DEVELOPMENT OF A SITE SELECTION TOOL BASED IN LIFE CYCLE ASSESSMENT (LCA), FOR TIDAL POWER SCHEMES

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ABSTRACT

This thesis discusses the development of a site selection tool for positioning Tidal Stream Generators (TSG) with respect to both the financial and environmental impact that the site selection process has. This is particularly important due to the current commercialisation of the tidal stream industry, which is presently transitioning from testing and refining device designs to fully functioning device deployment and even tidal stream arrays.

Tidal power is billed as a green and renewable energy source that has the advantage of being reliable and predictable. However, current site selection techniques typically look purely at the feasibility and the financial elements of a project. The methodology proposed in this thesis combines the results from a typical Technical Feasibility Study (TFS) with a Life Cycle Assessment (LCA) to account for the Global Warming Potential (GWP) that occurs during the life cycle of a TSG. These results are combined with respect to a user-defined weighting system that will enable the user to weigh the importance of each of these elements. This results in the creation of a novel decision-making support tool for site selection of tidal devices, with both financial and environmental assessment aspects right at its core.

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Finally, a tremendous thanks should also go to my family and friends for supporting and encouraging me throughout my time working on my thesis. I would like to especially thank my parents, Sean Kelly and Jacqueline Prosvic and, also, Ms Grace Pinn, all of whom have been there continually motivating and supporting me throughout the entire endeavour.

Finally, remember, it is carbon intensity, not carbon insanity!

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LIST OF ABBREVIATIONS

CAD	Computer-Aided Design
Cp	Coefficient of Performance
EMEC	European Marine Energy Centre
GIS	Geographical Information Systems
GWP	Global Warming Potential
LCA	Life Cycle Assessment
ROI	Return on Investment
TFS	Technical Feasibility Study
TSG	Tidal Stream Generator

CHAPTER 1: INTRODUCTION

1.1. Summary

This chapter serves as an overall introduction to the thesis, initially detailing the background and rationale behind the project before defining the scope of the research in the format of the aims and objectives. Following this, the thesis structure is outlined, providing a summary of each chapter. Finally, the contributions to this research are detailed via a list of publications generated throughout the undertaking of the investigation.

1.2. Project Background

Tidal power is an emerging renewable energy technology that is currently generating significant financial investment interest in the UK. Subsequently, the UK has become a world leader in this form of power generation, with developers looking to take advantage of the significant tidal resources that are located just offshore. As a result of this, as well as government funding for renewable technologies, a number of new and next-generation tidal power schemes are being proposed, developed and deployed. The stakeholders in each of these schemes are looking to take advantage of this renewable, dependable energy source which is, most importantly, reliable and predictable.

These findings are in line with a number of reports including the "*Accelerating the development of marine energy: exploring the prospects, benefits and challenges*" (Jeffrey, Jay, & Winskel, 2013), which identified the potential growth of the still-fledgeling tidal energy industry that can be achieved with commercial investment in tidal technology. As this report predicted, commercial interest has started to mature and refine, leading to increased development of tidal power schemes designed to take advantage of this reliable source of power. Of course, the advantages of renewable and predictable energy sources are well known in a world tackling the threat posed by global warming and energy insecurity, but is tidal power the solution?

Tidal power generation offers an appealing, renewable method of producing electricity; however, that does not automatically guarantee that this type of renewable power generation is an environmentally-friendly method. With devices being placed in offshore locations, a substantial quantity of resources including time, energy and financial outlay, need to go into the manufacturing, deployment, grid connection, maintenance and final recovery of the device during its lifetime. All of these stages and activities - from creation, operation and even disposal have a direct influence and impact on both the planet and, of course, the operator's balance sheet.

Current site selection methodology revolves around maximising the profits from a scheme without having a negative impact on the local infrastructure or environment, particularly wildlife. This is achieved via a two-stage process where initially a site is identified from a wider area via a feasibility study and the preferred sites shortlisted for further investigation. The shortlisted sites are then examined in detail to corroborate the findings of the initial feasibility study and examine them further, specifically with the undertaking of a Wildlife Assessment to ensure that the deployment of the device will not have an adverse effect on the fauna. Typically this is relatively costly as the surveys often involve long periods of monitoring at the site to corroborate the resource data used in the feasibility study and determine the impact on the local wildlife.

As a result of this methodology, the optimal site is chosen with respect to the financial implications and whilst the local environment is considered the global environmental impact of the device is not.

In an attempt to help ascertain the true and holistic impact of tidal devices, this thesis sets out to determine the impact that a tidal energy device has on the environment. This will be achieved by incorporating the environmental impact within a site selection 'tool' from the initial stage of site selection. However, the environmental impact alone is not enough to site-select a tidal turbine location. By their very nature, commercial companies will, with very few exceptions, continue to prioritise business profits over the environmental costs unless those costs are mandated. Hence, the finished site selection tool will have to be able to factor in both the environmental and financial aspects of each site. This will create a comprehensive Decision Support Tool for selecting potential deployment sites of a Tidal Stream Generator (TSG).

It is expected that the site selection process will have a direct influence on both the outcomes of a financial and environmental assessment of the deployment of a TSG. Particularly with respect to the following key areas;

- Power generation
    - Different sites have different properties that affect the output power that can be generated by a turbine.
- Distance to infrastructure

- Maintenance activities – greater distances require the maintenance vehicles and (water-capable craft) to operate longer, burning more fuel; increasing cost and environmental impact as well as operator costs.
- Cables – longer grid connection cables lead to increased material usage and hence increased cost and environmental impact.

In order to account for this, the tool developed will seek to combine a typical Feasibility Study, which is used to assess site suitability, and an LCA, which is used assess the holistic environmental impact of the device. The combination of the data produced will result in the generation of a novel tool for site selection of tidal devices with respect to both financial and environmental factors. In turn, this will aid in the initial decision support for the identification of deployment sites for TSG's.

1.3. Rationale and Hypothesis

This investigation assumes that it is possible to develop a tool for selecting optimal deployment sites for tidal turbines, by combining an LCA study with the current practice of carrying out an initial Technical Feasibility Study (TFS) to identify sites. This assumption is made owing to the perceived impact that site selection has on the results of each of the methodologies, and the identification of the possibility to generate and share data between them.

As a result of this, the project will seek to develop a unique methodology that combines the results of a typical feasibility study with environmental data generated during the LCA study. This will create a novel methodology for selecting a site with respect to both environmental and financial factors. Ultimately this will enable developers to identify sites for future deployment using a site selection tool with the environmental impact factored in.

In order to develop this methodology, initially, a full literature review will be conducted. This is required in order to understand the process of LCA application, while additionally to explore the methods and techniques used in the construction and logistics of tidal power components.

The second stage of the project will involve developing a suitable methodology framework for providing decision support in site selecting tidal turbines. This will consist of the following significant stages:

- Stage 1: Site and device identification and selection
- Stage 2: Development of a generic LCA model that can identify the ideal method of tidal energy extraction at a potential site, by taking into account the technical and environmental factors relative to the system under scrutiny. Alongside this, a TFS will be conducted to determine the financial impact that the deployment of a turbine will have
- Stage 3: Development of a combination tool to amalgamate the results from the LCA and TFS. This will then be used to identify the preferred site for tidal power generation so that it serves as a highly applicable decision-making tool that can be used to identify a site with respect to both the financial and environmental factors

The final stage of the project will strive to validate the developed methodology with a case study involving a specified site and device, with the goal of identifying the optimal site for a device. The site identified will be specified with respect to the financial and environmental elements of the tool.

