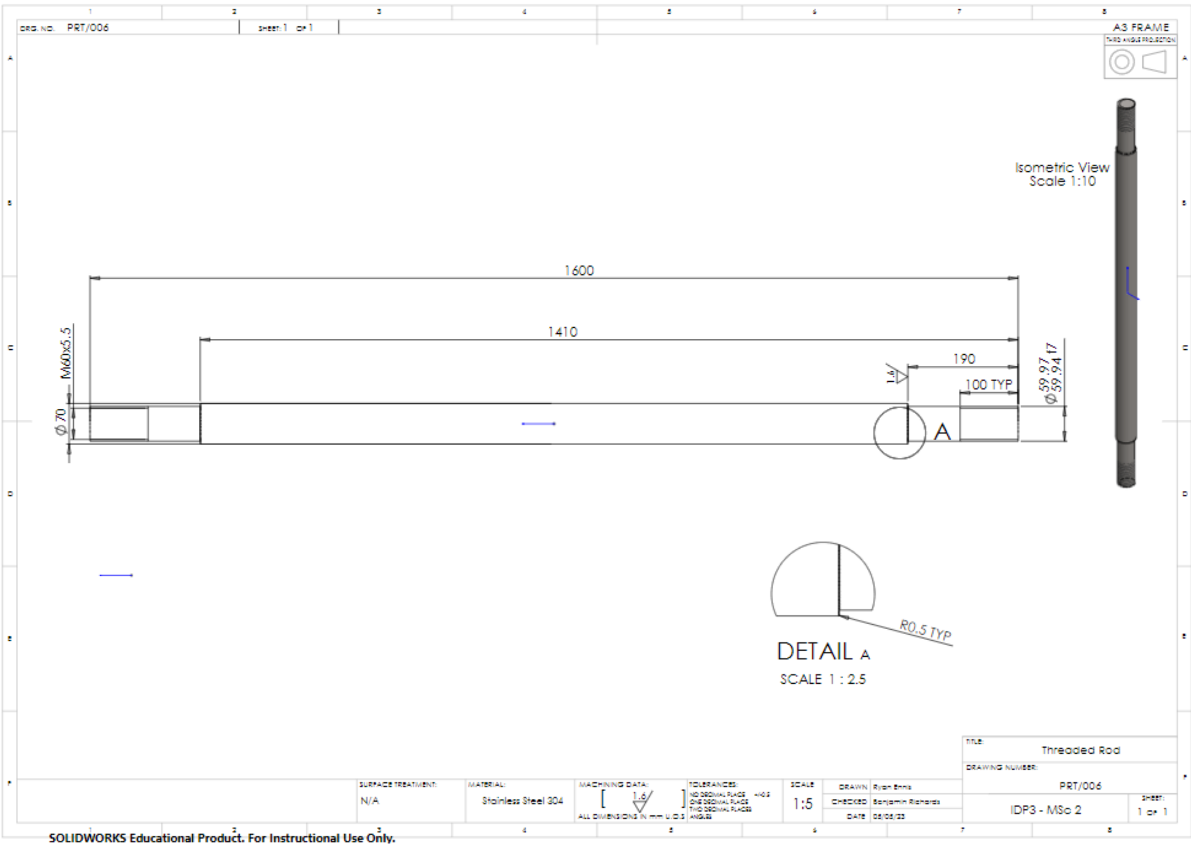



*Figure 34- Threaded Rod CAD Drawing*

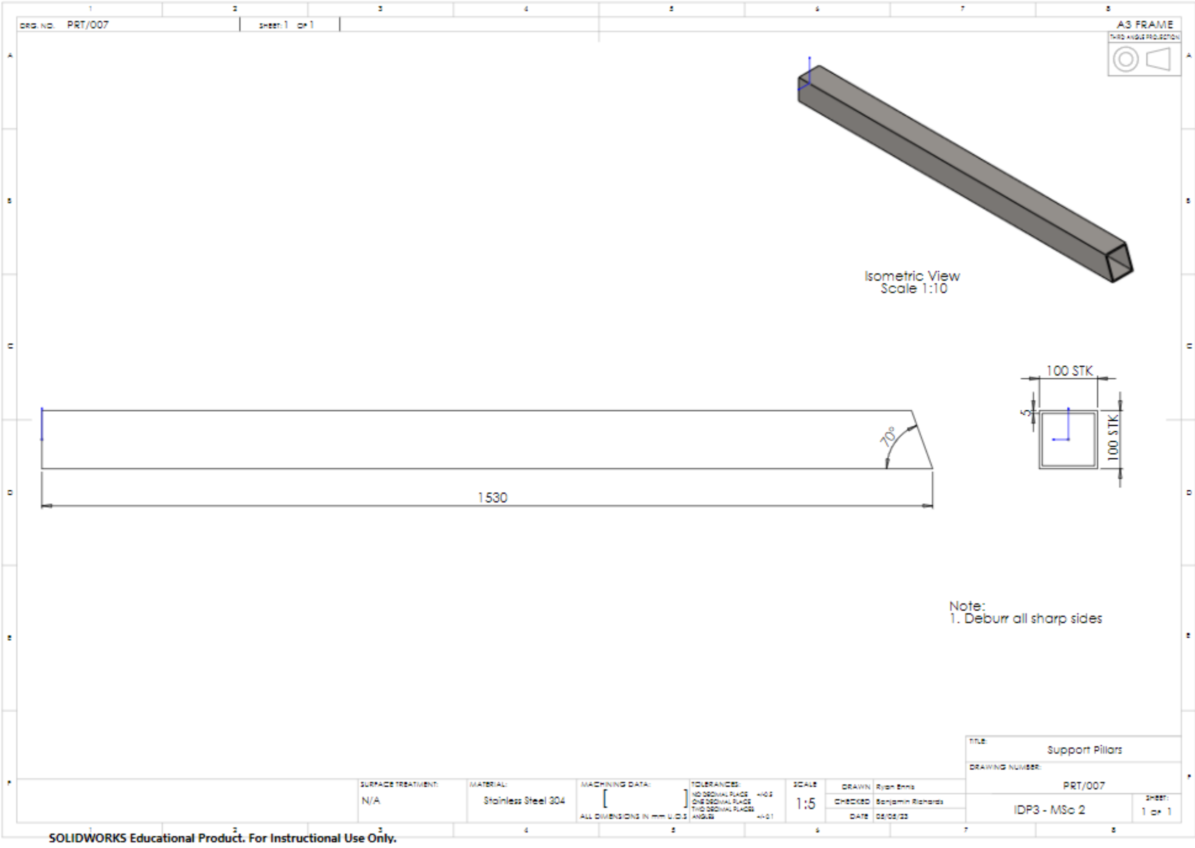



*Figure 35- Support Pillar CAD Drawing*

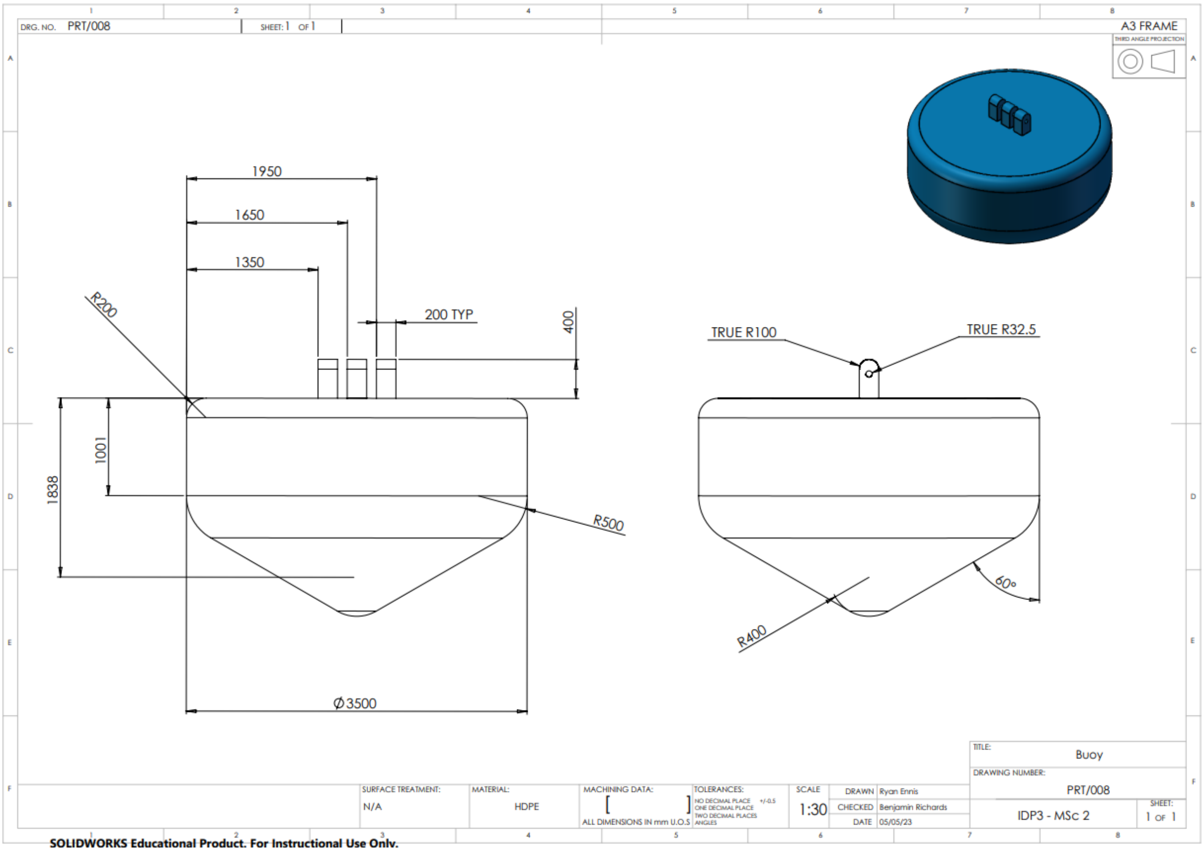



*Figure 36- Buoy CAD Drawing*

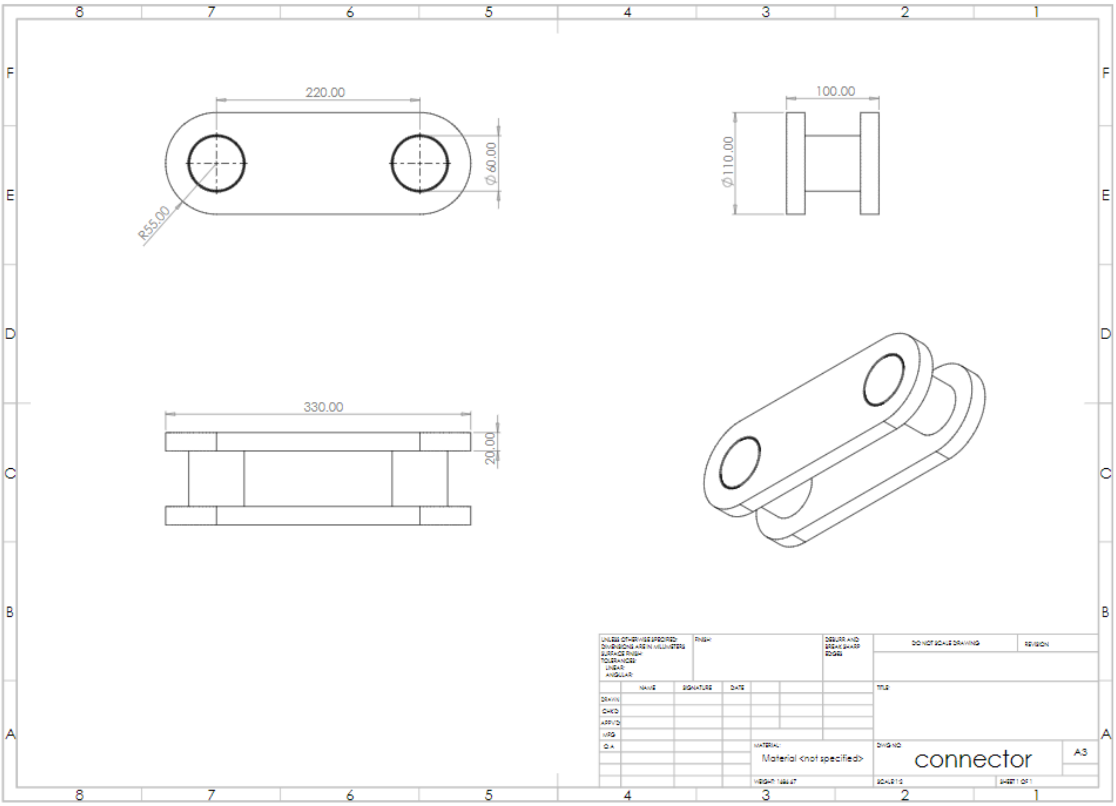



*Figure 37- Piston Connector CAD Drawinf*

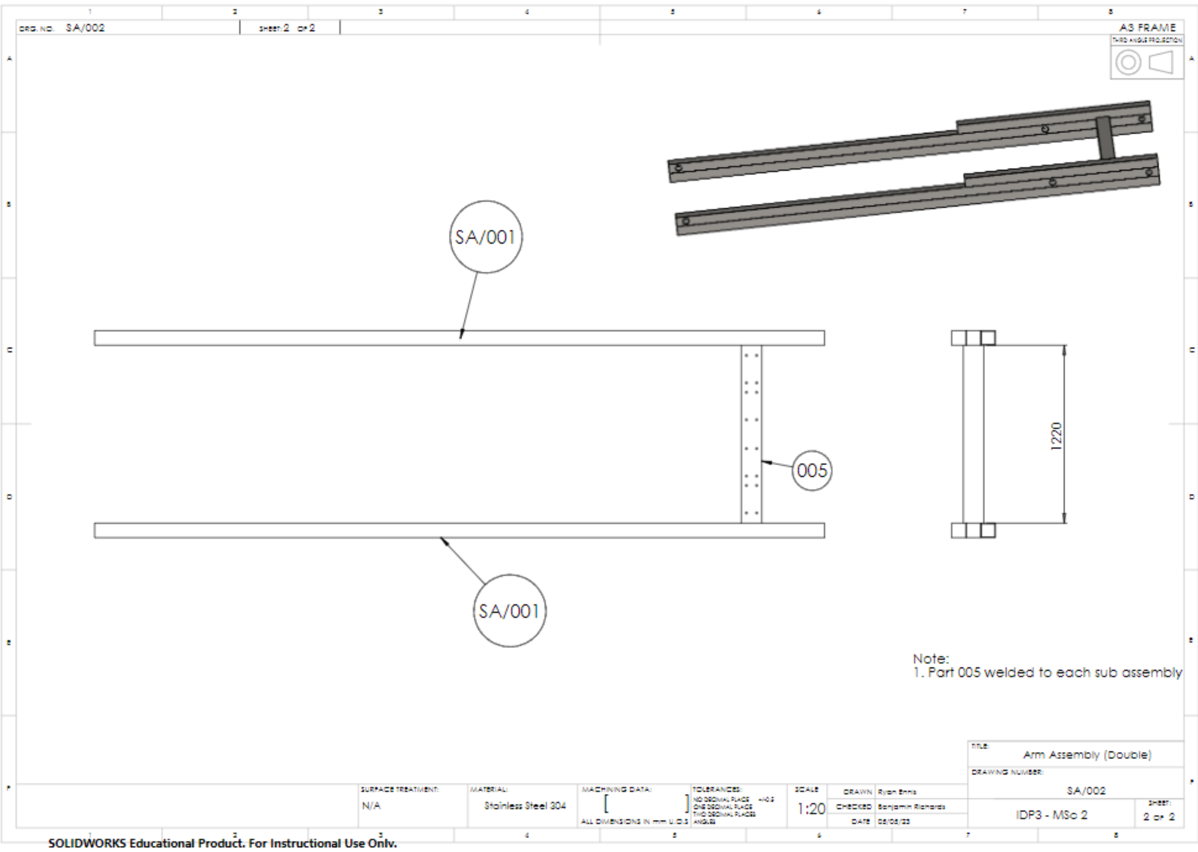



*Figure 38- Arm Assembly  (Double) CAD Drawing*

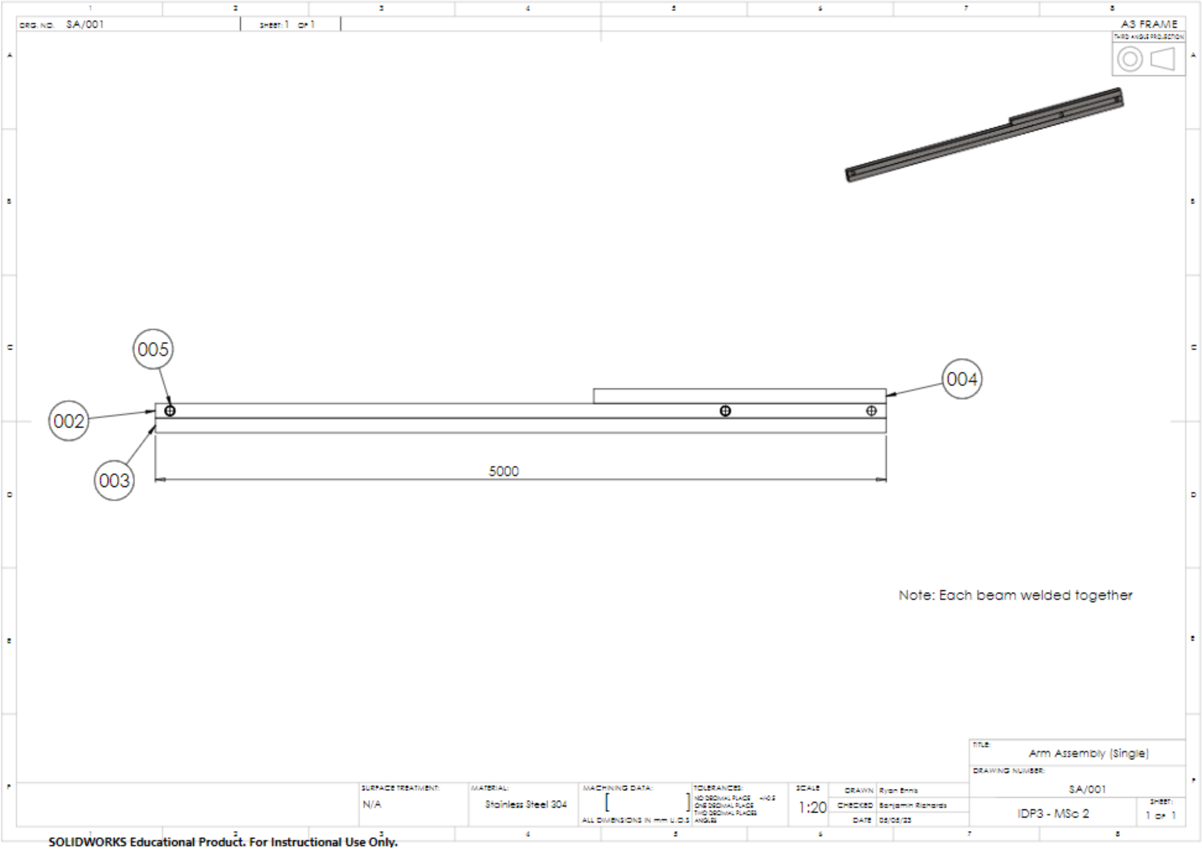



*Figure 39- Arm Assembly (single) CAD Drawing*

## 7.2. Appendix B: Routing Sheets

### 7.2.1. Part Sheets

*Table 20: Column Routing Sheet*

| Routing Sheet | | |
|---|---|---|
| Part Name: Column | | Part No.: 001 |
| Quantity: 380 | Matl: AISI Stainless Steel 304 | Planner: Ryan Ennis |
| Revision No.: 1 | Date: 25/04/23 | Order No.: |
| Op. No. | Description | Machine Tool |
| 1 | Drill 60mm diameter holes through side (x1) | Drill Press |
| 2 | Deburr holes | Deburring Tool |
| 3 | Inspection | |

*Table 21: Main Arm Routing Sheet*

| Routing Sheet | | |
|---|---|---|
| Part Name: Main Arm | | Part No.: 002 |
| Quantity: 380 | Matl: AISI Stainless Steel 304 | Planner: Ryan Ennis |
| Revision No.: 1 | Date: 25/04/23 | Order No.: |
| Op. No. | Description | Machine Tool |
| 1 | Drill 65mm diameter holes through side (x2) | Drill Press |
| 2 | Drill 60mm diameter holes through side (x1) | Drill Press |
| 3 | Deburr holes | Deburring Tool |
| 4 | Inspection | |

*Table 22: Winch Connection Bar Routing Sheet*

| Routing Sheet | | |
|---|---|---|
| Part Name: Winch Connection Bar | | Part No.: 006 |
| Quantity: 190 | Matl: AISI Stainless Steel 304 | Planner: Ryan Ennis |
| Revision No.: 1 | Date: 25/04/23 | Order No.: |
| Op. No. | Description | Machine Tool |
| 1 | Drill M16 holes 42mm deep (x16) | CNC Milling Machine |
| 2 | Deburr Holes | Deburring Tool |
| 3 | Inspection | |

*Table 23: Threaded Rod Routing Sheet*

| Routing Sheet | | |
|---|---|---|
| Part Name: Threaded Rod | | Part No.: 007 |
| Quantity: 570 | Matl: AISI Stainless Steel 304 | Planner: Ryan Ennis |
| Revision No.: 1 | Date: 25/04/23 | Order No.: |
| Op. No. | Description | Machine Tool |
| 1 | Turn down each end of the rod until required diameter met (60mm) | CNC Lathe |
| 2 | Cut a fillet (0.5mm rad) on each end of the rod | CNC Fillet Tool |
| 3 | Cut an external M60 thread 100mm on each end of the rod | CNC Lathe |
| 4 | Turn down rod until required surface finish is obtained | CNC Lathe |
| 5 | Inspection | |

*Table 24: Support Pillars Routing Sheet*

| Routing Sheet | | |
|---|---|---|
| Part Name: Support Pillars | | Part No.: 013 |
| Quantity: 380 | Matl: AISI Stainless Steel 304 | Planner: Ryan Ennis |
| Revision No.: 1 | Date: 25/04/23 | Order No.: |
| Op. No. | Description | Machine Tool |
| 1 | Cut a 20 degree angle from one end | Miter saw |
| 2 | Deburr sharp edges | Deburring Tool |
| 3 | Inspection | |

*Table 25: Piston Attachment Routing Sheet*

| Routing Sheet | | |
|---|---|---|
| Part Name: Piston Attachment | | Part No.: 016 |
| Quantity: 190 | Matl: AISI Stainless Steel 304 | Planner: Ryan Ennis |
| Revision No.: 1 | Date: 25/04/23 | Order No.: |
| Op. No. | Description | Machine Tool |
| 1 | Cut raw material to shape | CNC Milling Machine |
| 2 | Drill 60mm hole | Drill Press |
| 3 | Drill 55mm hole | Drill Press |
| 4 | Deburr sharp edges | Deburring Tool |
| 5 | Inspection | |

### 7.2.2 Operations Sheets

*Table 26: Column Operations Sheet*

| Operations List | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Part Name: Coulmn | | | | | | | | Part No.: 001 | |
| Revision No.: 1 | | Date: 25/04/23 | | Page 1 of1 | | | | Planner: Ryan Ennis | |
| Op. No. | Description | Machine Tool | Tooling | Cutting Speed (m/min) | Spindle Speed (rev/min) | Feed (mm/min) | Set-up time (min) | Op. time (min) | Remarks |
| 1 | Drill 60mm diameter holes through side (x1) | Drill Press | Carbide Drill Bit | 18 | 96 | 13 | 0.50 | 0.48 | |
| | | | | | | Total Times | 0.50 | 0.48 | |

*Table 27: Main Arm Operations Sheet*

| Operations List | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Part Name: Main Arm | | | | | | | | Part No.: 002 | |
| Revision No.: 1 | | Date: 25/04/23 | | Page 1 of1 | | | | Planner: Ryan Ennis | |
| Op. No. | Description | Machine Tool | Tooling | Cutting Speed (m/min) | Spindle Speed (rev/min) | Feed (mm/min) | Set-up time (min) | Op. time (min) | Remarks |
| 1 | Drill 60mm diameter holes through side (x2) | Drill Press | Carbide Drill Bit | 18 | 96 | 13 | 0.50 | 0.480769 | |
| 2 | Drill 65mm diameter holes through side (x2) | Drill Press | Carbide Drill Bit | 18 | 88 | 13 | 0.50 | 0.568182 | |
| | | | | | | Total Times | 1.00 | 1.05 | |

*Table 28: Winch Connection Bar Operations Sheet*

| Operations List | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Part Name: Winch Connection Bar | | | | | | | | Part No.: 006 | |
| Revision No.: 1 | | Date: 25/04/23 | | Page 1 of1 | | | | Planner: Ryan Ennis | |
| Op. No. | Description | Machine Tool | Tooling | Cutting Speed (m/min) | Spindle Speed (rev/min) | Feed (mm/min) | Set-up time (min) | Op. time (min) | Remarks |
| 1 | Drill M16 holes 42mm deep (x16) | CNC Milling Machine | Carbide Drill Bit | 46 | 910 | 16 | 0.50 | 0.03 | |
| | | | | | | Total Times | 0.50 | 0.03 | |

*Table 29: Threaded Rod Operations Sheet*

| Operations List | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Part Name: Threaded Rod | | | | | | | | Part No.: 007 | |
| Revision No.: 1 | | Date: 25/04/23 | | Page 1 of1 | | | | Planner: Ryan Ennis | |