The novelty behind this proposal is the use of LCA as an environmental analysis that is incorporated, into a generic model that can be highly applicable as a feasibility and decision-making tool for commercial entities in the still-emerging renewable energy industry.

1.4. Research Aims and Objectives

The investigation proposed here-in would seek to develop a forward-thinking methodology, which combines an LCA investigation with a typical feasibility study, in order to improve and advance the current method of site selecting for tidal devices. The new methodology created will act as a decision support tool for the identification of deployment sites for tidal devices, and will be of particular importance due to the relative infancy of the tidal power industry. This will be achieved by helping developers focus on the environmental impacts that renewable energy devices have, by accounting for not only the technical and financial factors of different sites but the environmental costs that each one will incur, from raw material acquisition right through to decommissioning. These impacts are expected to be increasingly scrutinised by project stakeholders, including investors and planning officials in the coming years.

To achieve this aim, the following objectives will need to be met:

1. Conduct a comprehensive literature review to identify current LCA methodology and its application in similar fields/industries.

2. Conduct a comprehensive literature review, with regards to contemporary tidal power systems, and the state-of-the-art designs as well as the operation and evaluation of the surveying procedure required for site identification.

3. Develop a suitable LCA framework that can be applicable to use within the tidal power industry and, more specifically, analyse/choose preferred sites.

4. Develop a suitable feasibility framework that can be used to assess a proposed site with respect to the financial aspects of the deployment of a device.

5. Combine the documentation into a concise methodology to evaluate the performance of tidal power generators against the financial and environmental factors. This will result in the development of a tool that aids in the site selection of tidal devices.

6. Test and evaluate the methodology developed using a case study in order to validate the methodology developed and show the "*real world*" application.

1.5. Thesis Outline

The thesis is arranged into ten chapters, which are supported with documentation in the Appendix. Following the Introductory chapter, a complete literature review is carried out in Chapter 2 to determine the extent of the research into tidal power, LCA and relevant software packages. Using the findings of the literature review, the methodology for site selecting with respect to LCA and TFS is detailed and defined in an overview in Chapter 3. The key stages of the methodology defined in Chapter 3 are then detailed in the subsequent Chapters; 4, 5, 6 and 7. The developed methodology is then applied in the case study undertaken in Chapter 8. This case study acts as a test case for the defined methodology detailing its application to a real-world site and device. The results of this application are then discussed in Chapter 9 before a conclusion summarising the key findings of the research is provided in Chapter 10.

The following defines the key elements of each of the identified chapters:

Chapter 1: Introduction

This chapter outlines the justification of the project by detailing the project background, aims and objectives. Additionally, a clear overview of the structure of the thesis is provided.

Chapter 2: Research Design

This chapter outlines the methodology used to guide the thesis research. This is achieved by outlining the critical stages for undertaking a research project and identifying the key findings that should be expected from each stage and how they will be used to create the finished developed tool methodology.

Chapter 3: Literature Review

The literature review sets out to define the current state of research in the proposed topic areas; this acts as a method to ensure that the research produced is both novel and relevant. In addition to this, the literature review helps to outline and shape the direction of the project with respect to the findings. In this case, the main topic areas assessed are; Tidal power, LCA and software. The literature review focuses on the basic theory and current methodologies as well as other relevant information for both the TFS and LCA components. The final section discusses the specialist software packages that are available to assist in the development of the methodology. These are defined with respect to the three key methodologies: TFS, LCA and, ultimately, the combination tool.

Chapter 4: Developed Methodology Overview

This chapter defines the development of the generic site selection methodology with respect to the findings of the literature review. This results in the development of a methodology that consists of three key stages: Stage 1 - Site and Device Specification, Stage 2A – TFS, Stage 2B – LCA and Stage 3 – Combination Tool. Initial information for each of these stages is outlined, alongside details of how the data is shared between them. Each of the key stages identified is then further expanded upon in detail in the subsequent dedicated chapters 5, 6, 7 and 8.

Chapter 5: Site and Turbine Specification (Stage1)

This chapter defines the initial phases of the developed methodology with the specification of the site and turbine. This chapter outlines the required information that must be gathered and collated for each in order to conduct the remaining stages of the methodology.

Chapter 6: Technical Feasibility Study (Stage 2A)

This chapter details the undertaking of the TFS with respect to site and device characteristics determined in chapter 4. This is achieved by assessing each of the sites against determined inclusion/exclusion criteria to assess if the selected turbine is suitable for deployment at the site. Power generation is then calculated using tidal flow information from a specialist tidal flow software for each site. Power calculations for both a fixed and yawing device are determined with respect to the parameters for the turbine selected. The resulting power outputs are then used to determine the financial impact of positioning the turbine at each site.

Chapter 7: LCA Study (Stage 2B)

States the process for conducting the LCA methodology, which was developed with respect to the four stages defined in the ISO standards. Namely; the Goal and Scope definition, Inventory Analysis, Impact Assessment and Interpretation of the results. In addition to this, a Sensitivity Analysis identifies the requirements to corroborate the results of the undertaken LCA.

Chapter 8: Combination Tool (Stage 3)

This summarises the final stage of the developed methodology, discussing the development of the combination tool using a normalised weighting system. This allows the user to assess the site with respect to the previously calculated financial (Stage 2A) and environmental (Stage 2B) impacts that the positioning of a TSG will have. The resulting output of the methodology is then detailed, and a conclusion of the entire developed methodology is provided.

Chapter 9: Case Study

The Case Study showcases the application of the developed methodology in an industrial/real-world setting. This process demonstrates the application of the methodology and is used to both test and refine the method while demonstrating its applicability. As a result of this process, the methodology developed is verified and proven its applicability to inform decision-making in such *real-world* situations.

Chapter 10: Discussion

The development of the methodology is discussed and evaluated to determine its applicability to the end-users. Additionally, limitations of the methodology are outlined, and recommendations for further research are provided to address them.

Chapter 11: Conclusion

The conclusion summarises the key research findings from the thesis and the contribution to knowledge.

1.6. Publications Generated

The following publications have been generated during the duration of the PhD research,

- Kelly, C. L., Blanco-Davis, E., Michailides, C., Davies, P. A., & Wang, J, "Site Selection Appraisal for Tidal Turbine Development in the River Mersey", *Journal of Marine Science and Application*. 112-121, online March 2018.

- Kelly, C. L., "Investigation into the Uses of Life Cycle Analysis (LCA) as an alternative method of selecting tidal power schemes" *LJMU Faculty Research Week 2018 Proceedings*: 234-238, May 2018.

These publications are displayed in Appendix A - Site Selection Appraisal for Tidal Turbine Development in the River Mersey – Abstract and Appendix B- Investigation into the uses of Life Cycle Analysis (LCA) as an alternative method of selecting tidal power schemes - Conference paper.

1.7. Conclusion

The project background for the development of the site selection tool for tidal power devices is defined, outlining the current methods for site selection of tidal devices and the need to consider the environmental impact that they pose over their lifetime and not just at a local - but a global - level. From this initial background information, the aims and objectives have been defined to fulfil the requirements of developing a site selection tool that combines a typical TFS and LCA. The method is further detailed in the thesis outline, which provides an overview of the main chapters required to meet the aims and objectives of the research. Finally, the publications generated from the research have been listed showing the current stage of contribution to research from the project.

CHAPTER 2: RESEARCH DESIGN METHODOLOGY

2.1. Summary

The following chapter summarises the research methodology adopted for this investigation. Initially, an overview of the research design is provided before each of the key stages are discussed. These stages are defined in the overview as the literature review, methodology development, testing and evaluation.

2.2. Overview

This research assumes an initial rationale and hypothesis, which identifies that it might be possible to integrate LCA into the site selection process of selecting tidal power schemes.

This hypothesis was based on an initial observation that tidal power site selection typically revolves around capitalising on device power output - and hence profits - when site selecting tidal power schemes (Kelly, Blanco-Davis, Michailides, Davies, & Wang, 2018). Little to no consideration is paid to the environmental impact of the turbine outside of the local area. Furthermore, this initial investigation identified that whilst there have been some LCA investigations focusing on tidal turbines, there is currently no methodology that uses LCA for site selection purposes.

This initial research identified that a methodology encompassing both LCA and a typical tidal feasibility study could be a novel contribution to the pool of knowledge, and therefore worthy of further investigation.

In order to investigate this hypothesis further, a research methodology must be adopted to ensure that the project aims and objectives are achieved. Figure 2-1 showcases the four stages of the methodology adopted for the undertaking of this research. It essential to understand that the findings of each key stage are used to inform decisions in the subsequent stages in order to complete the investigation successfully.

The following subchapters define each of the key stages identified in the proposed research design and outline the critical functions of each stage.

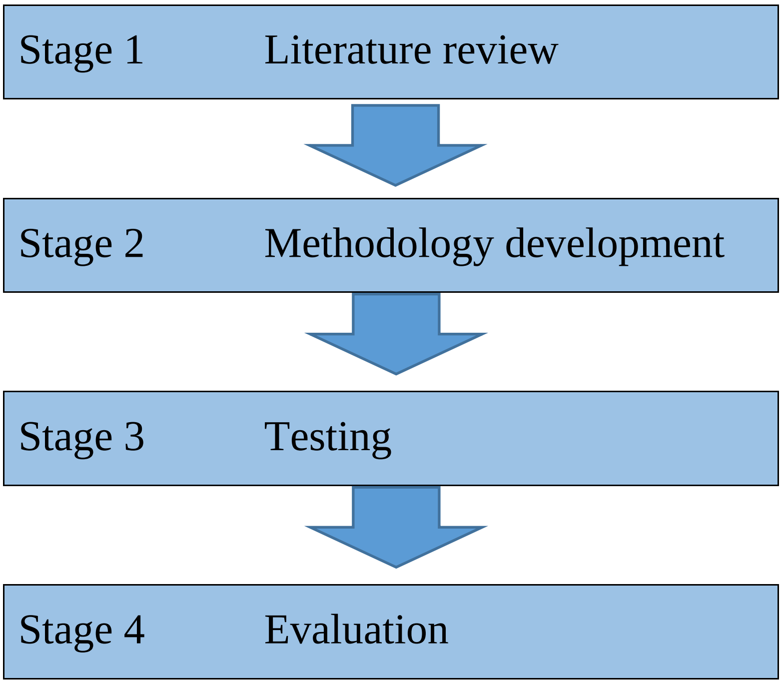


Figure 2-1: Adopted research methodology

2.3. Literature Review

The literature review will set out to investigate the initial hypothesis and rationale behind the project; this will act to validate the initial notions behind the research. In addition to this, the literature review will identify any relevant research in the appropriate fields. In the case of this investigation, this will include documentation on the following key areas, Tidal power, feasibility studies, renewable energy finance, LCA, LCA standards and previous LCA studies. The collation of all this research will help define the development of the proposed methodology by providing a scientific background to the research project.

2.4. Methodology Development

The methodology developed will seek to develop a unique and novel methodology for site selecting tidal power schemes. In order to achieve this, the methodology should incorporate findings from the literature review, and specifically, any learnings form any previous LCA's or feasibility studies investigated. This provides a robust foundation for the development of a methodology that combines an LCA and typical feasibility study. It should be noted that any additional research that might be relevant should also be used in this process.

The methodology generated in this thesis has to focus on incorporating the findings of the two aforementioned pre-established methodologies and be easy to understand for any user. As a result, the methodology developed will have to be easy to undertake, and the results should be displayed in a user-friendly way to make it appropriate for potential commercial use. Consideration should be paid to the type of data required to undertake the assessment, and the methodologies should be tailored to accommodate this. Once completed, it can then be used in a case study to assess a test site.

2.5. Testing

Once the methodology has been developed, it then has to be tested to ensure that it is working in the correct manner and identify any issues that may be encountered by a user. In order to test this in a "real world" setting, it is proposed that a case study is undertaken in order to analyse the effects of using the developed methodology. In order to achieve this, it is expected that a large amount of data will be required including; Flow speeds, bathymetric data as well as device and financial information. The collation and use of this information in the methodology will showcase its application in site selection and allow for evaluations to be made.

2.6. Evaluation

The final phase of the research design is the evaluation of the methodology against the goals and objectives identified for the project. This will involve critically discussing the developed methodology and its application during the case study in order to identify its strengths and weaknesses. By evaluating the finished tool, any concerns can be outlined and addressed with the intention of improving the methodology. Finally, any further development areas of the methodology can be signposted for future work.

2.7. Conclusion

The adoption of a methodological approach for this thesis investigation provides additional scientific rigour to the process of developing this thesis methodology. This is achieved by systematically outlining the criteria of each task, providing a path for the development of a new methodology within this thesis. It should be noted, its incorporation in the thesis can be identified from the thesis layout, which is defined by the stages outlined in this methodology.

CHAPTER 3: LITERATURE REVIEW

3.1. Summary

The following chapter outlines the key findings of the literature review conducted. The findings are displayed under three main subsections outlining the research findings in the following key areas: Tidal Power, LCA and Software. Each area is explored in-depth, with informed decisions made from the findings. Lastly, the conclusion of the chapter summarises the outcome of the review by highlighting key points in bullet point form.

3.2. Tidal Power

Tidal power is the generation of power from the movement of the tides. In order to explain this concept, the following subsections outline: tidal theory, current tidal technology, Tidal Stream Generators (TSG), test centres, tidal feasibility studies and the current methodology for renewable energy financing in the UK.

3.2.1. Tidal Theory

Tides occur naturally throughout the world and are generated due to the gravitational interactions between the Sun, Earth and Moon. The following subsections detail the formation of tides on a daily and lunar cycle. Additionally, the effects of meteorological conditions and geographical structures on tidal flows are detailed.

Daily Tidal Cycles

The Earth is continuously undergoing two high and low tides. This is due to the gravitational effect of the Moon on Earth. This gravitation interaction can be seen in Figure 3-1. This figure shows how the gravitational force diminishes from one side of the Earth to the other, as the distance from the Moon changes.

Effectively this change in force acts to stretch the Earth. The land, being fixed, is unable to move. However, the oceans being a fluid are affected by this varying gravitational force. This results in high tide bulge forming on either side of the Earth as the side closest to the Moon is pulled towards the Moon, but the Earth is also pulled away from the water on the opposite side of the Earth. As a result of this, a Low tide occurs at the midpoint between these bulges. This is due to the gravitation effect of the Moon acting perpendicular to the surface of the water and hence not lifting it.