| Op. No. | Description | Machine Tool | Tooling | Cutting Speed (m/min) | Spindle Speed (rev/min) | Feed (mm/min) | Set-up time (min) | Op. time (min) | Remarks |
| 1 | Turn down each end of the rod until required diameter met (60mm) | CNC Lathe | Carbide Turning Tool | 82 | 370 | 62 | 3.00 | 0.03 | |
| 2 | Cut a fillet (0.5mm rad) on each end of the rod | CNC Fillet Tool | Carbide | | | | | | |
| 3 | Cut an external M60 thread 100mm on each end of the rod | CNC Lathe | Carbide Turning Tool | 82 | 440 | 72 | 2.50 | 0.02 | |
| 4 | Turn down rod until required surface finish is obtained | CNC Lathe | Carbide Turning Tool | | | | | | |
| | | | | | | Total Times | 5.50 | 0.05 | |

*Table 30: Support Pillars Operations Sheet*

| Operations List | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Part Name: Support Pillars | | | | | | | | Part No.: 013 | |
| Revision No.: 1 | | Date: 25/04/23 | | Page 1 of1 | | | | Planner: Ryan Ennis | |
| Op. No. | Description | Machine Tool | Tooling | Cutting Speed (m/min) | Spindle Speed (rev/min) | Feed (mm/min) | Set-up time (min) | Op. time (min) | Remarks |
| 1 | Cut a 20 degree angle from one end | Miter saw | Carbide blade | | | | 1.70 | 1.20 | |
| | | | | | | Total Times | 1.70 | 1.20 | |

*Table 31: Piston Attachment Operations Sheet*

| Operations List | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Part Name: Piston Attachment | | | | | | | | Part No.: 016 | |
| Revision No.: 1 | | Date: 25/04/23 | | Page 1 of1 | | | | Planner: Ryan Ennis | |
| Op. No. | Description | Machine Tool | Tooling | Cutting Speed (m/min) | Spindle Speed (rev/min) | Feed (mm/min) | Set-up time (min) | Op. time (min) | Remarks |
| 1 | Cut raw material to shape | CNC Milling Machine | Carbide Turning Tool | 46 | 113 | 33 | 3.00 | 5.70 | |
| 2 | Drill 60mm hole | Drill Press | Carbide | 18 | 96 | 13 | 0.50 | 0.48 | |
| 3 | Drill 55mm hole | Drill Press | Carbide Turning Tool | 18 | 104 | 13 | 0.50 | 0.44 | |
| | | | | | | Total Times | 4.00 | 6.62 | |

## 7.3. Appendix C: Group Contribution/ Peer Review

*Table 3232- Group Contribution*

| Member Name | Contribution | Proposed Mark Adjustment |
|---|---|---|
| Benjamin Richards | Project manager<br>Personal sections: executive summary, project management, assumptions, business plan<br>Contributed to sections: PDS, concept selection, buoy shape, actuating mount, piston selection, hydraulic system, turbine selection, generator selection, hydraulic fluid, ethical and social, sustainability, risk evaluation, outsourced components<br>Culminated report (referencing and figures)<br>Assessment 1 presentation<br>Prototype production | 110 |
| Ryan Ennis | Personal Section: actuating mount, routing sheets<br>Contributed to sections: PDS, concept selection, assumptions, buoy shape, outsourced components, manufacture (buoy, actuating mount, piston connector)<br>Assessment 1 presentation | 110 |
| Gurparas Singh | Personal section: Hydraulic fluid<br>Contributed to sections: PDS, concept selection, assumptions, turbine selection, hydraulic fluid, hydraulic fluid, ethical and social, sustainability outsourced components<br>Assessment 1 presentation | 110 |
| Didin Issac | Personal section: Turbine Selection<br>Contributed to sections: PDS, concept selection, outsourced components, risk evaluation, CAD drawings<br>Assessment 1 presentation | 100 |
| Yicheng Chen | Personal Section: Buoy Shape<br>Contributed to sections: PDS, concept selection, CAD drawings | 90 |
| Zeyu Sun | Personal Section: Piston Selection<br>Contributed to sections: PDS, concept selection, outsourced components, sustainability, risk evaluation, CAD drawings | 100 |
| Jiyao He | Personal Section: Generator selection<br>Contributed to sections: PDS, concept selection, outsourced components, risk evaluation | 80 |

## 7.4. Appendix D: Gantt Chart

**MSc Mechanical Engineering**
**Group 2** **Wave Harvesting** Project start: Mon, 30-Jan-2023
Display Week: 1

| TASKS | PROGRESS | START | END |
|---|---|---|---|
| **1.0 Project Initialisation** | | | |
| 1.1 Team formation | 100% | 30-Jan-23 | 05-Feb-23 |
| 1.2 Challenge allocation | 100% | 30-Jan-23 | 05-Feb-23 |
| **2.0 Initial Research** | | | |
| 2.1 Enviromental Factors | 100% | 06-Feb-23 | 12-Feb-23 |
| 2.2 Energy Harvesting Methods | 100% | 06-Feb-23 | 12-Feb-23 |
| 2.3 Locations and Suitability | 100% | 06-Feb-23 | 12-Feb-23 |
| **3.0 Concept Generation** | | | |
| 3.1 Initial Requirements | 100% | 13-Feb-23 | 19-Feb-23 |
| 3.2 Define Brief | 100% | 13-Feb-23 | 19-Feb-23 |
| 3.3 Selection Matrix | 100% | 20-Feb-23 | 26-Feb-23 |
| 3.4 PDS | 0% | 20-Feb-23 | 26-Feb-23 |
| **4.0 Presentation 1 Preperation** | | | |
| 4.1 Belbin/Personality Testing | 50% | 27-Feb-23 | 05-Mar-23 |
| 4.2 System Breakdown | 0% | 27-Feb-23 | 05-Mar-23 |
| 4.3 Presentation 1 Formation | 50% | 27-Feb-23 | 09-Mar-23 |
| **5.0 Prelimenary Design Research** | | | |
| 5.1 Sub-System 1 | 0% | 13-Mar-23 | 26-Mar-23 |
| 5.2 Sub-System 2 | 0% | 13-Mar-23 | 26-Mar-23 |
| 5.3 Sub-System 3 | 0% | 13-Mar-23 | 26-Mar-23 |
| 5.4 Sub-System 4 | 0% | 13-Mar-23 | 26-Mar-23 |
| 5.5 Sub-System 5 | 0% | 13-Mar-23 | 26-Mar-23 |
| **6.0 Validation** | | | |
| 6.1 Flow Analysis- CFD | 0% | 27-Mar-23 | 09-Apr-23 |
| 6.2 Stress Analysis- FEA | 0% | 27-Mar-23 | 09-Apr-23 |
| 6.3 Material Selection- EduPack | 0% | 27-Mar-23 | 09-Apr-23 |
| **7.0 Manufacturing** | | | |
| 7.1 Process Optimisation | 0% | 10-Apr-23 | 16-Apr-23 |
| 7.2 Costing | 0% | 17-Apr-23 | 23-Apr-23 |
| **8.0 Final Submission** | | | |
| 8.1 Writing of Report | 5% | 13-Feb-23 | 08-May-23 |
| 8.2 Prototpe Generation | 0% | 10-Apr-23 | 12-May-23 |

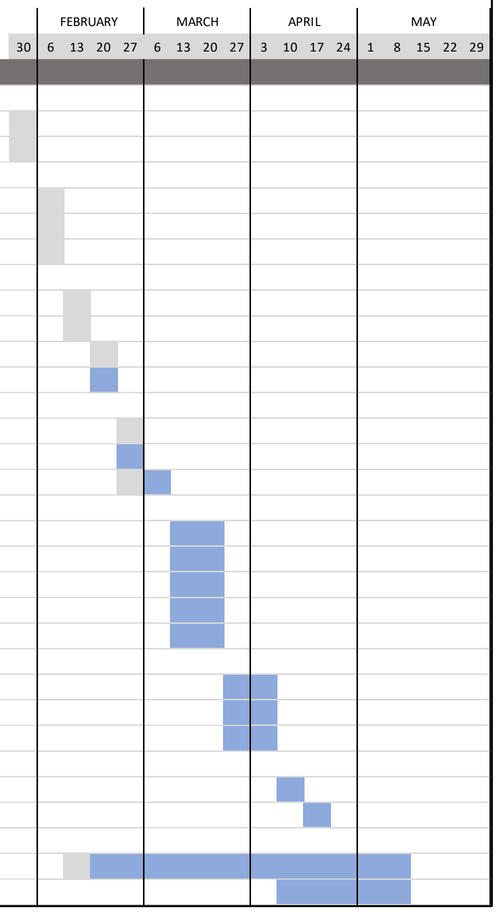



*Figure 40- Gantt Chart Plan*

## 7.5. Appendix E: Meeting Minutes

*Table 33 33- Meeting Minutes*

| Meeting: | Date: | Absentees: | Actions Completed: | Actions to be Taken: |
|---|---|---|---|---|
| 1 | 03 February 2023 | | Personal introductions | Compile email and student numbers for MS Teams |
| | | | Organised weekly meeting time | |
| | | | Discussed project | |
| 2 | 10 February 2023 | DM, ZS, YC, JH, RE | Discussed team meeting | Research into Offshore Energy Islands |
| | | | Not enough of the team present to complete larger actions | Answer respective questions |
| | | | | |
| 3 | 17 February 2023 | | Rearranged meeting time and spoke about supervisor meet | Distributed research into Enviromental factors |
| | | | Discussed new team project idea | Distributed research into wave energy harvesting |
| | | | Individually presented research from previous week | |
| 4 | 24 February 2023 | | Arranged secondary meeting + presentation practice slots | Distributed research into specific forms of harvesting |
| | | | Collaborated on a brief to direct concept selection | Gantt Chart |
| | | | Discussion session with team leader to clarify project vision | Start presentation document |
| 5 | 28 February 2023 | | Collated harvesting method research | Team role/personality test |
| | | | Started and completed concept selection matrix | Define sub-systems for role distribution |
| | | | Discussed Gantt chart and presentation progress | |
| 6 | 03 March 2023 | | Discussed progress on sub-system research | Fill in respective presentation slides |
| | | | Discussed concept presentation progress | Continue sub-system research |
| | | | Worked on presentation together | |
| 7 | 07 March 2023 | | Worked on presentation together | Fill in respective presentation slides |
| | | | Practiced presentation in a 1h group session in library rooms | Practice presentation script |
| | | | Wrote a presentation script together | |
| 8 | 09 March 2023 | | Worked on presentation together | Practice presentation script |
| | | | Practiced presentation in a 2h group session in library rooms | |
| | | | | |
| 9 | 10 March 2023 | RE, YC, JH | Congratulations after presentation | Continue sub-system research |
| | | | Discussion into sub-system research requirements | Start individual report |
| | | | Reviewed meeting times | |
| 10 | 22 March 2023 | | Discussed presentation feedback + new questions channel | Continue individual report |
| | | | Present individual report to date | |
| | | | Organised easter break calls | |
| 11 (online) | 04 April 2023 | YC | First meeting over easter break checking progress | Continue individual report |
| | | | Discussed any questions | |
| | | | Discussed team wide vs group wide wave data | |
| 12 | 18 April 2023 | | Presented reports so far | Continue individual report |
| | | | Discussed validation methods for each part | Complete equations/validation |
| | | | Finalised tasks to be completed before 5th May Deadline | |
| 13 | 25 April 2023 | GS, RE, DM, ZS | Presented reports so far | Finalise individual reports |
| | | | Discussed tasks to be completed before 5th may deadline | |
| | | | Tasks posted to Teams platform | |
| 14 | 02 May 2023 | GS | Discussed completion of routing sheets | Finalise routing sheets |
| | | | Discussed completion of CAD drawings | Finalise CAD drawings |
| | | | | |

## 7.6. Appendix F: Miscellaneous

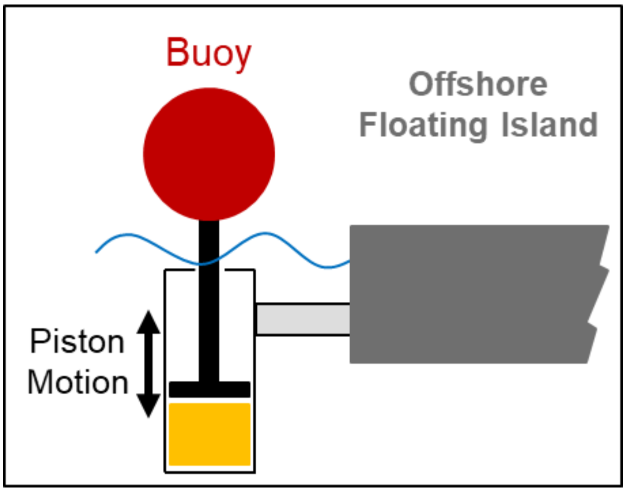



*Figure 41- Design Idea 2*

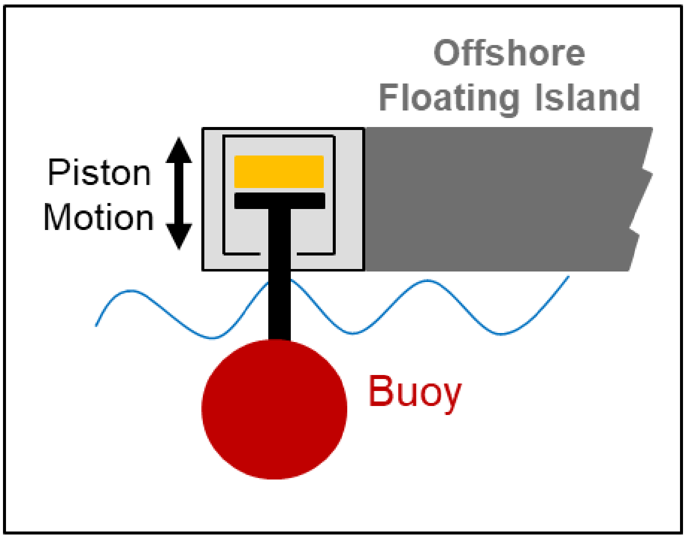



*Figure 42- Design Idea 3*

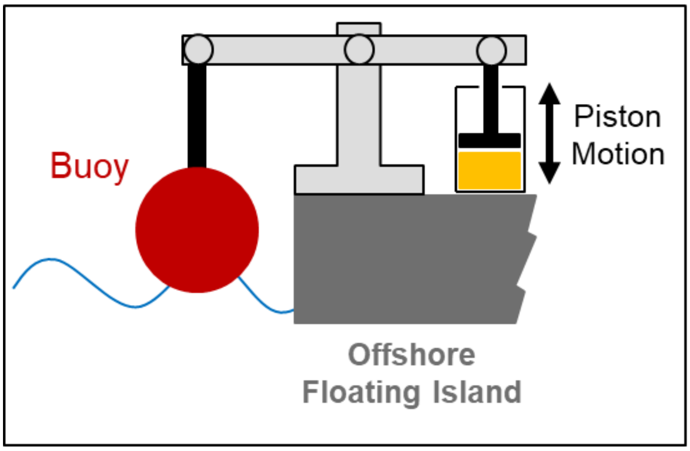



*Figure 43- Design Idea 4*

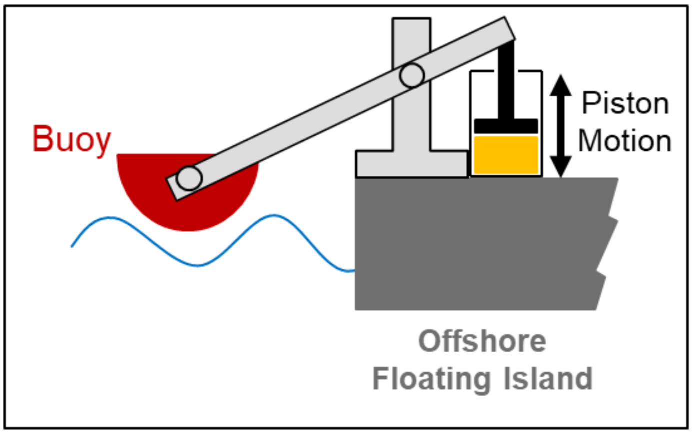



*Figure 44- Design Idea 5*

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**University of Birmingham**

School of Engineering

# Integrated Design Project 3

**FINAL GROUP REPORT**

**EESE**

**BEng**

**Power Systems and the Internet of Things**

| | |
|---|---|
| **Team Number** | 3 |
| **Group Number** | BEng EESE 3 |

| Student Names | ID Numbers |
|---|---|
| Karun Dhindsa | 2149584 |
| Michael Abram | 2049747 |
| Ahmed Al-massry | 2186957 |
| Mohammed Ali | 2181620 |
| Mate Lorincz | 2201834 |
| Alexandru Spinu | 2111022 |

| Feedback | | |
|---|---|---|
| Reflecting on the feedback that we have received on previous assessments, the following issues/topics have been identified as areas for improvement: | 1 | Improve communication within the report to have a logical set of design choices. |
| | 2 | Perform modelling and integration of different designs. |
| | 3 | Inclusion of justification by using references from experts. |
| In this assignment, we have attempted to act on previous feedback in the following ways: | 1 | Being clear and concise as well as presenting information in a logical format that is easily understandable. |
| | 2 | By designing multiple models and integrating them whilst performing simulations to evaluate performance. |
| | 3 | By carrying out research into various areas such that the choices made have strong justification. |
| Feedback on the following aspects of this assignment (i.e. content/style/approach) would be particularly helpful to us: | 1 | The structure and flow of information throughout the report. |
| | 2 | The clarity of information and limitations of using the approach that the group took. |
| | 3 | Feedback on the integration with other groups and the teamwork aspect of the project. |

# Executive Summary

The report focuses on the planning, design, and modelling of the electronic and electrical systems that the sustainable offshore energy island required. The electronic and electrical systems were designed with reference to the design specification which outlined what the overall group design must produce. To streamline the design process, the group was split into two sub-groups where a description and breakdown of the groups were provided, and the timeline of the electronic and electrical system design was illustrated using a GANTT chart. The technical area of the design was broken down into two key areas which were power systems and the Internet of Things. These technical designs included the research and modelling of the various subsystems within the two key areas and there was justification for why an approach was taken before evaluating the success of the approach that was taken. The report also highlighted the wider engineering implications where ethics, privacy and environmental factors were of focus and importance. In addition to this, there was a cost breakdown to understand the feasibility of the project followed by a technical review which highlighted the key findings of this report and what could be improved.

## Table of Contents

# Introduction

The project focused on building a sustainable offshore energy island which focuses on the design of artificial islands which house renewable energy sources to provide additional energy to the grid. The electronic and electrical engineering team focused on two key areas which were Power Systems and the Internet of Things (IoT). The Power Systems consisted of the design and operation of the power distribution network that transmits the energy from the renewable energy source back to the Australian Grid. IoT technologies were used to monitor and control the power distribution network.

These subsystems were designed to interface with the mechanical and civil groups' designs and through these interfaces' knowledge, expertise as well as any conflicts in design was shared to ensure that the subsystems were comprehensive and realistic. These subsystems were created by the evaluation of existing processes as well as the development of new protocols. The report covers a technical justification for why the final design approach was selected, observed the wider implications of the design, and considered the financial and business position.

# Scope

The scope of the design was to design, model and build the power distribution network and the IoT systems for the offshore energy island. The following key areas were developed:

1. The design of the power distribution network included a solar farm and two wave energy converters. The design also considered an energy storage system. SIMULINK was used to model and simulate the power distribution network.

2. The development of the IoT system would include a network of sensors, communication protocols as well as emergency protocols to monitor and control the power distribution network and the communication to companies within Australia when there is a need for maintenance.

3. The collaboration with stakeholders, such as the Australian government, technology companies and local communities ensures that the design adheres to legal regulations whilst aligning with the goals of promoting environmental sustainability and energy security.

The focus on Power Systems and IoT systems allowed the group to contribute to the development of a sustainable and efficient offshore energy island whilst focusing on collaboration with industry leaders.

# Group Interfaces and Project Management

## Group Interfaces

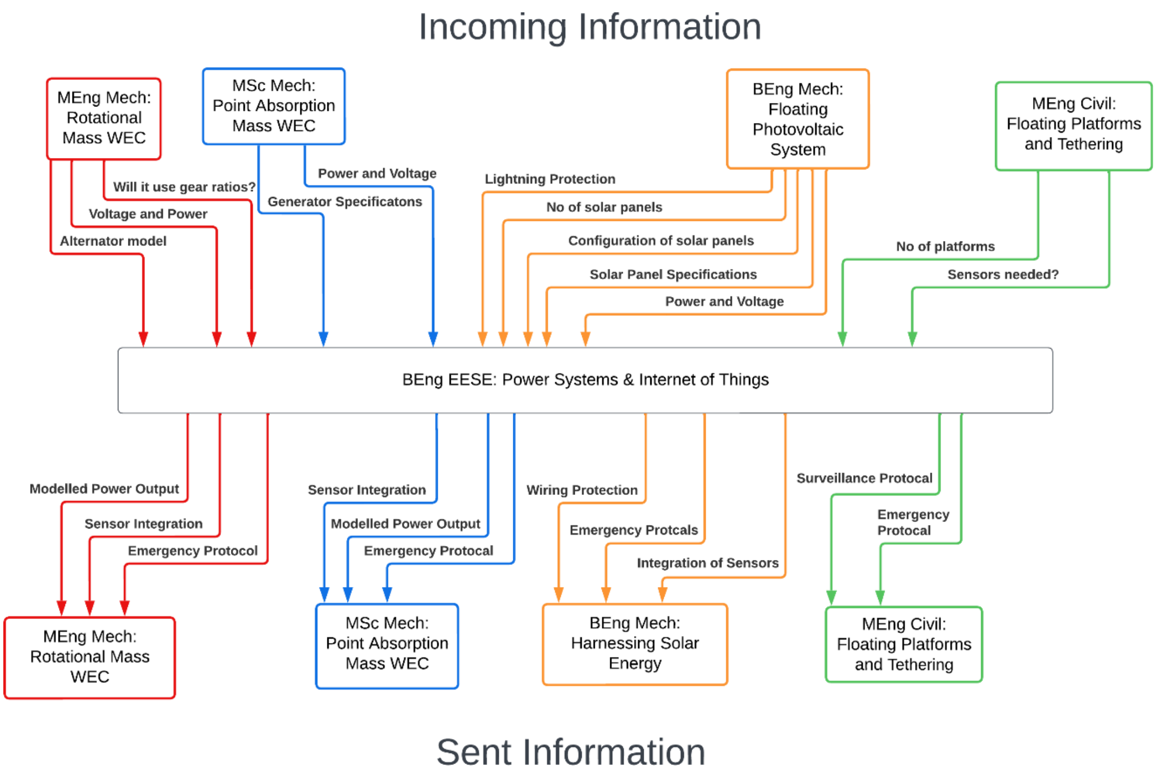


*Figure 1 - Diagram showing the inbound and outbound information between the various groups*

*Figure 1* represented the flow of information between our group and the mechanical and civil groups. The top of the diagram showed the information that was sent to the group which allowed us to create models and diagrams that would be accurate to what the sustainable offshore energy island needed. The information that was received was critical in the design and optimisation of the power distribution network and the IoT systems, as it allowed us to identify the constraints and opportunities of the project.

Similarly, the bottom of the diagram showed the information that was sent to the other groups which included the modelled values of the power output and protocols which ensured that our design met the requirements of the other groups and that the entire project was integrated and cohesive.

Overall, the diagram highlighted the importance of collaboration between the different groups whilst working on a sustainable offshore energy island. The sharing of information ensured that the project was successful and met the needs of the stakeholders.

## Project Management

Due to the size of the project, it was necessary to have efficient and effective project management. This was done by holding group meetings regularly (meeting minutes are shown in the appendix). Objectives were set for the meeting before such that all meetings ran efficiently. Within the meetings, all the opinions of the group were listened to before any objectives were set regarding what the group needed to do to ensure that the design met the requirements and was integrated into the project. There were also regular meetings with the group supervisor to ensure that the designs that were proposed met the technical requirements of the challenge (meeting minutes are shown in the appendix).

In addition to the meetings, subgroups were created (as shown in *Figure 2)* such that members could focus their attention on certain areas instead of focusing on all aspects of the design – this approach allowed greater detail in the design. The group leader monitored the progress of the group members to streamline their design which contributed to the overall design and ensured that deadlines were met such that the design was delivered on time. As well as managing other the group, the group leader also consulted with the other groups before significant decisions were made to allow cohesiveness between the groups.