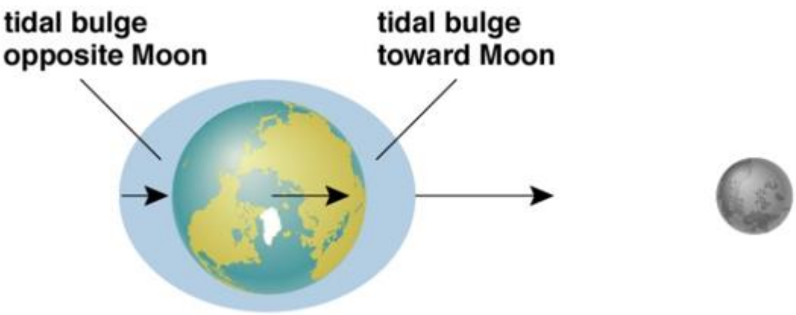


Figure 3-1: The gravitation effect of the Moon on the Earth (Phases and Tides, 2014)

It takes the Earth 24 hours to complete one rotation (one earth day); however, the Moon is orbiting the Earth in the same direction as the Earth's rotation. As a result of this, it takes on average 24 hours and 50 minutes for the Moon to realign above the same point on the Earth. During this period, two tidal cycles are experienced with each tidal period lasting around 12 hours and 25 minutes.

Lunar Cycle

On average it takes the Moon 27.5 days to complete a full orbit of the Earth. However, a lunar month is described as the time taken for the Moon to realign with the Earth and sun due to the Earth orbiting the sun. This results in an average time period of around 29.5 days, but there is some variation. For example, in 2020 a lunar month will range from 29 days 17 hours 56 minutes (29.747 days) at its longest to 29 days 8 hours and 19 minutes (29.347 days) at its shortest. (McClure, 2019). As a result of this, there are slight variations between tides.

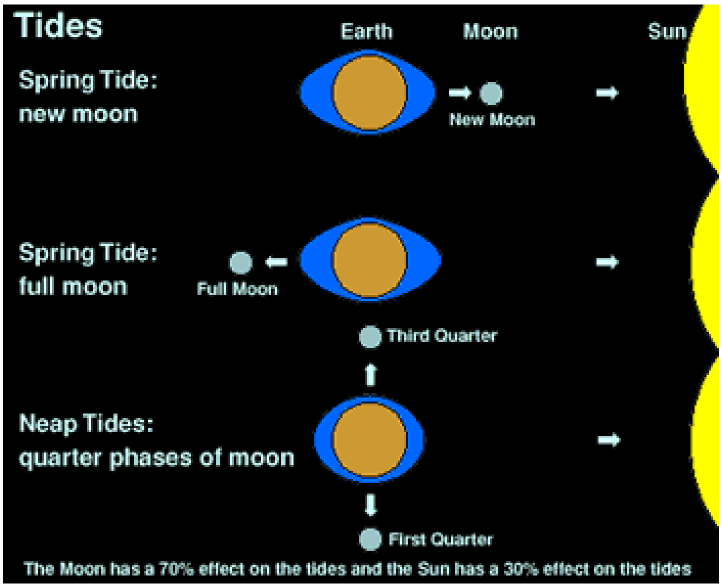


Figure 3-2: Formation of Spring and Neap tides (Davey, 2000)

The resulting combination of the daily and lunar cycles can be seen in Figure 3-3. This shows a plot of the tidal height over a lunar month observed at the mouth of the River Mersey. From the plot, it is clear to see the variation of the tides over time from spring to neap and back over the lunar month. In addition to this, the daily shifts in tidal height due to the daily tidal cycle can be observed.

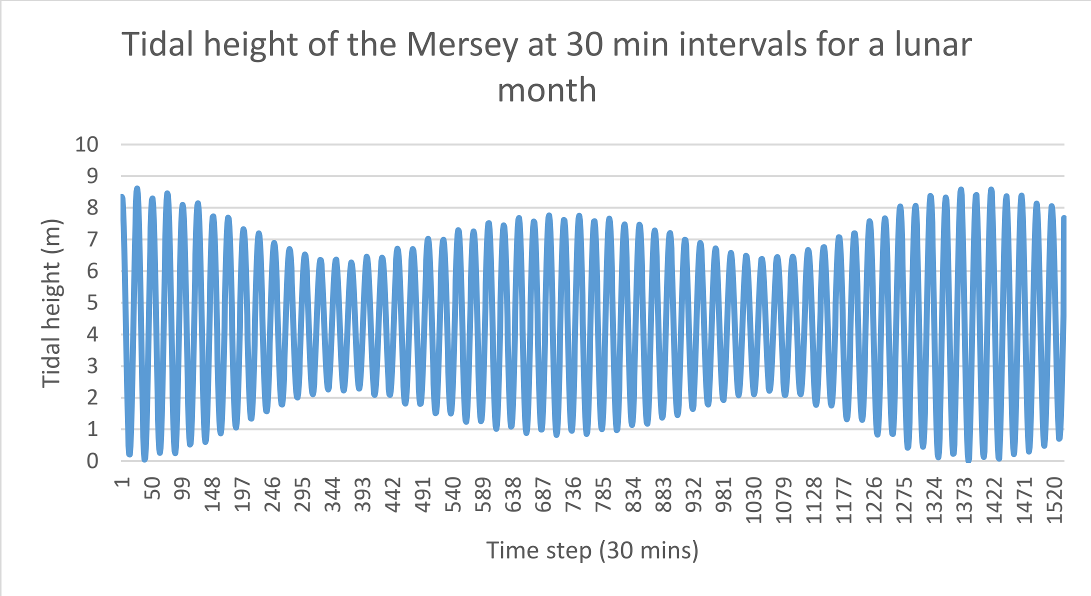


Figure 3-3: Tidal height (m) at Gladstone lock measured at 30-minute intervals over a lunar month

With a complete understanding of how the gravitational interactions between the Sun, Earth and Moon, tides can be predicted up to 50 years in advanced with a reasonable degree of accuracy (UK Hydrographic Office, 2019). This makes tidal power very predictable and reliable as a source of renewable power. However, there are a number of reasons that the tidal height observed at a site might not precisely match the predicted height. These include the following.

Meteorological Effects on Tidal Height

Typically there is a small variation between the predicted lunar tide and the actual tidal height observed at a location. This can be due to meteorological conditions experienced at the site, specifically the wind and the atmospheric conditions.

A change of 1 millibar (mb) in atmospheric pressure roughly equates to a change of 0.01m in the recorded tidal height (Baker, 2006). This change can either be positive when there is a decrease in atmospheric pressure or negative if there is an increase. On average, in the UK, the change in tidal height caused by atmospheric pressure rarely exceeds 0.3m (National Oceanography Center, 2009).

Wind speed and direction also has a similar effect on the tidal height. When there is a strong onshore wind, the wind interacts with the water surface creating surface waves. This effectively impacts the height of the observed tide as waves are either pushed towards the site, increasing the observed tidal height or driven away, decreasing it (National Oceanography Center, 2009).

3.2.2. Current Tidal Technology

Whilst tidal power is currently perceived as the harnessing of power from the shifting tides in order to generate electrical power; this has not always been the case. There are records detailing the operation of tidal mills dating back as far as 787, with the oldest site in the UK being documented as having been built in 1170 (Tidalpower, 2015). These mills originally harnessed the power of the tide to mill wheat into flour mechanically. This was achieved by trapping large volumes of water at high tide before releasing it through a water wheel as the tide ebbed. With the advent of electricity and the simplicity of using alternative non-renewable methods of power generation, these devices fell out of favour. However, in recent years with the global concern of climate change, the technology is being revisited and revised as a method to produce renewable, reliable and predictable power.