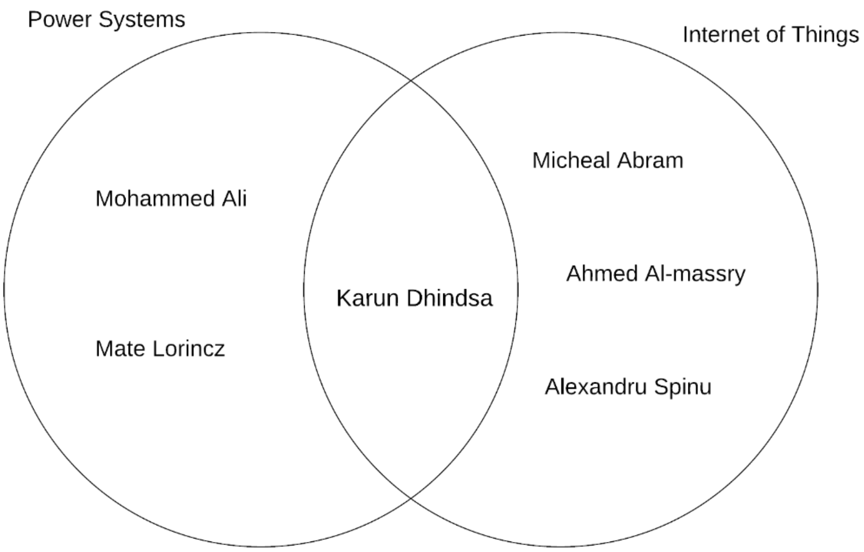


*Figure 2 - Venn Diagram showing the focus area for each group member*

| Objective | Objective Type | Start Date | End Date | Duration | | Week 3 (w/c 13/2) | | | | | Week 4 (w/c 20/2) | | | | | Week 5 (w/c 27/2) | | | | | Week 6 (w/c 6/3) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Fri | Mon | Tue | Wed | Thu | Fri | Mon | Tue | Wed | Thu | Fri | Mon | Tue | Wed | Thu | Fri | Mon | Tue | Wed | Thu | Fri |
| Research questions to build design specification | Research | 11-Feb | 14-Feb | 3 | | | | | | | | | | | | | | | | | | | | Presentation Deadline | |
| Research questions to build design specification | Research | 14-Feb | 21-Feb | 7 | | | | | | | | | | | | | | | | | | | | | |
| Reseach questions to finalise the building of design specifications | Research | 21-Feb | 27-Feb | 6 | | | | | | | | | | | | | | | | | | | | | |
| Work on Design Brief, Product Design Specification, and further presentation requirement | Task Completion | 23-Feb | 06-Mar | 11 | | | | | | | | | | | | | | | | | | | | | |
| Complete PowerPoint slides for presentation | Presentation | 03-Mar | 06-Mar | 3 | | | | | | | | | | | | | | | | | | | | | |
| Contribute to Team-Level Presentation design | Presentation | 06-Mar | 08-Mar | 2 | | | | | | | | | | | | | | | | | | | | | |

*Figure 3 - GANTT chart (Week 3 - Week 6)*

| Objective | Objective Type | Start Date | End Date | Duration | Week 7 (w/c 13/3) | | | | | Week 8 (w/c 20/3) | | | | | | Week 9 (w/c 17/4) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Mon | Tue | Wed | Thu | Fri | Mon | Tue | Wed | Thu | Fri | Easter Break (3 Weeks) | Mon | Tue | Wed | Thu | Fri |
| Power Systems Modelling | Design | 13-Mar | 21-Apr | 39 | | | | | | | | | | | | | | | | |
| Model Integration | Design | 13-Mar | 21-Apr | 39 | | | | | | | | | | | | | | | | |
| Protocol Designs | Design | 13-Mar | 21-Apr | 39 | | | | | | | | | | | | | | | | |
| Cloud Service Design | Research | 13-Mar | 21-Apr | 39 | | | | | | | | | | | | | | | | |
| Sensor Design | Research | 13-Mar | 21-Apr | 39 | | | | | | | | | | | | | | | | |

*Figure 4 - GANTT chart (Week 7 - Week 9)*

| Objective | Objective Type | Start Date | End Date | Duration | Week 10 (w/c 24/4) | | | | | Week 11 (w/c 1/5) | | | | | Week 12 (w/c 8/5) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Mon | Tue | Wed | Thu | Fri | Mon | Tue | Wed | Thu | Fri | Mon | Tue | Wed | Thu | Fri |
| Report Draft | Report | 21-Apr | 09-May | 18 | | | | | | | | | | | | Report Deadline | | | |
| Final Draft and Comments | Report | 21-Apr | 21-May | 18 | | | | | | | | | | | | | | | |

*Figure 5 - GANTT chart (Week 10 - Week 12)*

The group also used a GANTT chart (as shown in *Figures 3, 4 and 5*) to manage the project timeline, which allowed the group to keep up with the deadlines. The GANTT chart also provided a visual representation of the activities that were required for the project design, and their dependencies and durations. The use of the GANTT chart allowed for the monitoring of the progress against the planned progress which allowed us to identify deviations or delays which allowed us to take any corrective action. The adoption of this approach allowed us to remain on track and not fall behind schedule.

# Design Requirements

*Table 1 - Design Specification*

| Design Factor | | Description |
|---|---|---|
| 1 | Performance and Product Requirements | • Receive power output from generators in AC or DC.<br>• Store the received power from generators and solar panel farms.<br>• Provide additional power to the Australian grid.<br>• Have 1 central location for energy control centre.<br>• Have 1 central location for the substation. |
| 2 | Power Conversion | • Use a DC-DC converter to ensure power from solar panels is stable.<br>• Use an AC-DC converter to ensure power from AC generators is stable.<br>• Use IGBT due to its suitability with high voltages and power. |
| 3 | Power Transformation | • Power output from the generators will need to be transformed to a high voltage to ensure there is a minimal power loss and the power is compatible with the Australian grid |
| 4 | Power Transmission | • Submarine cables will have to transmit energy to a power station in southern Victoria, Australia.<br>• Energy must be transmitted at 500 kV to match the voltage used by the 500 kV transmission line in the Australian grid (NEM).<br>• Cables need to be designed according to an approximate specification at 500 kV<br>• The conductor of the cable needs to be made of suitable material to withstand high voltages. |
| 5 | Power Storage | • Able to provide continuous power throughout peak times.<br>• Responds adequately to fluctuations.<br>• Able to store up to 200 MWh of power.<br>• Withstand harsh environmental conditions.<br>• Be based on ‘green’ materials.<br>• Scalability in deployment<br>• Reasonable longevity of battery lifecycle<br>• Lessen maintenance needs. |

| | | |
|---|---|---|
| 6 | Control | • Ensure that the power sent to the grid is the demanded amount of power to not face any penalties.<br>• Use Thyristors to allow precise control of power delivery |
| 7 | Internet of Things | • Establish overall architecture.<br>• Decide upon communication protocol.<br>• Server type and location (local and/or cloud)<br>• Data transfer technology<br>• Data types<br>• Security algorithm |
| 8 | Safety | • Use fuses and circuit breakers to protect a circuit against overcurrent and short circuits.<br>• Surge protectors protect electronic devices and equipment from damage caused by power surges.<br>• Disconnector to isolate a section of a circuit for maintenance, repair, or inspection purposes.<br>• Protection from extreme weather events |
| 9 | Environmental | • Minimal disruption to local ecosystems, especially migratory routes<br>• Damages won’t result in the spilling of hazardous chemicals |
| 10 | Legal | • Licenses need to be obtained by the state to transmit energy. |

*Table 1* shows the final design specification which outlines the requirements that the design must meet to ensure that it is successfully integrated into the overall project. Also, the design specification serves as a blueprint where it acts as a bridge between the initial concept idea to the final design. Furthermore, the comprehensiveness of the design specification led to a clearer and shared understanding of what was required which led to a more efficient design process.

# Technical Design – Power Systems

## Overview of Power System Network

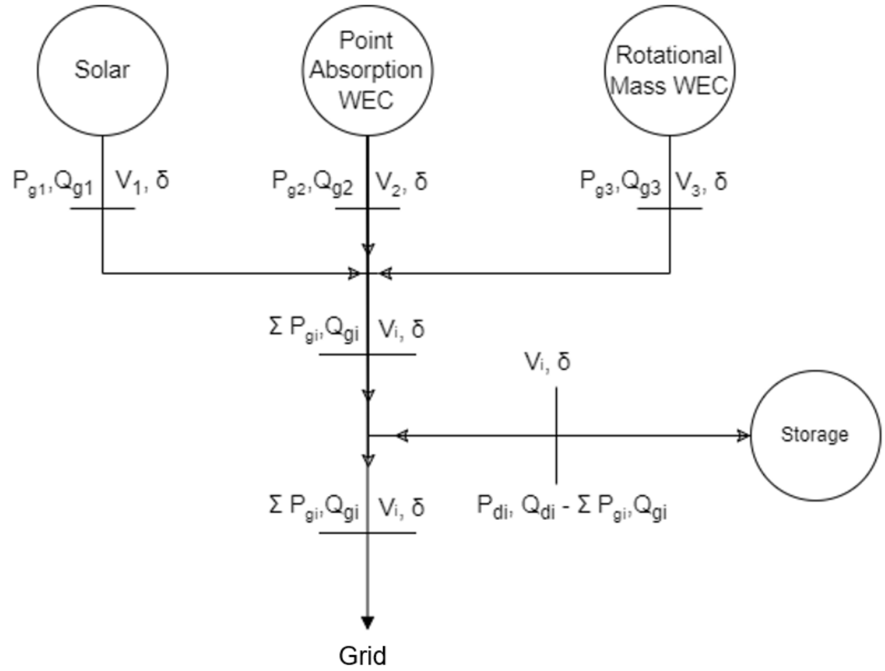


*Figure 6 - High-Level Diagram of the Power Distribution Network*

As shown in *Figure 6* there are three energy sources: solar, point absorption wave energy converter (WEC) and Rotational Mass WEC. At a high level, the energy from the three sustainable energy sources is combined where during low periods of demand the energy would be sent to storage. In retrospect, during periods of high demand, the energy would be sent from storage heading towards the Australian grid. The energy accumulated from the three energy sources and/or storage was transmitted to the Australian grid whilst making sure that the transmission of energy met the standards and regulations that were set by the Australian Energy Market Commission (AEMC) [1].

To meet the requirements set out by the AEMC and the storage units step-up and step-down transformers were implemented to ensure that the correct voltage and power were used to store energy and transmit energy to the Australian grid. With reference to *Figure 6* once the energy from the three sustainable renewable energy sources is accumulated the energy received from storage would be sent to a High Voltage Direct Current (HVDC) Transformer. HVDC had the necessary advantage that we can transmit energy over long distances due to there being no technical restriction of the maximum permissible cable [2].

Due to the complexities of the HVDC transformer the design of the power distribution network required the use of Siemens due to their speciality in HVDC transformers and experience in developing offshore substations. Using the HVDC Plus Transformer technology allowed us to consult with Siemens to design a transformer that would be suitable for the power distribution network. Siemens HVDC Plus Transformer allowed for the energy transmission back at 500 kV as they allowed for customisation [3]. The collaboration with Siemens and the Prysmian Group allowed for the housing of the energy control centre, storage unit and other components that were needed for the power distribution network as the stakeholder had experience building other offshore substations such as SylWin1 [4].

# Power System Protection

The integration of High Voltage Direct Current (HVDC) into power systems emerged in the mid to late 20$^{th}$ century [5] and offers several benefits, including bulk electricity delivery, long-distance transmission, asynchronous interconnections, and reduced transmission costs and environmental impact [2]. However, the HVDC system is also vulnerable to DC faults, which generate a high peak and steady values of fault current within a few milliseconds. Therefore, high-speed fault detection and isolation methods are essential to ensure the reliable operation of an HVDC grid [6].

Various devices will be employed throughout the design to protect the system in case any faults arise creating inadequate operating conditions, lowering the efficiency of power generation and harming components in the system. The main components of the protection system involve: Current transformers (CT) and voltage transformers (VT) to measure the operating conditions of the device, protective relays to detect faults using values from the CT and VT, circuit breakers to isolate the faulty equipment and allow troubleshooting and maintenance, and communication channels to transmit the necessary data to and from the protective devices [7]. The protection system is designed following the requirements specified in Table 2.

*Table 2: Requirements of Power system protection:*

| Requirement | Definition |
|---|---|
| Selectivity | Detect and isolate the specific faulty component. |
| Stability | Leave healthy circuits intact for continuity of power supply. |
| Speed | Operate as quickly as possible to minimise damage to components, stability, and personnel. |
| Sensitivity | Detect even the smallest values of faulty current before severe damage. |

Table 3 goes through the faults that may occur in the transformer and the devices used to deal with these faults.

*Table 3: Transformer Protection*

| Fault | Cause | Protection Method |
|---|---|---|
| Transformer Overheating | Too much power on the secondary transformer side | Thermocouple |
| Damage to transformer windings | Conductor meeting an earth ground or an abnormal connection between phases | Overcurrent relay |
| Overcurrent | Short circuit/phase to ground | Overcurrent relay |
| Internal faults | Insulation failure, manufacturing defects, human error, overloading | Differential relay |

Table 4 goes through the faults that may occur in the transmission lines and the devices used to deal with these faults.

*Table 4: Transmission Line Protection*

| Fault | Cause | Protection Method |
|---|---|---|
| Line overheating | A drop in line impedance | Distance relay |
| Over voltages | Lightning/switching | Pre-set over voltage relay |
| Generator and system losing synchronicity | Line switching/ loss of a generator | Out-of-step relay |
| Over Current | Short circuit/phase to ground | Over-current relay |

Table 5 goes through the faults that may occur in the generator and the devices used to deal with these faults.

*Table 5: Generator Protection*

| Fault | Cause | Protection Method |
|---|---|---|
| Frequency variations | Poor speed regulation/power grid disruption | Frequency relay |
| Over/under voltages | Automatic Voltage Regulator malfunction/sudden voltage drop | Over/under voltage relay |
| Loss of synchronicity | Line switching | Out-of-step relay |
| Internal faults | Phase to phase/phase to ground/manufacturing defects | Differential relay |
| Overcurrent | Short circuit/phase to ground | Overcurrent relay |

Table 6 goes through the faults that may occur in the battery storage and the devices used to deal with these faults.

*Table 6: Battery Storage Protection*

| Fault | Cause | Protection Method |
|---|---|---|
| Overcurrent | Short circuits/phase to ground | Overcurrent relay |
| Overvoltage | Voltage spikes/surges | Overvoltage relay |
| Overheating | Short circuit | Thermocouple |

# Energy Farm 1 – Solar

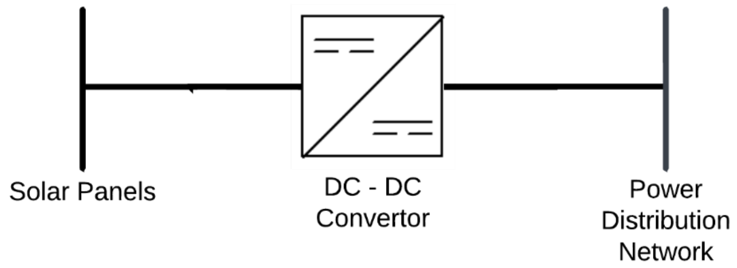


*Figure 7 - High-Level Diagram showing the Power Flow from the solar panel to the power distribution network*

*Figure 7* denoted how the energy from the solar panel was sent to the power distribution network. The output of the solar panel depends on various factors such as temperature, luminance, humidity and much more [8]. Hence, there was a need for a DC-DC converter to smooth the output of the solar panels. The DC-DC converter consisted of a boost converter to provide two advantages which were the smoothing of the output and boosting of the voltage [9]. The boost converter normally consists of an inductor, MOSFET, diode and capacitors [9] to reduce the ripple voltage at the output stage. Due to the high power voltage output, the MOSFET was changed to an IGBT as it can handle higher voltages better due to its ability to withstand higher voltage differentials without breakdown [10]. Through these design choices, *Figure 7* was modelled as shown in *Figure 8* such that the performance could be evaluated.

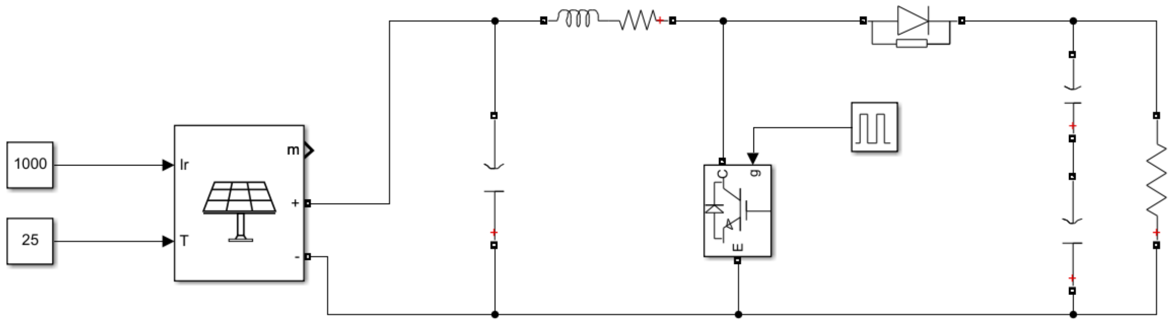


*Figure 8 - Circuit Diagram (designed using  SIMULINK) of the solar panel connected to a boost converter*

## Energy Farms 2 and 3 - Wave Energy Converters

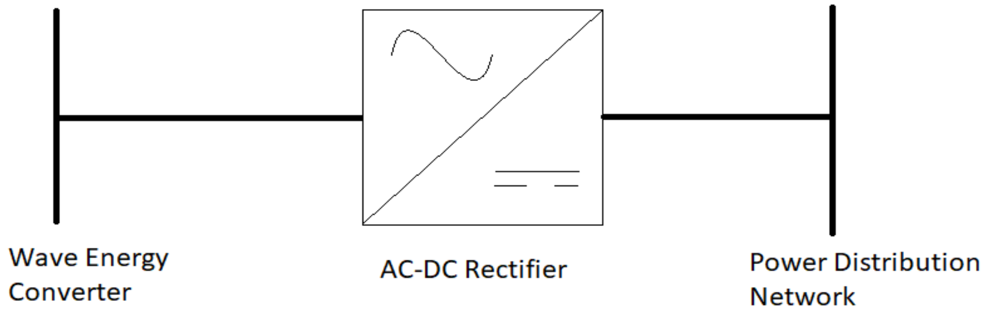


*Figure 9 – High-Level Diagram showing power flow from WECs to the network*

Functionally the 2 types of wave energy converters behave the same in an electrical grid. Waves provide kinetic motion which provides rotation to an alternator. Though the parameters of the alternators are different, they both output AC currents which need to be rectified to allow the battery system to be charged. Each WEC requires its own rectifier before being linked with others on its platform, as the specific conditions will vary even within the platform groups. A rectifier based on thyristors is used, shown in *Figure* 10 as it allows more precise control over the output, especially regarding overspeed where the alternators provide too much power.

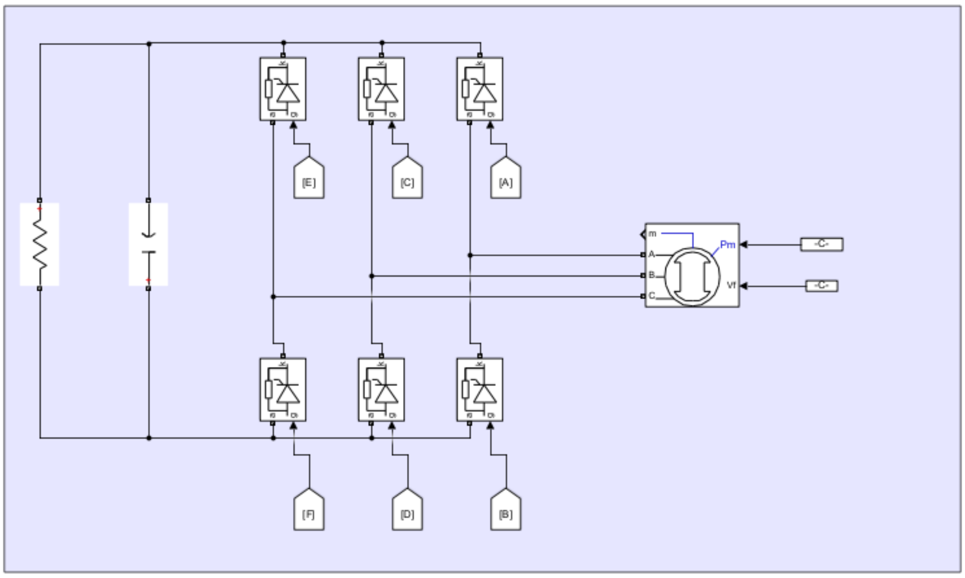


*Figure 10 – Circuit diagram of the rectifier and alternator modelled by a synchronous machine block*

## Storage

Energy islands are self-sustaining power systems and thus require energy storage systems that can ensure a reliable and consistent power supply. Several storage forms can be used on an energy island such as batteries, pumped hydro storage and thermal energy storage. Batteries are a popular form of energy storage because of their high efficiency, response time and flexibility. They can be used for both long-term and short-term storage, allowing for emergency use, and are particularly suited to off-grid applications. Examples of battery technologies used on energy islands include lithium-ion batteries, flow batteries and liquid-metal batteries, such as those developed by Ambri [11].

Liquid-metal batteries pose many great advantages in the context of use for storage on an offshore energy island, including:

- High energy density: Liquid metal batteries can store a large amount of energy in a small space, making them ideal for applications where space is limited, such as an energy island [12].
- Long life cycle: Can be charged and discharged many times without losing capacity, making them an efficient and cost-effective form of storage [12].
- Safe and environmentally friendly: Made from non-toxic and non-flammable materials and can be easily recycled at the end of their lifetime [13].
- Scalability: Can be scaled up and down to suit the requirements of the energy island, making them a flexible and versatile energy storage solution [13]

## Design of storage system

When designing such a system, it is important to ensure that power can be sent to and from storage at the required voltages (450 V stepped up) with minimal power losses. Minimising power losses allows for a more efficient and environmentally friendly communication of power from generation to storage, and to the grid.

To address the issue of power output dependency on the weather (PV panels depend on available sunlight, which can significantly vary over time) [14], the storage system can be used to store excess energy generated in periods of high sunlight, then release it back into the grid when the PV panels are not generating enough power.

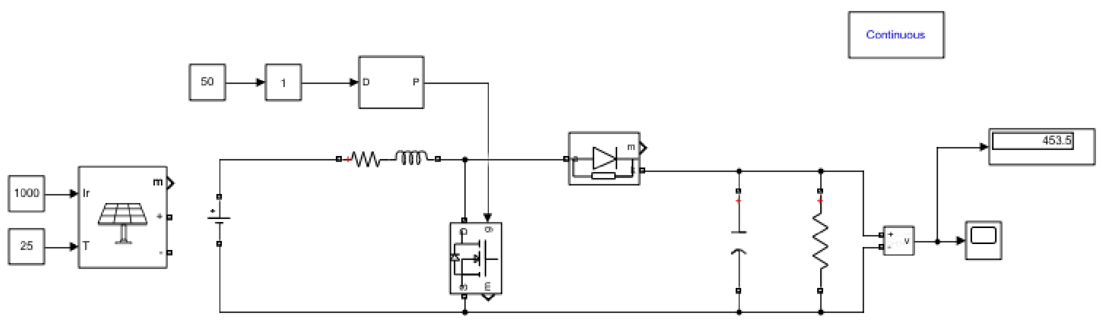


*Figure 11 - Case of the liquid metal batteries releasing the power back into the grid*

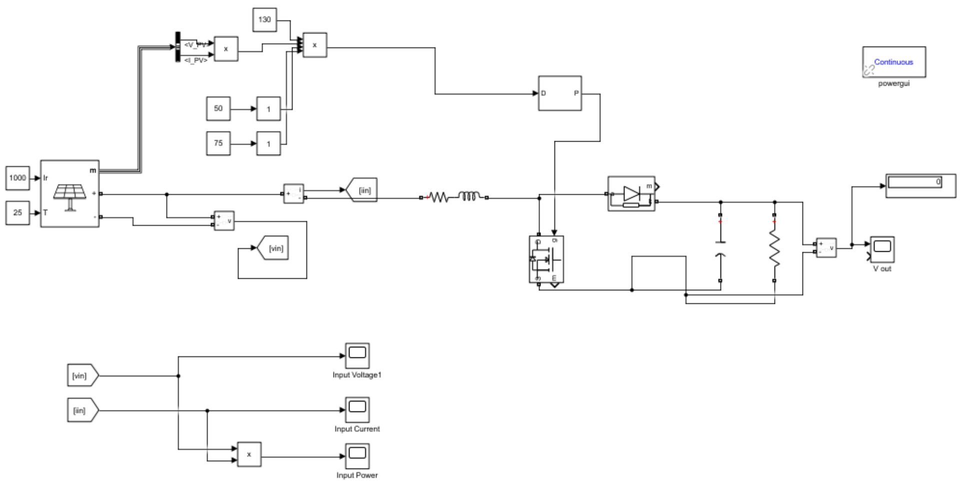

*Figure 12 - case of PV panels, rotational mass and point absorption sending excess power to storage. Point absorption and rotational mass are denoted here by constants 50 and 75, each individually adjustable by the slider based on performance.*

As displayed in both cases, the system can send excess power to the grid within the tolerance of the required voltage to be able to transport the energy back to the mainland (with a step of 2), as well as the case of stepping down the voltage to charge the batteries. The use of calculated values represented by constants allows for the simulation of these specific cases. The components used to achieve this include:

- MOSFETs for faster switching speeds, lower switching losses and higher efficiency [15].
- Transformers (emulated using a slider) step up or step down the voltage of the power being sent to or from the grid and isolate the storage system from the grid for safety and reliability purposes [16].
- Diodes to rectify the power and ensure flow in one direction only. When used in conjunction with the other components, such as the capacitor in this analysis, the voltage waveform is smoothed out to reduce ripple [17].

## Underwater Cables

Submarine power cables are becoming more important each decade. They have been used to transfer offshore renewable energy from wind, tidal and wave onto land. There are inter-connector cables that are used to move energy around Europe, therefore making them essential in designing a sustainable environment [18]. Underwater cables are essential to transmit energy from our island ashore as it is the only current way to do so. Therefore, we will be using submarine cables to transmit our energy.

When transmitting energy over longer distances, the cable would have to be of HVDC (High Voltage Direct Current) as AC cables are limited by how far they can go. If the cable length would need to be extended, then a higher system voltage can be applied. We will in return, be using HVDC cables to send our energy back to the mainland [18].

The length of the cable would have to be 90 km to be able to follow the route back to the mainland and the route to the power station after the energy has been transmitted ashore.

*Table 7 – Cable Structure and Conditions*

| Type | Parameter | Boundary condition | |
|---|---|---|---|
| | | ±800 kV | ±1100 kV |
| Structure | Conductor area $s$ | $s \leqslant 4000$ mm$^2$ | $s \leqslant 4500$ mm$^2$ |
| | Insulation thickness $d$ | $d \leqslant 45$ mm | $d \leqslant 43$ mm |
| Current | $I$ at 1.0 pu | 2500 A (4000 MW), (5000 A) 8000 MW | 5454 A (12000 MW) |
| | $I$ at 1.2 pu | 3000 A (4000 MW), 6000 A (8000 MW) | 6545 A (12000 MW) |
| Working Temperature | $T$ | $T \leqslant 110$ °C | |

*Table 8 – Cable Conditions*

| Type | Parameter | Boundary condition | |
|---|---|---|---|
| | | ±800 kV | ±1100 kV |
| Laying condition | In water | Cable gap 50 m, outer temperature 30 °C, thermal conductivity factor 400 W/(m$^2$·K) | |
| | Laying under water | Cable gap 50 m, outer temperature 4 °C, thermal conductivity factor 1 W/(m$^2$·K) | |
| | Laying onshore | Cable gap 50 m, outer temperature 25 °C, thermal conductivity factor 1 W/(m$^2$·K) | |

From Tables 7 and 8, we can observe how the structure of the cables would differ under different conditions, so we can estimate how our cables would be designed for them to be suitable under our conditions. Since the voltage and power would be transmitted at 500 kV and 56 MW respectively, the insulation thickness would be an estimated 46 mm, while the cross-sectional area of the conductor used in our cables, will be estimated at 2500 mm$^2$ [19].

The material of our cables will include a conductor made from copper, while the insulator will be out of cross-linked polyethene (XLPE). The XLPE insulator is specifically designed to handle high voltages as it has the electrical properties needed [20].

# Evaluation – Power Systems

## Evaluation Strategy

### Energy Farm 1 – Solar

The evaluation of the solar farm involved looking at the power and voltage output across the solar farm per platform and how it would scale with the total number of platforms which was 130. The analysis of the voltage and power waveforms ensured that the subsystem was working as expected and where its limitations were. This was achieved using SIMULINK simulations after the circuits were modelled.

The analysis of the simulated power curve allowed for the comparison with the desired power output of the solar panel array, which provided the identification of any discrepancies in the subsystem design and how the model could be improved.

### Energy Farms 2 and 3 – Wave Energy Converters

Evaluation of the WECs involved modelling the chosen alternators as closely as possible to ensure control was possible when handling large power generation. Analysis of the voltage and power outputs could be used to gauge how large an impact the WECs had on the network. SIMULINK simulations were used to provide a visual representation of the output(s).

### Power Output to Australia

The evaluation of the three combined energy farms looked at the SIMULINK simulations considering the total number of platforms. These simulations allowed us to understand if the voltage regulations for transporting energy to mainland Australia were being met had how the circuits handled the large power outputs.

### Storage:

It is important to evaluate the voltage and the smoothness of the voltage waveform to ensure the correct operation of the system and that it is within the required specifications [21]. This can be achieved using simulation.

A key parameter considered was the voltage level. In grid-connected systems such as this one, this involved ensuring the voltage being sent to the grid was within the specified range of 400-515 V [22], which can then be stepped up and transported to the mainland using the underwater cables at 500 kV.

Another crucial factor to consider is the smoothness of the voltage waveform. Distortion can be caused by a variety of factors such as non-linear loads, transients, and the presence of harmonics [23]. In addition, the presence of high-frequency noise on the power signal itself can also affect the performance of the storage system. It is therefore important to evaluate the waveform quality to ensure that it meets the required specifications and does not adversely affect the performance of the system.

## Results of Evaluation

Energy Farm 1 – Solar

The solar panel was designed with ideal characteristics with 1000 W/m$^2$ for the irradiance and 25 °C for the temperature. These parameters and the required information from the solar panel group allowed for the solar panel to be modelled correctly where the power and voltage approximately were 81 kW and 550 V respectively as shown in the figures below.

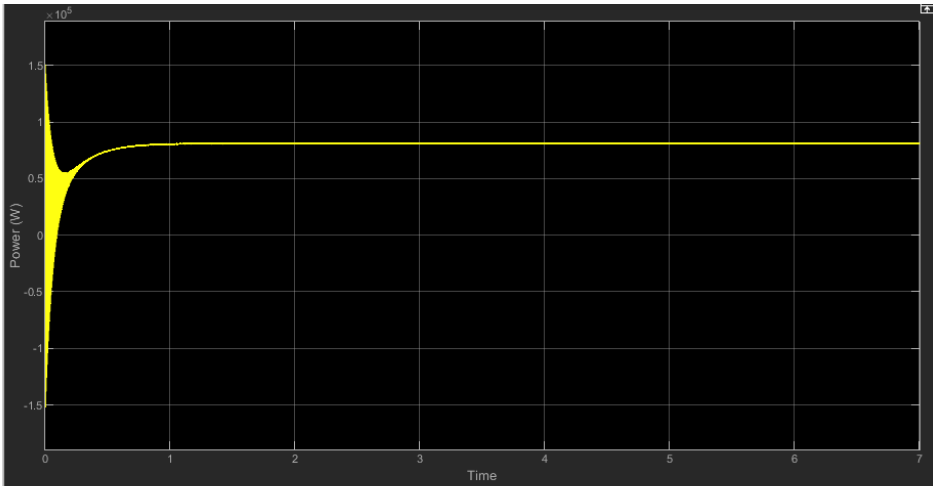


*Figure 13 – Power Output Waveform of the PV Array*

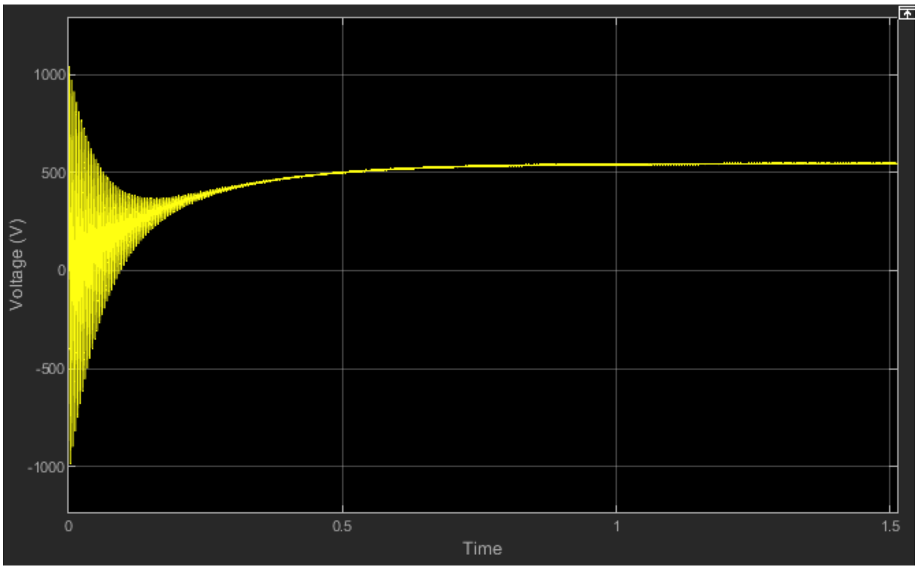


*Figure 14 – Voltage Output Waveform of the PV Array*

As seen in the figures above at the start of the operation the waveform diagrams are undesirable as the output needed to settle for some time and over the lifecycle of the solar panel due to the spikes it would result in the reduction of the lifetime of the solar panel. Therefore, as mentioned above in the technical design the DC-DC converter helped in smoothing these waveforms whilst preventing any spikes due to the inductors and capacitors within the circuit as shown in *Figure 8.*

Once the DC-DC converter was implemented the output power and voltage from the DC-DC converter were approximately 81 kW and 573 V respectively.