One specific advantage of tidal power compared to other sources of renewable energy is its predictability, which, unlike wind and solar, can be heavily impacted by the effects of atmospheric conditions. Tidal power is predicted to a reasonable degree of accuracy for hundreds of years in advance. This is a significant advantage as it provides a reliable source of power generation to the local electrical grid. This is particularly important when dealing with energy security, as the device can be relied upon to contribute to the country's National Grid baseload.

Currently, it is accepted that there are four main methods for extracting tidal energy at a commercial level: Tidal barrages, Tidal lagoons, Dynamic tidal power and Tidal Stream Generators (TSG's) (Nicholls-Lee & Turnock, 2008). The aforementioned methods are discussed further in the following subsections.

Dynamic Tidal Power

Dynamic tidal power is a novel and as yet untested form of tidal power generation. The idea is currently being explored by a collaboration between the Dutch and Chinese governments. Between them, they are assessing the viability of this method with the construction of a demonstration facility along the East coast of China. This decision was made owing to the completion of a number of successful computational fluid dynamic simulations. These led to developments in the design and showcased the method as a viable form of tidal power generation (Steijn, 2015).

The dynamic tidal power concept involves building a long T or Y shaped dam-like structure perpendicular to the coast. This structure is intended to interact with tidal flows running parallel to the coast. Whilst some water can flow around the structure, the interaction between the dam and the flowing water results in water getting trapped on one side of the structure. This process creates a difference in pressure head between the two sides, which the water naturally wants to correct. Turbines housed within the structure of the dam allow water to transit between each side, and in the process, generate electrical power. The use of multidirectional turbines allows for power generation to occur with varying tidal flows. The concept is illustrated in Figure 3-4, which shows the interaction of the flow with the structure. Areas of high pressure are highlighted in dark red and lower in dark blue.

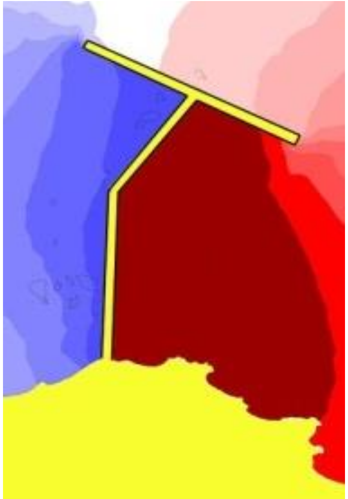


Figure 3-4: Illustration of how the Dynamic tidal power concept works (Walton, 2012)

Whilst still in the development phase, the concept looks promising. However, there have been some concerns regarding the effect that the structure will have on the following: sediment transportation, shipping and marine wildlife.

Tidal Barrages

Tidal barrages are dam-like structures that are built to create an artificial reservoir in conjunction with existing geographical features. The structure and surrounding geography act to trap large volumes of water. Water is allowed to flow between the reservoirs and the ocean via turbines and in the process produce power. Sluice gates can be used to control this flow creating a pressure head between the tidal basin and the ocean, which increases power outputs from the turbines. This process can be seen in Figure 3-5 and with bi-directional turbines can be conducted on the inflow and outflow.

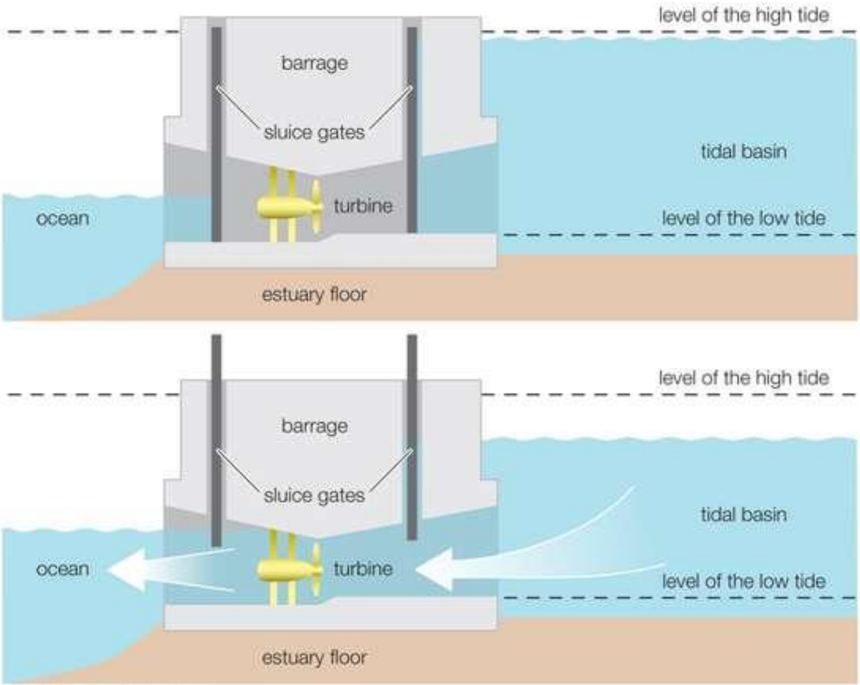


Figure 3-5: Operation of a tidal barrage (Encyclopaedia Britannica inc, 2019)

There are currently two operational tidal barrages in the world. The first one that became operational was in Brittany, France. This barrage, known as the Rance power station, is owned and operated by EDF and has been producing power since 1966. This makes it the longest-serving tidal power station globally. The barrage itself is 750m long and contains 24, 100MW, bulb turbines. This results in a combined rated capacity of 240MW. This set-up is capable of producing 500GWh/year of energy (EDF, 2019). An aerial image of the barrage can be seen in Figure 3-6.

The second barrage is located on Sihwa Lake in South Korea. The tidal plant has been operational since its commissioning in 2011 and is capable of producing 550GWh annually from 10, 25.4MW turbines. (Pacific Northwest National Laboratory, 2019). The combined 254MW rated capacity of the barrage surpassed the value of the La Rance power station, making it the largest operational tidal power plant.

Figure 3-6: La Rance tidal barrage in Brittany France (EDF, 2019)

There are operational concerns regarding the environmental effects of tidal barrages, especially with regards to the loss of habitats such as naturally occurring mudflats. In addition to this, there are a number of technical difficulties, such as silting of the area behind the dam and the impact on shipping, that need to be addressed.

Tidal Lagoons

Much like tidal barrages, Tidal lagoons operate by trapping large volumes of water and releasing it through turbines. The only discernible difference between the two is the requirement to build an artificial lagoon instead of using existing geographical features to trap and contain water. This means that the scheme can be used in areas where large tidal shifts occur but without the requirements of the geographical criteria required by barrages. As a result, more areas can be exploited for tidal power generation.

Currently, there are no operational tidal lagoons. However, there have been a number of proposed sites, particularly along the Welsh coast. The Swansea Bay tidal lagoon was meant to be the flagship project for the development of the tidal lagoon concept. As seen in Figure 3-7, the planned lagoon would be capable of generating 530Gwh per year (11% of the Welsh electrical consumption) from 320MW of installed turbines (Tidal Lagoon Plc, 2018).

Figure 3-7: Planned Swansea Bay tidal lagoon (BBC, 2018)

Unfortunately, the Swansea Bay project has stalled, despite having £200 million in funding support from the Welsh government. This has been attributed to the rejection by the UK government to subsidise the project with a 90-year contract for difference valued at £89.90 per MWh of produced electricity. This decision was made due to the length and value of the contract, which is less favourable than the other schemes such as the new nuclear power scheme at Hinckley Point C (BBC, 2018).

Tidal Stream Generators

Tidal Stream Generators (TSG) also referred to as tidal stream converters, consist of devices that are positioned directly into flowing tidal streams. These devices come in a variety of designs varying from the traditional 'bladed' tidal turbines to the more unfamiliar, such as tidal kites and oscillating hydrofoils.