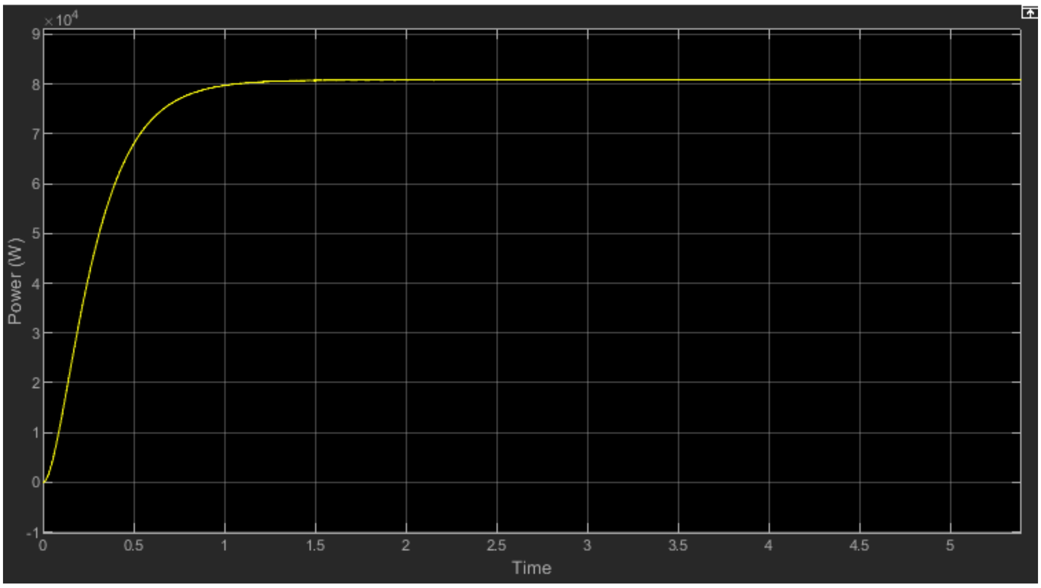


*Figure 15 - Power Output waveform from the DC-DC converter*

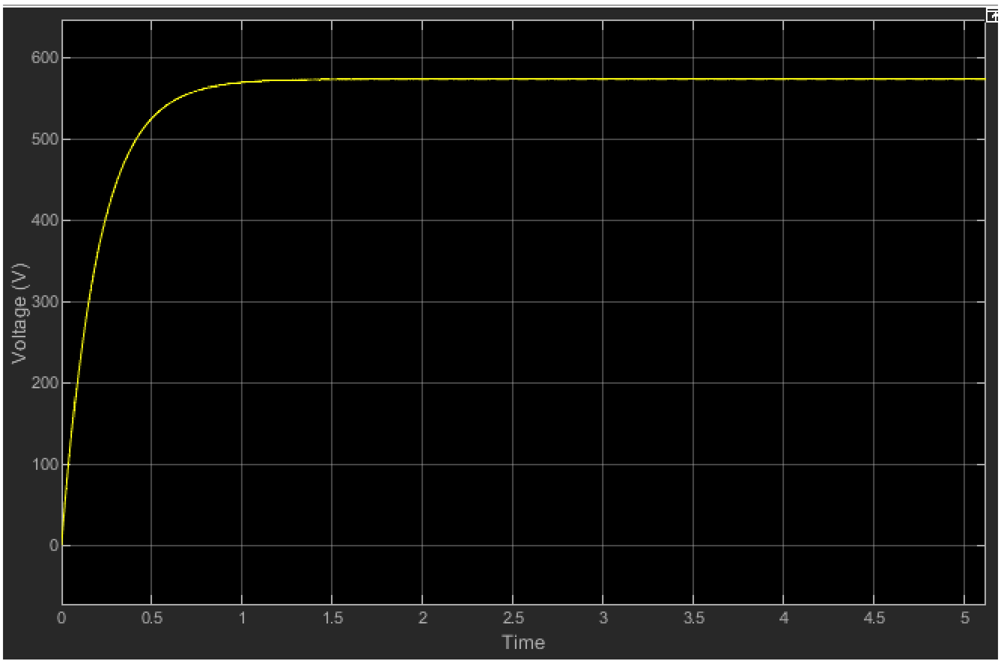


*Figure 16 - Voltage Output waveform from the DC-DC converter*

Therefore, as shown from the figures above the problem from the PV array was fixed where the voltage and power output were acceptable to be integrated into the rest of the grid. These figures also have shown that from the use of capacitors and inductors, the voltage and power waveforms quickly settle within 1.5 seconds when simulated. As these graphs show the voltage and power per platform, due to the modular design of a project these values can be easily scaled (using 130 platforms) to find the total power and voltage output which were approximately 10.5 MW and 75 kV respectively.

## Energy Farm 2 and 3 – Wave Energy Converters

Using the datasheet of the chosen alternator, the model could be made extremely accurate in parameters, but without large amounts of testing and data gathering of weather patterns only ideal constants could be used for the mechanical input.

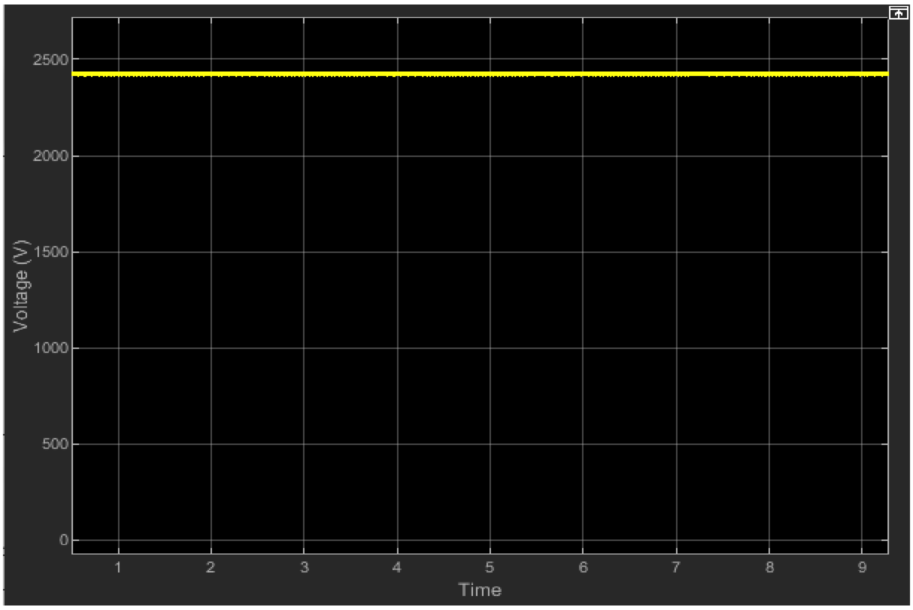


*Figure 17 – Voltage Output from the two WECs (after inverter), minimal oscillation approximately 2400 V*

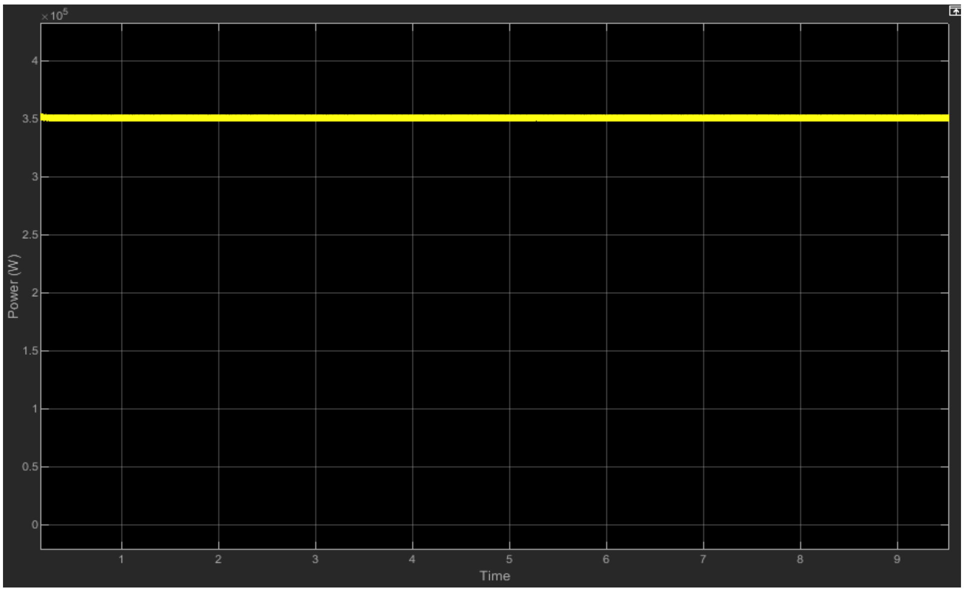


*Figure 18 – Power Output showing slight oscillation at around 350 kW*

As shown by *Figures 17 and 18* after the AC was rectified to give a DC output the voltage and power output were 2400 V and 350 kW respectively. As this number is combined from the two WECs the total power and voltage output can be found due to the modularity of project design. As the subsystems were modelled under ideal conditions and from the information from the other groups looking allowed the voltage and power output for the two WEC farms were approximately 312 kV and 45.5 MW.

## Power Output to Australia

Combining the three energy farms and using a transformer provided the following waveforms which are shown in the figures below.

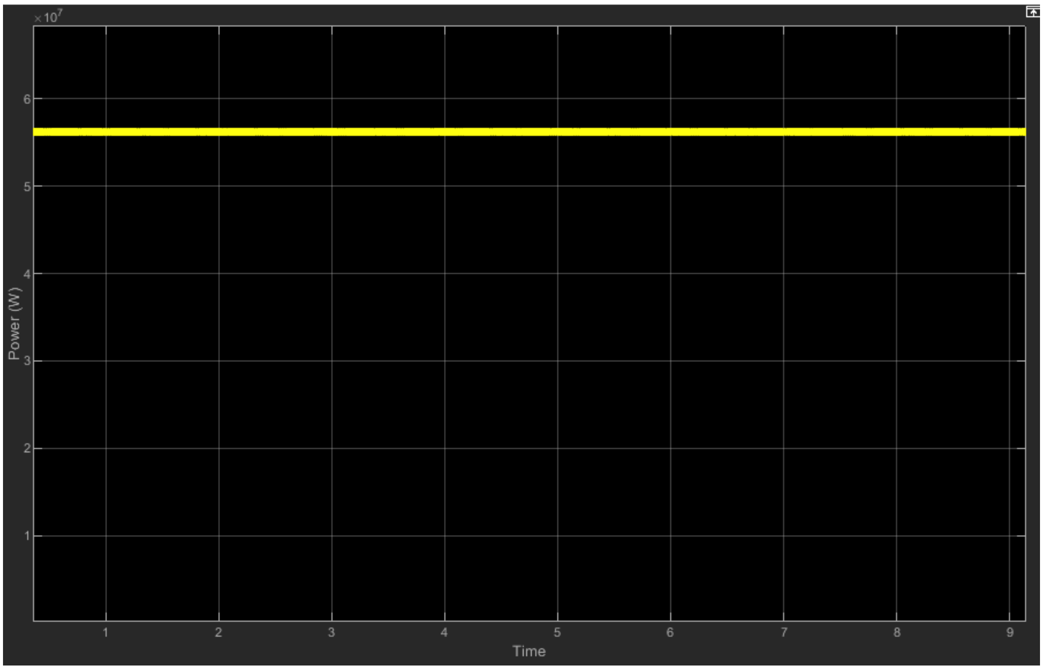


*Figure 19 – Power Output after the HVDC transformer, approximately at 56 MW*

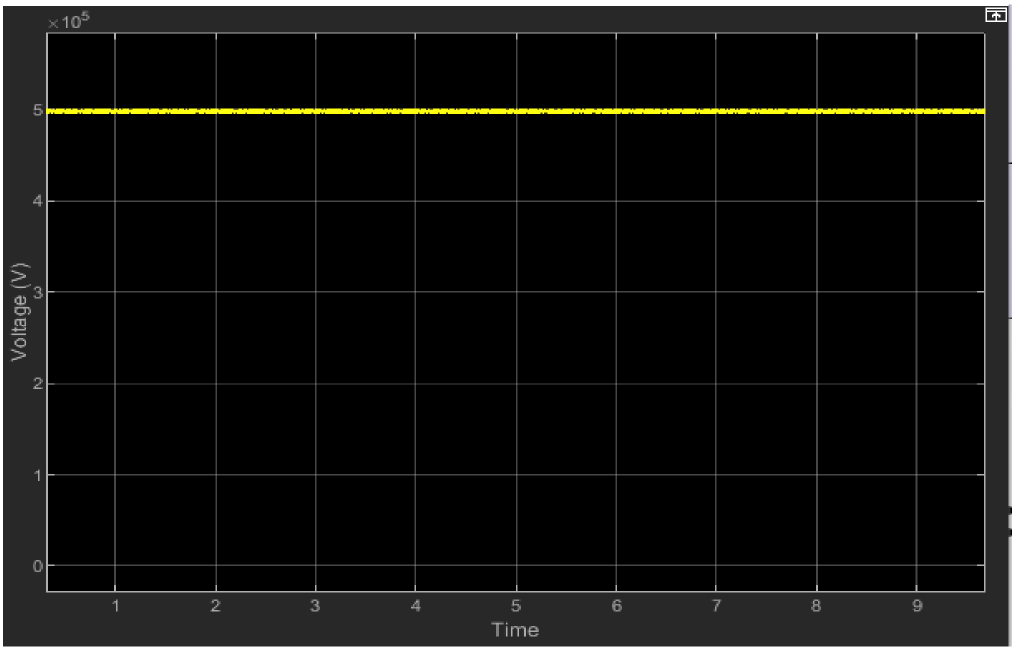


*Figure 20 – Voltage Output after the HVDC transformer, approximately at 500 kV*

As shown in the figures above from the waveforms confirm the regulation of sending the energy to Australia adhered to the regulations set out in *Table 1* which was 500 kV for transmission. Also, as shown in the figures above the total power out to Australia was 56 MW however, it must be noted that due to fluctuations throughout the year and the energy from the batteries, these numbers could change.

## Storage

The first parameter which requires evaluation is the voltage level: is the voltage being sent to and from storage within the specified range? *Figure 21* shows that the voltage being sent to and from storage settles at 453.5 V, which comfortably satisfies the 400-515 V range for this application. This also satisfies the requirement for efficiency as losses are as minimal as possible when also factoring in the use of loads for smoothness.

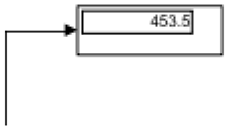


*Figure 21 – Display after the simulation has settled for both to and from cases*

The most crucial factor to consider is the smoothness of the waveform. The presence of harmonics would result in power losses and unreliable commutation between the components, so it is essential to consider this. *Figure 22* displays the voltage waveform over a simulated period of 10 minutes. From this graph, it can be observed that the voltage waveform settles quickly and efficiently, with no ripples in the waveform because of the use of capacitive loads to smooth out the output.

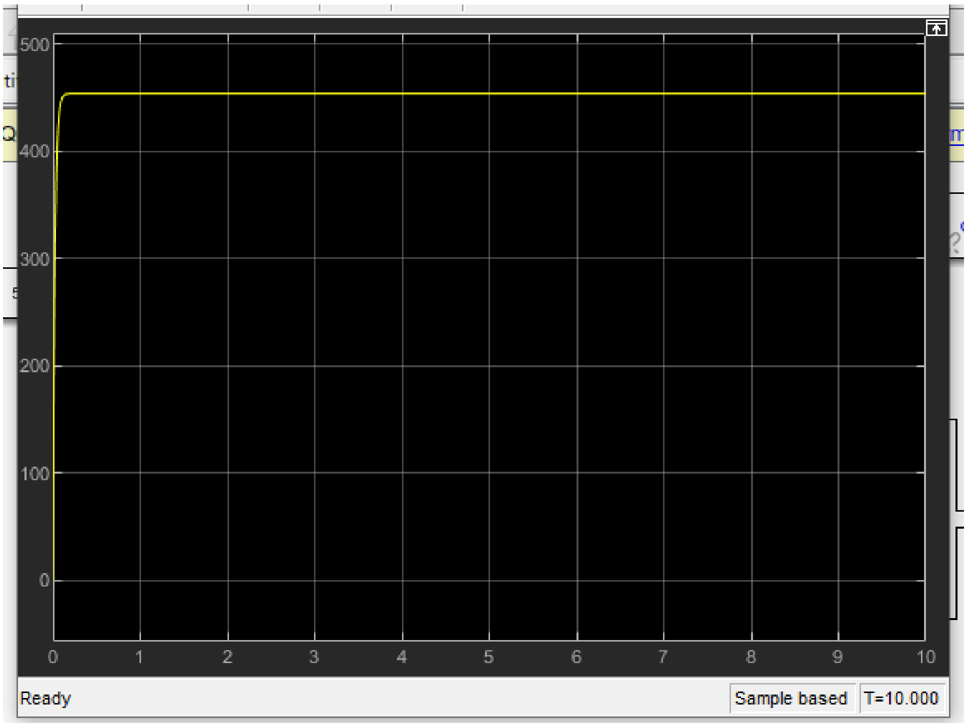


*Figure 22 – Voltage Output Waveform settling quickly at 453.5 V. This is further stepped down when storing and stepped up when sending to the grid.*

# Technical Design – Internet of Things

## Industrial Internet of Things

There are many energy harvesting methods, and the supervisory system will need to be required to accommodate all devices in a timely and secure manner. There are many integrated solutions however the best choice was Open Platform Communication Unified Architecture (OPC UA) [24] due to the advantages and disadvantages discussed in *Table 9*. The OPC UA endpoints attached to each platform would require a compatible device which is the "Simatic Cloud Connect 7, CC 712 IoT Gateway for connection of automation devices to cloud service" manufactured by Siemens [25]

*Table 9 – Advantages and disadvantages of OPC UA*

| Advantages | Disadvantages |
|---|---|
| • Specially tailored for industrial automation applications with a standardised information model.<br>• Compatible with a wide range of data types such as structures or custom-created datatypes, making it ideal for working with attribute-oriented applications.<br>• Has inbuilt and advanced up-to-date security features which include authentication, encryption, and access control ensuring safe data transmission between the nodes.<br>• Features alarms and events, ideal for monitoring real-time systems. | • Complexity will be a concern and will have to be carefully considered throughout the development stage to accommodate the service-oriented architecture.<br>• There would need to be licensing fees and training personnel in its specialised knowledge are quite steep. |

The data storage and processing were considered by evaluating the requirements that it needed to adhere to. Due to the remote location of the facility and the safety critical aspect of the power system network a hybrid approach would be taken where the data analytics would be stored and processed online whilst the monitoring and safety of the network would be on site. There are many web service providers with Amazon reigning as the top provider by market share [26] however, Microsoft was the most suitable option due to key arguments shown in *Table 10*.