All of these devices work to convert the energy of naturally flowing water into electricity, unlike the other three methods which generate power using a change in pressure head between two water levels. Currently, TSG technology is still in its infancy as a renewable source of energy. As a result of this, new devices are being developed and tested as companies compete with each other to develop their own technology to a commercial level, and provide a meaningful Return on Investment (ROI).

Owing to the development rate of this technology, and the opportunities to position smaller devices at a larger number of sites, this report will focus on site selecting TSG's. As a result, the remainder of the literature review will be focused on this technology.

3.2.3. Tidal Stream Generators (TSG)

TSG's are devices that convert the kinetic energy of flowing water into mechanical energy. The mechanical energy is then typically used to drive a generating device producing electrical energy. Currently, the European Marine Energy Centre (EMEC) categorises TSGs into seven different design classes. Six of these categories can be seen in Figure 3-8. The seventh category is currently reserved for novel ideas that fall outside the established technologies identified in the other categories (The European Marine Energy Centre ltd, 2017). This covers the ongoing development of technology in the advent of a new concept. A further description of the six main categories is provided below alongside example turbines that conform to each of the specified categories.

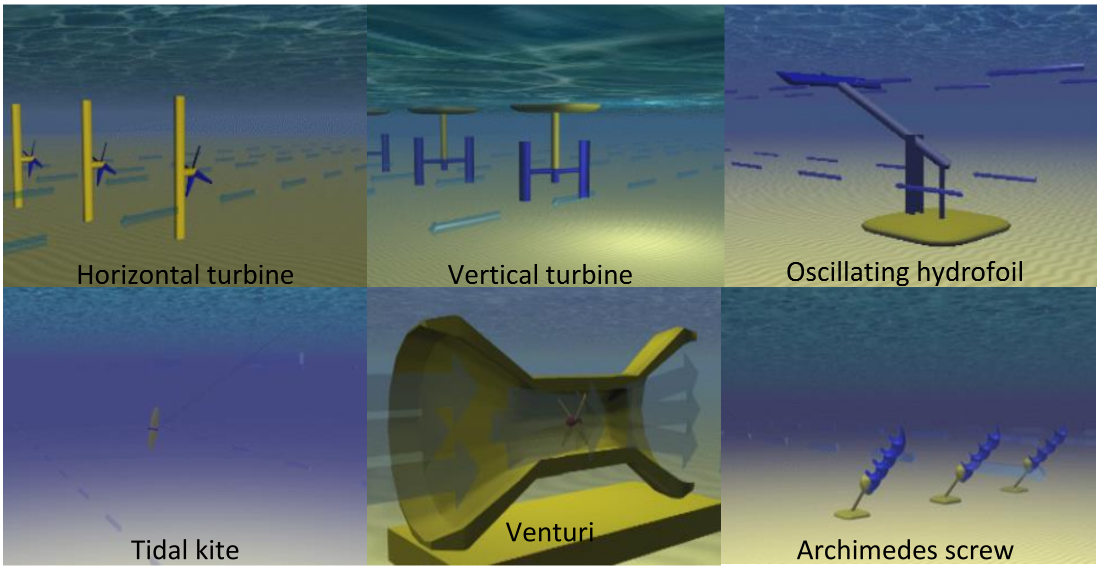


Figure 3-8: Types of tidal stream generators (AQUARET, 2008)

Horizontal axis turbines operate much like conventional wind turbines. The force of the tidal stream causes a mechanical rotation of the blades around a horizontal axis. The mechanical energy is then converted into electrical energy using a generator. Horizontal axis turbines are currently the most common design of TSG's, with a number of devices conforming to the defined design characteristics. These include the 300kW Seaflow turbine deployed initially off the coast of North Devon, the SeaGen in Strangford Lough, which has now been decommissioned (Marine Space, 2016) and the Orbital Marine Power (formally Scotrenewables) 2MW floating turbine, the SR2000 (Orbital Marine Power, 2019).

Vertical axis Turbines operate similarly to horizontal axis devices. Instead of operating in a horizontal plane, the blades rotate around the vertical axis. One advantage is that the device by design is typically multidirectional, and very little consideration has to be taken regarding device placement. One example of this system is Current2current's C2C Omni-directional converter, which is currently in its test stages with plans to develop devices capable of producing 1MW in the future (Current2Current Ltd, 2017).

Oscillating hydrofoil is a wing-like structure that changes its angle of attack to the oncoming water flow. This generates a lifting force across the wing which causes the wing to both rise and fall with the force of water flowing over it, creating an oscillation. This mechanical motion drives a hydraulic system in order to generate electrical power. One example of this turbine is the Stingray built by the Engineering Business (James Glynn, 2006).

Venturi turbines, also known as enclosed tips, are tidal devices that are housed in a ducted housing that helps funnel and direct the tidal stream into the blades of the device. The ducting makes use of the venturi effect to accelerate the flow of water through the device in order to increase the power output of the device. The ducting can also improve the efficiency of the device by reducing wake turbulence from the tips of the blades. One example of this technology is the Open Hydro turbine. However, this company was liquidated in July 2018 (European Marine Energy Centre (EMEC) Ltd, 2018).

Archimedes screws devices convert the flow of the tidal stream into electricity using a corkscrew-shaped device. This helical surface rotates with the force of the water moving across the surface, generating the spiralling motion as the water creates a lifting force on this surface. This mechanical motion is then converted into electrical energy in a generator. Currently, only the FluMill is being developed after it was tested in the Shapinsay Sound at the EMEC in 2011 (European Marine Energy Center Ltd, 2011).

Tidal Kite devices are a relatively new category of tidal device which accounts for the development of Minesto's tidal kite turbine concept. Tethered to the seabed with a cable, the device is allowed to "fly" in a figure 8 pattern swooping in the intersection. This swooping motion is due to the force imparted on the device's wing structure and is used to accelerate the device through the water. This increases the relative flow speed of water entering a small turbine mounted on the device, increasing the power generated by it. This system has the added advantage of being capable of generating power from relatively slow-moving tidal flows. The only example of this category is the Minesto tidal kite. This system is currently in the process of being tested and deployed off the coast of Holyhead, North Wales (Minesto, 2018)

Of the seven categories identified, it is clear that the majority of current and past tidal devices conform to the Horizontal axis turbine category. This technology seems to be the most established form of TSG devices, perhaps having taken inspiration from the development of wind turbines.

3.2.4. **TSG History**

TSG's are a relatively new method of producing renewable energy. Initial investigations into the technology only began in 1994, during which a period of river flow testing was carried out (Jeremy Thake, 2005). The following is an account of some of the key milestones achieved in the development of TSG technology since these initial tests. The findings outline a trend in the development of larger capacity turbines and show the rates at which they are being developed and deployed:

- Initial testing and proof of concept project were conducted by IT power. Scottish Nuclear & NEL in Loch Linnhe, Scotland, between 1994 and 1995 becoming the world’s first TSG producing 15kW from a rotor suspended underneath a catamaran pontoon (Fraenkel, 2008).