*Table 10 – Factors for why Microsoft was chosen*

| Factors | Description |
|---|---|
| Microsoft's investment in underwater servers and data centres | Microsoft has a track record and substantial investment in underwater servers and data centres used in |

| | |
|---|---|
| | augmenting its Cloud network, which may be deployed near a sustainable offshore energy island [27]. |
| Microsoft’s involvement in OPC UA | Microsoft had a founding role in the OPC UA preceding version, supporting a variety of functionalities such as Distributed Component Object Data Model (DCOM) data type. |
| Microsoft’s stake in Ambri Incorporated | Microsoft's recent stake in Ambri Incorporated which is the facilities storage supplier which improves the prospects of further integration. |

The platform network integration would occur in two stages. The initial stage has a controller (with a Wi-Fi Router) for each platform. These controllers would handle the low-level data flow including the collection and processing of sensor readings related to the power output and structural integrity. Furthermore, the controllers will regulate the power input by utilising Programmable Logic Controllers (PLCs) to control actuators and adjust the physical characteristics of solar and wave generators (*Figure* 23).

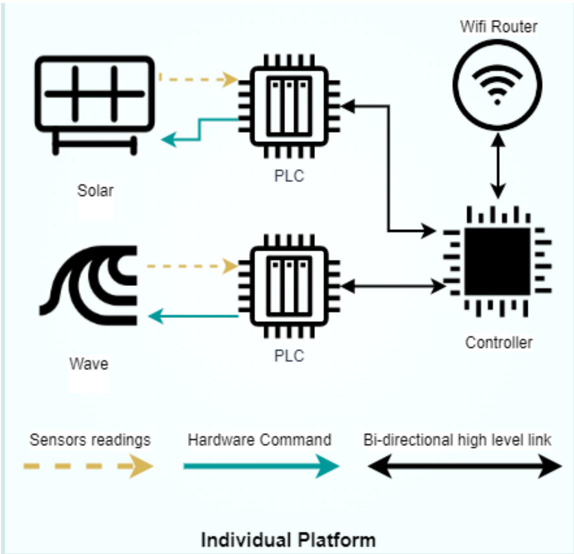


*Figure 23 – Integration of PLCs*

The higher-level links would be facilitated using the OPC UA framework. The platforms would act as edge devices connected to OPC UA servers in semi-independent clusters improving the resilience of the network as failures in software or hardware would be localised and undisrupted to the rest of the system. Due to OPC UA specifications, there are three types between the server and clients which are shown in *Table 11.*

*Table 11 – Types between servers and clients*

| | |
|---|---|
| OPC Historical Access | Used in moving large amounts of data in a non-sequential manner. |
| OPC Direct Access | Tailored for real-time communication ideal for overseeing and control. |

| | |
|---|---|
| OPC Alarms and Events | Used in rapid response time in case of emergencies (or any other predefined set of circumstances). |

From *Figure 25* the clients connected to the servers are shown in *Table 12.*

*Table 12 – Clients Connected to Server*

| | |
|---|---|
| Storage and Processing Cloud Service | Offloads non-critical calculations and operations to a facility capable of handling a large amount of data in a far more efficient manner, cutting down on energy waste and climate isolation losses through the under-water-cooled infrastructure. |
| Human Machine Interface | Point of contact for on-site personnel who are responsible for overseeing the facility. |
| Emergency Subsystem | Triggered by undesirable events providing a preliminary response and forwarding the situation to the technicians. |

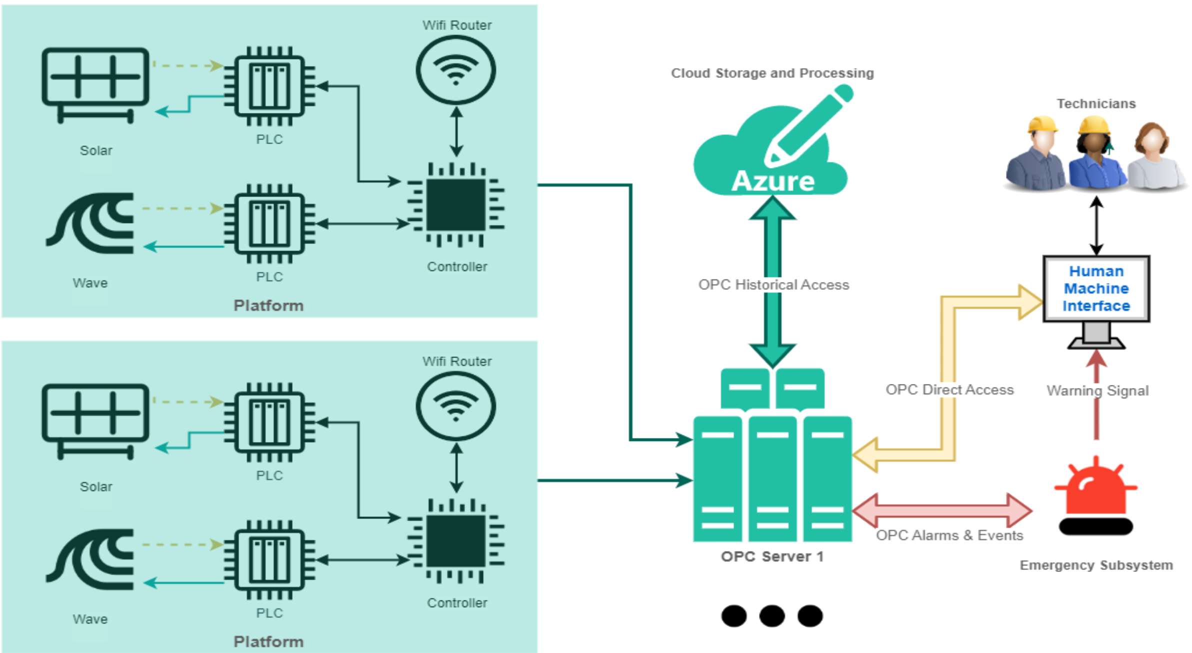


*Figure 24 – Diagram of the client connected to the servers*

# Internet of Things – Protocols

## Emergency Reaction:

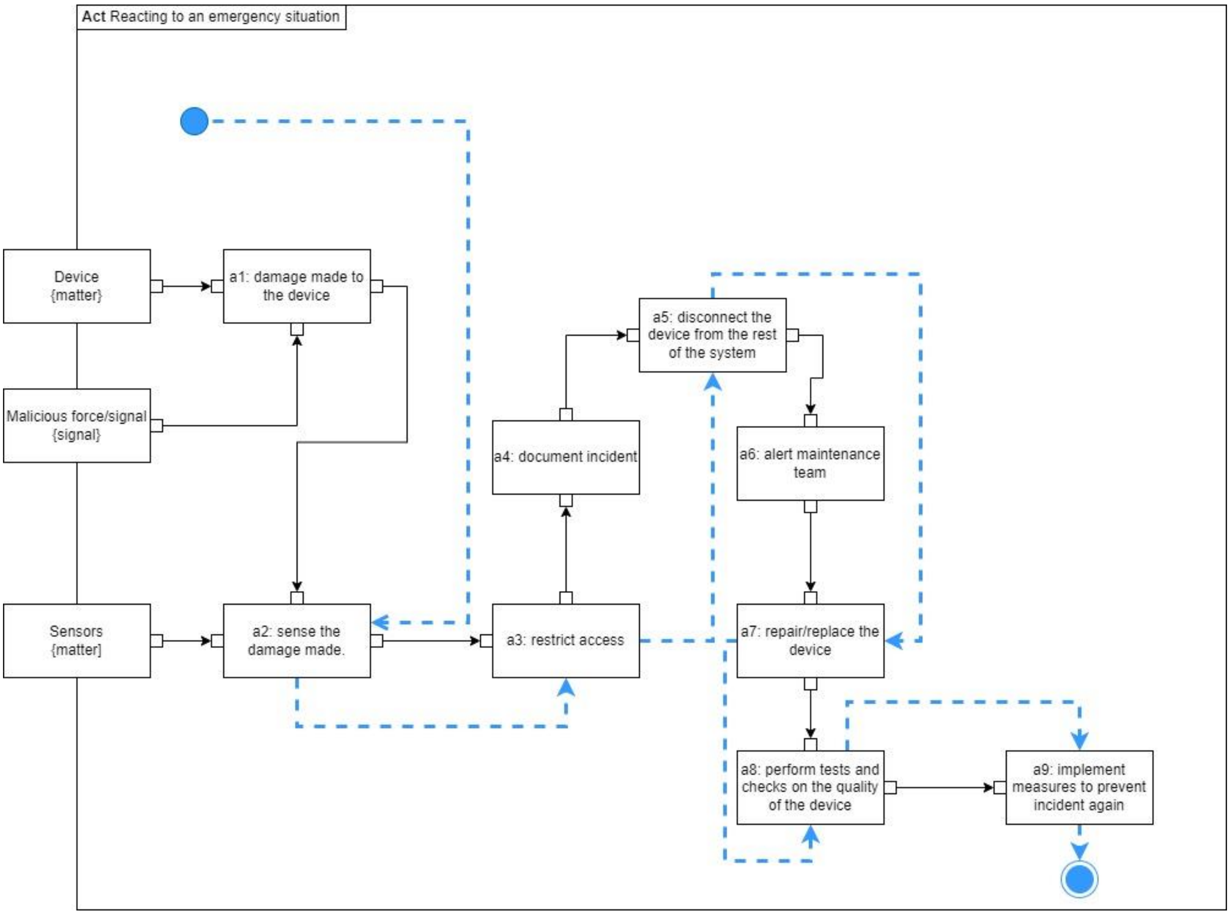


*Figure 25 - SysML activity diagram showing how an emergency is dealt with.*

During an emergency, the safety of everyone is the most important part to consider, which is why that would be our first cause of action after the damage has been sensed when the area gets cleared before the maintenance team gets called. Replacing and repairing the device could take a long time and the area would continue to be restricted to anyone who is not part of the maintenance team. Finally, making sure that the device is working well and making sure the incident does not happen again would be one of the main goals when a device breaks.

## Data sent to the cloud:

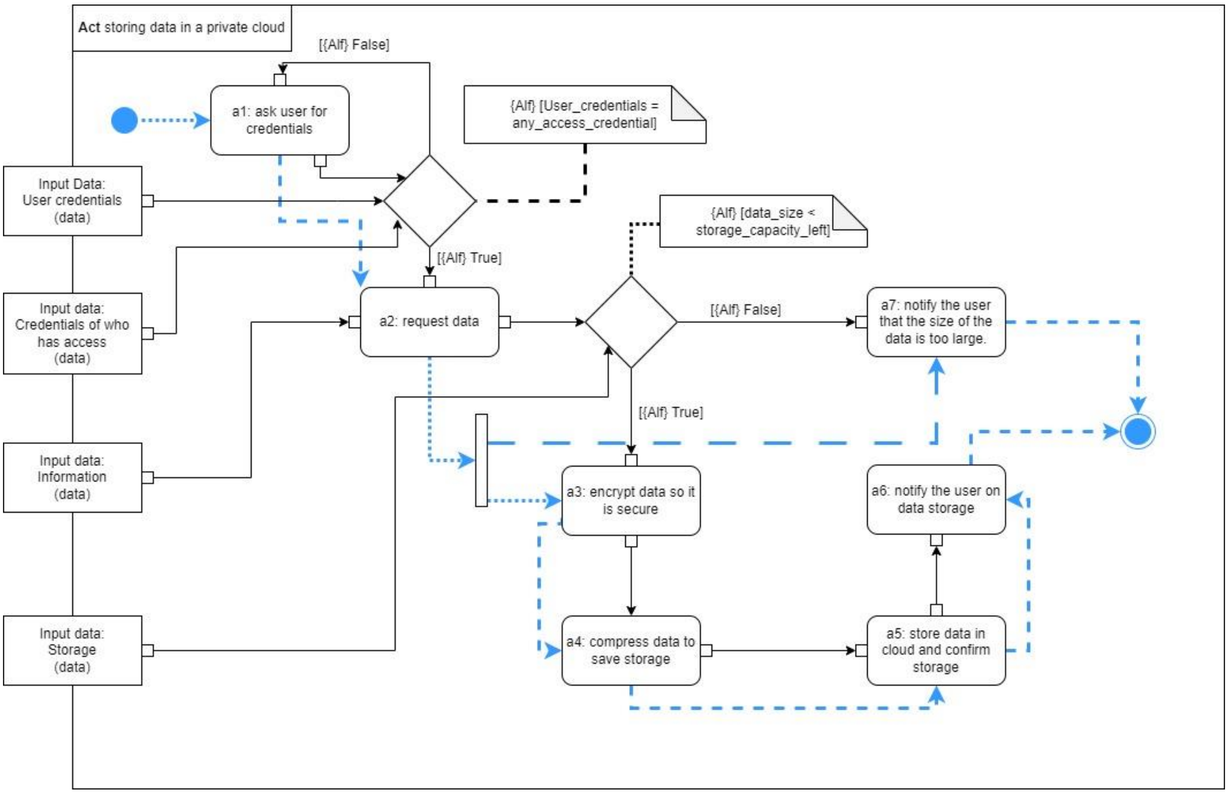


*Figure 26 - SysML activity diagram on data getting sent to a private cloud.*

We have chosen to store our data in a private cloud as the security and privacy of our data is of high importance and compared to storing data in a public cloud, a private cloud would be beneficiary in that aspect. In addition to better security, this will also allow us to incorporate zero latency for local applications, higher speed and better reliability as the infrastructure is not shared [28].