- Stingray was built by The Engineering Business and then successfully deployed in Yell Sound, Shetland, in September 2002 producing 150kW from an oscillating hydrofoil (The Engineering Business Ltd, 2005).
- The Seaflow 300kW single rotor turbine was successfully installed off the coast of Lynmouth in Devon during May 2003. It was the first bladed turbine to operate in exposed conditions but was not grid-connected (Fraenkel, 2008).
- SeaGen became the first TSG to deliver power to a national grid (the UK National Grid) in July 2007 when it started producing 1.2MW from its twin 600kW turbines in the fast-flowing waters in Strangford Lough in Northern Ireland.
- In November 2009, the Seaflow turbine was entirely removed from its former site, becoming the first tidal turbine to be decommissioned entirely after an extended period of operation (Hughes Sub Surface Engineering Ltd, 2009).
- Nova Innovation became the first company to deliver power to a national grid from a tidal array when it connected the second of five 100kW turbines to the UK National Grid in August 2016 (Nova Innovation Ltd, 2016).
- In January 2016 it was announced that the SeaGen turbine would become the first commercial turbine (having supplied power to the grid) to be decommissioned after seven years of operation. This was to be the final phase of the SeaGen project and was used as a learning exercise to help improve the understanding of the entire lifecycle of the turbine. Decommissioning was completed in 2017 (Atlantis, 2017).
- In April 2016, Scot Renewable (now Orbital Marine Power) deployed their 2MW SR2000 floating turbine at the European Marine Energy Centre (EMEC) in Orkney. To date, this turbine jointly holds the record as the most powerful rated, grid-connected, turbine in operation with Open Hydro’s 2MW turbine which was deployed

in the Bay of Fundy, Nova Scotia, in Canada, during November of the same year. (Scotrenewables Tidal Power Ltd, 2016) (Openhydro, 2016).

As of the end of 2016, there was 14MW installed capacity for both wave and tidal stream devices in Europe. However, this figure is far below the anticipated 641MW that was set out in the National Renewable Energy Action Plan (NREAP). This 641MW value takes into consideration the 240MW tidal barrage currently operational in France. However, the difference can be attributed to a number of factors that have slowed down the roll-out of devices. Chiefly among the factors are development costs and the time taken to conduct site and related environmental surveys. It is expected that tidal power will continue to receive investment focus as a key form of renewable energy. This trend is predicted by current funding, which has been secured to increase tidal stream power generation to 71MW of installed capacity within the EU by the end of 2020. However, this figure could be expected to rise as high as 600MW as a number of different projects are in various stages of planning, including a new investigation into a River Mersey tidal barrage (BBC, 2017) and the possibility of building the Swansea Bay lagoon (Magagna, Riccardo, & Andreas, 2016).

3.2.5. **Power From a TSG**

The power available at a site is typically influenced by two things, the flow speeds (m/s) and the density of the water (kg/m^3). In order to calculate the power available per m^2, the following equation can be used. Where ρ is the density and v is the velocity of the water flow.

$$P = 0.5 \times \rho \times v^3 \qquad (3\text{-}1)$$

Typically the density of water ranges from between 1000kg/m3 for freshwater and 1025kg/m^3 for seawater (Shaikh, Tousif, Md, & Taslim, 2011) and flow speed required for rated power production from a turbine is around 2m/s, depending on the device design. It should be noted that flow speeds continuously change with the tidal conditions with faster flows occurring during spring tides.

In order to calculate the power output of a typical horizontal axis turbine, the device specification needs to be taken into account. This includes the swept area of the device, the area that the blades turn through, and the Coefficient of Performance (Cp) of the turbine. This is the mechanical efficiency of the turbine accounting for losses. This means the power equation is expanded to the following equation, where A is the swept area (m^2) and Cp is the Coefficient of Performance of the device (%) (Shaikh, Tousif, Md, & Taslim, 2011). This equation has been previously used to assess power outputs in the site selection of tidal turbines in the River Mersey (Kelly, Blanco-Davis, Michailides, Davies, & Wang, 2018)

$$P = 0.5 \times \rho \times A \times v^3 \times Cp \qquad (3\text{-}2)$$

In addition to this, the power from a device might be limited due to the design of the device. It is commonplace for a turbine to have a cut-in point and a rated maximum capacity. This is the designed operating limits of the turbine and is illustrated in Figure 3-9, which shows the power curve of the 1.2MW SeaGen turbine. From the image, it is clear to see that below water speeds of 1m/s there is not enough power in the water flow to generate electricity. Hence the turbine is “non-operational” and produces no power. Equally, at flow speeds of 2.4m/s and above, the water flowing into the turbine hits the turbines rated power, the maximum power the turbine is capable of producing and hence the power remains at 1,200kW. Between these two points, the turbine is considered to be “cutting in”, as water speeds are sufficient to produce power, but not yet reach the rated limit of the turbine.

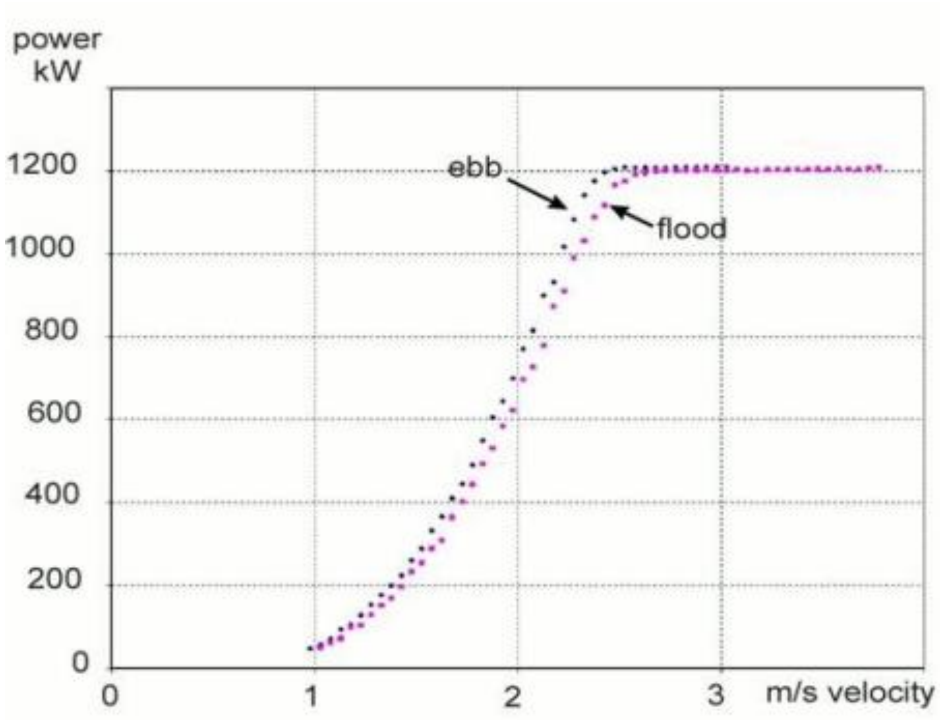


Figure 3-9: Power Curve of the 1.2MW SeaGen turbine deployed at Strangford Lough (Elsevier Ltd., 2010)

3.2.6. **Test Centres**

As briefly mentioned earlier, one of the biggest challenges to the development of tidal power is the financial cost. One of the larger contributing factors to this is the conducting of environmental site surveys. These are carried out after a site has been identified but before a turbine is deployed to determine the local environmental impact that the turbine will have, specifically on the local marine wildlife. This is conducted as part of the current standard deployment methodology, Survey Deploy Monitor. This methodology ensures that the impact of any device on the immediate ecosystem is reduced. However, the cost of carrying this out is both financial and in time (initial site surveys can often take a year or two) (Crown, 2016). It should be noted that additional methodologies such as Risk-Based Consenting for Offshore Renewables (RICORE) (RiCORE project, 2016) have also been investigated as a replacement for Survey Deploy Monitor in order to speed up the process of deploying devices on a commercial scale at other sites.