## Surveillance System:

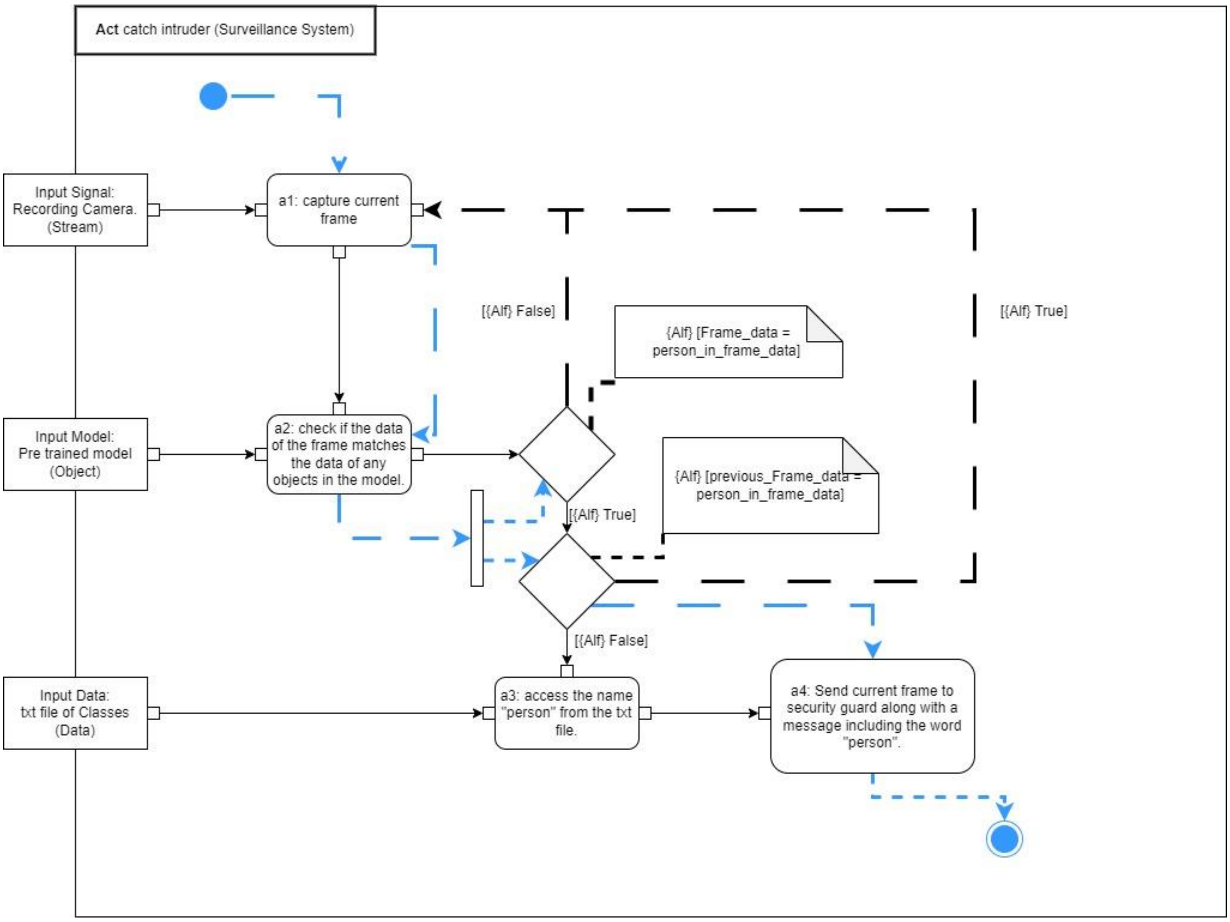


*Figure 27 - SysML activity diagram of a surveillance system run by YOLO (You Only Look Once) method.*

The facility can be monitored in various ways using a surveillance system for many distinct reasons, with the main reason being to catch an intruder. A Picture or video would be sent to the security personnel on-site with a message showing where in the facility they are at. There may be a case where there is a false alarm, which is solved, as a picture or recording is sent to the security guard to confirm. It can work in different procedures, one of which uses a VNC (Virtual Network Computing) viewer to detect human presence. When someone appears in the area, a PIR (passive infrared) sensor will detect their movement as they pass, it will capture an image and then send it to the security personnel, who can then confirm if it is an intruder or not [29]. Another way in which it can work is by using a pre-trained YOLO (You Only Look Once) model, which uses the OpenCV library to perform human detection. This takes place when the intruder comes in range of the camera, a video or photo is then recorded and sent to the security within the facility with a notification message [30]. The YOLO technique would be much more efficient, quick, and cost-effective compared to using a PIR sensor, while also being more durable as it is a software library, therefore using YOLO with the OpenCV library would be the more effective procedure to monitor the facility.

## IoT in Power Systems

Temperature, moisture content, and different combustible gases that arise from the transformer oil degradation without disrupting the normal functioning of the transformer can lead to fatal issues in the transformer operation [31].

*Table 13 - Sensors for Transformer Protection*

| Sensing Method | Purpose |
|---|---|
| Dissolved Gas Analysis sensor | Identifies the levels of various gases created in transformer operation, including hydrogen, carbon monoxide, carbon dioxide, ethylene, and acetylene. |
| Thermocouple | Detect excessive temperatures out of the transformer operating conditions |
| CTs and VTs | Monitor electrical parameters to check the transformer is working within operating conditions. |

Over time, underwater cables are susceptible to significant faults because of partial discharge, temperature increases, and the natural ageing process, which can cause wear and tear on the cable [31].

*Table 14 - Sensors used in underwater cables.*

| Sensing method | Purpose |
|---|---|
| Distributed acoustic sensor system | Monitors the cable for any vibrations caused by partial discharges along fibre optics inside the cables |
| Fibre Bragg Grating sensor | Monitors the temperature along the cables. Integrated into the distributed acoustic sensor system |

Battery storage systems are susceptible to fires and explosions from thermal, mechanical, or electrical runaway caused by temperature spikes, mechanic deformation, overcharging, undercharging or short circuits [31].

*Table 15 – Sensors used in the battery storage system.*

| Sensing method | Purpose |
|---|---|
| Photoionization detector | Uses ultraviolet light to ionize and detect analytes appearing in the system |
| Thermocouple | Detect any excessive temperatures |
| Humidity sensor | Monitor humidity to detect any potential moisture issues occurring |
| CT and VT | Estimate state of charge and health. |

The protective sensors are capable of communication with most sensors wired to the control centre and some sensors are wirelessly connected to the control centre via their microprocessors. The use of wireless sensors and connections significantly reduces the cost of cabling and deployment of these sensors by up to 70 % [32] The sensors provide valuable data that is uploaded to the SCADA system through OPC UA protocols, which provide a secure and reliable communication method. After analysis of the data by the SCADA system, appropriate action is taken in case of faults, including communication with protective systems and circuit breakers, and alerting personnel when necessary.

# Consideration of Wider Engineering Implications

The design of the electrical systems of a sustainable offshore energy island has a variety of engineering implications. These include the factor as shown in the table below.

*Table 16 - Wider Engineering Implications*

| Wider Engineering Implications | Power Distribution Networks | Internet of Things |
|---|---|---|
| Sustainability | The integration of sustainable renewable energy sources such as the ones discussed in this design allowed for the environmental impact to be minimised whilst reducing the overall dependency on fossil fuels. | From the use of IoT technology, the operation and maintenance of the power distribution network are closely monitored whilst improving energy efficiency due to the real-time information on how the power distribution network performs which provided |

| | | |
|---|---|---|
| | | more sustainable practices. |
| Ethics | The implementation of the surveillance system with signage ensures transparency and that the privacy concerns of the individuals within the power distribution network are respected. | The data collection, monitoring, and automation with IoT devices would only be implemented after having consent and disclosure from individuals that are under surveillance whilst having restricted access to the camera history which could only be accessed by authorised personnel. |
| Legal Compliance | There would need to have a planning permit and license to operate the network [33]. The state of Victoria would provide us with the permit and license. | There would be adherence to the legal requirements including the standard for data security and privacy including device usage to ensure that the design is compliant with the relevant regulations. |
| Social Impact | The implementation of safety measures within the power distribution network by the implementation of emergency protocols whilst only allowing access to authorised personnel only provide the required and necessary safety for the individuals on site. | Addressing the issue of social concerns, the data collected from the IoT sensors and devices would be transparent to enhance energy accessibility by third-party services whilst promoting social welfare. |

| | | |
|---|---|---|
| Health and Safety | There would be safety measures within the network including circuit breakers to deal with the surge in voltages. In addition to this, there the caballing allows for the safe transmission of power throughout the offshore energy island. | There would be security on the IoT devices and the associated networks to mitigate risks and safeguard the user's well-being and prevent unauthorised access. |
| Data Security | There would be an implementation of user credential systems, access controls and incorporation of a firewall to enhance data security from unauthorised parties. | Implementation of robust data measures including encryption and secure communication channels to protect the sensitive data collected and transmitted from the IoT devices. |

# Financial Evaluation

## Component Costings

*Table 17 – Cabling Cost*

| Voltage (kV) | Capacity (MW) | Price difference ($/kWh) | Economic targets (single circuit, $ million/km) |
|---|---|---|---|
| ±500 | 2000–3000 | 0.78–3.53 | 2.5 |
| ±600 | 4000 | 1.01–3.43 | 3.0 |
| ±800 | 4000 | 1.25–6.32 | 3.8 |
| ±800 | 8000 | 1.25–6.32 | 7.0 |

*Table 18 – Component Costing Table*

| Component | Costing | Justification |
|---|---|---|
| Offshore Substation | £620 million - £800 million | From the collaboration with Siemens and other partners, the cost of designing and buying the offshore substation was estimated by looking at similar projects such as BorWin2 which was valued at €500 million [34]. As the design is like BorWin2 and many others it would be slightly more expensive due to the size of the project and the need for futureproofing. This price includes the storage system, energy control centre, transformers, converters, inverters and many more components that would be necessary for the operation of the power distribution network. The current conversion rate of €1 = £0.89 was used |
| Cabling | £36 million | From *Table 17*, we can estimate the price of our cables with the parameters that we will produce, with 56MW at ±500kV, the price |

| | | |
|---|---|---|
| | | of our cables will be around £400,000/km and as the cables will be extending through 90kms |
| IoT Gateway | £143,548.60 | These devices are manufactured by Siemens [25] in which each device costs £1,104.22 per unit. There would be a total of 130 of these devices as there would need to be one per device |
| Storage and Data Analytics | £37,036.08 | The monthly cost was £3,086.34 (breakdown found in the appendix) and scaled up to find the costs for the entire year |
| OPC UA Licence fee | £4280 - £ 6420 | The cost initially considered a detriment would be offset by the sheer scale of the project as the licence fee would be fixed [35] |
| Sensors | £542,669.40 | This cost contains the sensors that would be needed throughout the power distribution network (breakdown found in the appendix) |
| Total Cost | £656,727,534.10 – £836,729,674.10 | This includes all of the setup costs and running costs |
| Yearly Running Costs | £37,036.08 | This was from the storage and data analytics cost |

# Technical Review

## Conclusion

The group has significantly contributed to the team challenge of sustainable offshore energy island specifically in the areas of power systems and IoT. In terms of power systems, we have successfully designed and simulated a power distribution network that integrated renewable energy farms achieving the desired power and voltage output of 56 MW at 500 kV adhering to the regulations set out by Australia. Additionally, the use of IoT has allowed for the monitoring and analysis of the power distribution network where protocols were created to address the safety concerns. The implications of the electronic and electrical systems heavily focused on the safety, ethics, and privacy of those on-site where the protocols that the group have designed address these concerns. Considering all the components used within the design the total cost of the design was £656,727,534.10 to £836,729,674.10 and the yearly running costs were £37,036.08. Finally, these achievements as seen throughout the design emphasises the group's commitment to sustainable energy solutions whilst providing advancements in offshore energy infrastructure.

## Further Development

The group design could have been improved by using real data to model the power distribution network such that more realistic voltage and power outputs could have been obtained. In addition to this, further control implementation would allow the power network to be more automated which would have further integrated power systems and the Internet of things. IoT could have been improved by integrating sensors to look at the structural integrity of the platforms to make early decisions on maintenance.

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# Appendix

## Breakdown of Costing

| Microsoft Azure Estimate | | | | | |
|---|---|---|---|---|---|
| **Your Estimate** | | | | | |
| **Service category** | **Service type** | **Region** | **Description** | **Estimated monthly cost** | **Estimated upfront cost** |
| Storage | Storage Accounts | Australia Southeast | Data Lake Storage Gen2, Standard, LRS Redundancy, Hot Access Tier, Hierarchical Namespace File Structure, 100,000 GB Capacity - Pay as you go, Write operations: 4 MB x 10 operations, Read operations: 4 MB x 10 operations, 10 Iterative read operations, 10 Iterative write operations, 10 Other operations. 1,000 GB Data Retrieval, 1,000 GB Data Write, 1,000 GB Meta-data storage | $1,991.82 | $0.00 |
| Analytics | Data Lake Analytics | Australia Southeast | Monthly commitment type, 1,000 included hour(s), 0 overage hour(s) | $909.00 | $0.00 |
| Support | | **Support** | 1000 | $0.00 | |
| | | **Licensing Program** | **Microsoft Customer Agreement (MCA)** | | |
| | | **Billing Account** | | | |
| | | **Billing Profile** | | | |
| | | **Total** | | $3,900.82 | $0.00 |
| | | **Total in GBP** | | **£3,086.34** | |

*Figure 28 – Cloud Service Cost Breakdown*

| Sensor | Cost per unit | Units | Total cost | Source |
|---|---|---|---|---|
| Dissolved Gas Analysis sensor | £957 | 1 | £957.00 | Hach.com |
| Thermocouple | £10.60 | 140 | £1,484.00 | Farnell.com |
| CT | £116 | 140 | £16,248.40 | trinityenergy.co.in |
| VT | £77 | 140 | £10,780.00 | trinityenergy.co.in |
| Distributed acoustic sensor system | £76,500 | 1 | £76,500.00 | Farnell.com |
| Fibre Bragg Grating sensor | £47 | 9000 | £427,320.00 | Made-in-China.com |
| Photoionization detector | £3,500 | 1 | £3,500.00 | Frontline-safety.co.uk |
| Humidity sensor | £42 | 140 | £5,880.00 | Farnell.com |
| Total cost | | | £542,669.40 | |

*Figure 29 – Sensor Cost Breakdown*

# Meeting Minutes

| Meeting: | Date: | Absentees: | Actions Completed: | Actions to be Taken: |
|---|---|---|---|---|
| | | | Initial ideas for project brainstorm | Conduct Research |
| | | | Started Research | |
| 1 | 09-Feb | | | |
| | | | Identified group level project design | Focus research on the group design |
| | | | | Begin design specification |
| 2 | 16-Feb | | | |
| | | | Desigin Specification started | Continue with design specification |
| | | | Research explained to each other | Continue with the research |
| 3 | 23-Feb | | | Start Presentation Work |
| | | | Presentation sections allocated | Work on design brief |
| | | | Research explained to each other | Presentation to be practised |
| 4 | 02-Mar | | | |
| | | | Discussed areas of limitations from the presentation | Finalise design specifications |
| | | | Discuessed potential areas for research | Conduct additional research for designs |
| 5 | 09-Mar | | Split group into two sub-groups | |
| | | | Complete list of what was needed from the other groups | Conduct research to highlight the limitations |
| | | | Identified limitations in the design | Discuss requirements with the other groups |
| 6 | 16-Mar | | | |
| | | | Discussed the requirements we need to provide | Start modelling of circuits |
| | | | Assigned design/modelling tasks for each group membe | Start research into specific IoT systems |
| 7 | 23-Mar | | Assigned research areas for each group member | |
| | | | Updated each other on the design work | Continue with the design work for Power Systems |
| | | | Discussed certain methods of approach with IoT | Continue with the design work for IoT |
| 8 | 30-Mar | | | |
| | | | Looked at the limitations of the designs | Continue with the design work for Power Systems |
| | | | Dicussed how the designs could be improved | Continue with the design work for IoT |
| 9 | 12-Apr | | | |
| | | | Discuessed the design solutions | Start on sensor research |
| | | | Explored further routes to be taken | Integrate Power System models |
| 10 | 19-Apr | | | |
| | | | Discuss areas of the report for each person to focus on | Start writing up the report |
| | | | | |
| 11 | 26-Apr | | | |
| | | | Identified areas of gaps within the report | Continue with the report |
| | | | | |
| 12 | 03-May | | | |

*Figure 30 – Group Meeting Minutes*

| Meeting: | Date: | Absentees: | Actions Completed: | Actions to be Taken: |
|---|---|---|---|---|
| | | | Met with supervisor | Establish the aims and objectives for the group |
| | | | Discussed the project idea | |
| 1 | 16-Feb | | | |
| | | | Direction of the project discussed | Continue with research |
| | | | Research areas explained | Start on design specifications |
| 2 | 21-Feb | | | |
| | | | Limitations of the research discussed | Complete the presention work |
| | | | Presentation day discussed | |
| 3 | 28-Feb | | | |
| | | | Presented the presentation to the supervisor | Implement the feedback into the presentation |
| | | | Feedback on the presentation | |
| 4 | 07-Mar | | | |
| | | | Presentation review discussed | Continue with the areas of reaearch |
| | | | Explored additional areas of research | |
| 5 | 14-Mar | | | |
| | | | Explained best design approaches to take | Start with the group desgin |
| | | | Discussed the potential routes for IoT | Foucus research onto communication protocols |
| 6 | 21-Mar | | | |
| | | | Discussed the project update | Continue with the report write up |
| | | | Discuessed limitations | |
| 7 | 04-May | | | |

*Figure 31 – Supervisor Meeting Minutes*

## Statement of Contribution

**Karun Dhindsa –** Karun's contribution included managing the group design project including the communication with the other teams to obtain the necessary information to complete the designs. He also significantly contributed to the write-up of the final report and within the technical design he designed, modelled, and simulated the solar panels.

**Michael Abram –** Micheal was on the Internet of Things group where he researched the sensors that were needed for the energy farms and the protection system that were needed for the power distribution network. He also contributed to the costings of the design.

**Ahmed Al-massry –** Ahmed initially researched the underwater cables that were needed and later went on to research and create the protocols that were needed by the project regarding the safety and surveillance of the power distribution network.

**Mohammed Ali –** Mohammed initially researched solar sensors but then moved on to the power systems group where he continued the research, design, and implementation of the storage system.

**Mate Lorincz –** Mate researched the integration of combining the three wave farms which included himself modelling and simulation the wave energy converter farms as well as the entire network.

**Alexandru Spinu –** Alexandru initially researched power storage solutions and later joined the IoT team where he researched and designed the communication protocols and web service options as seen in the Industrial Internet of Things section.