In an effort to ease this process, a number of test centres have been set up, which effectively make it easier for companies to test both full-sized and scaled devices in a controlled environment. This is facilitated by the removal of the requirements to complete lengthy assessments on the local marine life in these areas as they have already been conducted. In addition to this, these test centres provide monitored environments with the ability to connect the turbine to the grid. This has the added advantage of providing a developer with an income revenue during the testing phases of their concept. Currently, there are two major global test centres; however, other centres have been proposed.

European Marine Energy Centre (EMEC)

The EMEC was established in Orkney in 2003 to act as a centre for developers to develop, test and refine both wave and tidal power devices. Orkney was chosen for its strong tidal currents and wave conditions as well as the additional utilities such as its sheltered harbour and grid connection. The centre provides 14 full-scale, grid-connected test berths for wave and tidal devices as well as a number of test berths for small-scale testing (European Marine Energy Centre Ltd, 2016).

Fundy Ocean Research Center for Energy (FORCE)

FORCE is a dedicated test centre for in-stream TSGs, based in the Bay of Fundy, Nova Scotia, Canada. There are four test berths for full-scale designs providing grid connections. The facility provides a common infrastructure for developers to work with and helps provide device monitoring and fast-tracked permit applications, allowing developers to decrease the time it takes to test their devices (Fundy Ocean Research Center for Energy, 2016).

North Devon Demonstration Zone

The North Devon demonstration zone was formerly home to the 300kW SeaFlow turbine. Wave Hub proposed that a demonstration zone could be set up in the surrounding area along the North coast of Devon between Hangman Point and Foreland Point. It was envisaged that the site would be capable of generating 30MW in an area of 35sq km, with key infrastructure points located along the North Devon coast. (Wave Hub, 2014). However, it appears that Wave hub's plans for this site have been abandoned in favour of a different test facility focusing on wave power in Pembrokeshire.

3.2.7. Tidal Feasibility Studies

With the design and development phases of some turbines ending, companies have started successfully deploying their devices at new sites. This indicates the beginning of the commercial development of TSG's.

Much like other forms of power generation, TSG's are not just deployed randomly. Typically, a feasibility study will be carried out in order to evaluate and assess a chosen site against a set of criteria. This allows a user to determine the practicality of the project before undertaking the project. In addition to this, the findings from a feasibility study can also be used to inform decisions with respect to the size or type of device that will be deployed. In short, the undertaking of a feasibility study increases the likelihood that a device will operate as intended if the site is deemed suitable for deployment.

In order to undertake a feasibility study, there needs to be a large amount of data for both the site and the device. The entire process of the feasibility study can be used as an iterative feedback loop with the results from an initial analysis being used to inform and make decisions during additional stages. This allows the user to refine the results owing to factors. An example of this can be illustrated as follows;

A site is analysed initially assuming that the turbine will have a 10m diameter. The findings of the initial study indicate that the water depth is capable of hosting a 12m diameter turbine. The feasibility study can be re-run with the informed decision made to deploy a 12m turbine, and the results can be compared if required. This methodology allows the developer to make an informed decision between the 10 and 12m devices. Typically as with most projects, this decision is made with respect to the financial analysis of each system.

Whilst a developer will already have a large amount of information regarding the device they want to deploy, typically there is less available data regarding the site. As a result of this, a large amount of data has to be obtained from various sources. This includes information on water flow speeds, water depths, marine traffic, fishing areas, seabed composition and local infrastructure points such as grid connection sites and maintenance ports. By analysing the information with respect to each site against the known information about their device, namely the operational cost, power output, rated water speed, cut-in speed, operating efficiency, operational life span and maintenance required, the site can be analysed. This will allow the user to determine the following:

- Whether the device can be safely situated at the location
- The expected power outputs, with respect to the turbine and flow conditions at the site
- The cost associated with deploying the device at the location
- The potential earnings from the device

Because commercial decisions typically revolve around finance, the financial analysis of the device is typically used to select the optimal site. The undertaking of a feasibility study can be time-consuming and will require the gathering of data to support the assessment. However, this process is preferable to wasting money deploying devices unnecessarily. Once a site is located using a feasibility study, it is typically analysed further to validate the findings. This can include real-world measurements at the site to ensure that the findings of the feasibility study are accurate.

Whilst no references can be cited for a company running a feasibility study for a TSG; It is reasonable to assume that a number have been carried out, owing to the active deployment of devices. These reports will likely contain commercially sensitive data such as costs and device performance data that companies will not want in the public domain.

Whilst no commercial report can be found specifically for TSG's, there have been a number of feasibility reports for other large-scale government-funded tidal power projects. These include projects such as the River Mersey feasibility study carried out between 1988 and 1992 by the Mersey Barrage Company and repeated again between 2006 and 2011 by the Mersey Tidal Barrage Group (URS Scott Wilson Ltd, 2011).

These two studies looked at the feasibility of constructing a barrage across the River Mersey between New Ferry and Dingle and identified a scheme that was capable of producing 920GWh annual for an expected 120-year period.

In addition to this, the recent Swansea bay tidal lagoon report detailed the process of the application for funding support through the UK government's contract mechanism for renewable energy subsidies (Crown, 2015). The findings from both these reports identified strengths and weaknesses in the respective schemes but ultimately were used to determine the project's fate. In both of these cases, this meant the decision not to proceed with the project due to the staggering upfront construction cost of the Mersey barrage and the aforementioned contract requirements of the Swansea Bay lagoon.

3.2.8. Tidal Site Selection and Deployment

It is important to understand the stages of site selection from initial site identification through to the deployment of a device. Typically this process occurs over three stages to mitigate both the time and costs of the assessment in the case that the site is unsuitable for deployment. The following defined the three key stages.

Stage 1 – Initial site identification. Once an area is identified, an initial assessment is performed to shortlist ideal locations for deployment. This is typically conducted with the use of easy to obtain data sets, providing an initial low-cost assessment of the site.

Stage 2 – In-depth analysis. Once the preferred sites have been identified, they can be investigated further. Typically this requires the use of real-world measurements to assess the site resource and environmental impact to local wildlife. This typically requires onsite investigations that can be both time consuming and costly. However, they provide an invaluable set of data that can be used to select a preferred scheme/location for deployment.

Stage 3 – Deployment and then monitoring. This ensures that the device is performing as expected and not having an adverse effect on the local environment.

It is important to understand that the results of these stages can be used to inform decision-making with respect to the project. In the case that the findings are unfavourable, the project can be cancelled before any more time or money is wasted on the next stage. This process is showcased in the example of the 2006-2011 Mersey Tidal Barrage Group case study for a barrage on the Mersey River (URS Scott Wilson Ltd, 2011).

The initial stage of the project examined fourteen proposed sites for consideration and assessment, with three schemes being shortlisted for the second stage of the analysis. This analysis provided an in-depth assessment of each of these stages, identifying a preferred site between New Ferry and Dingle. Owing to the complexity of the project, further investigations were conducted for the preferred scheme. However, this identified a number of issues with the project, and as a result, the scheme was not implemented.

3.2.9. **Renewable Energy Finance**

In order to tackle climate change, the UK government proposed funding to support the development of renewable technologies such as wind, wave, tidal, solar and hydro. This support takes the form of subsidisation, with the allocation of contracts for difference, also known as strike prices. This effectively is an agreement to fix the value paid for electrical energy generated over a set period, typically ranging between 15-20 years.

These contracts provide suppliers with confidence in the value for the energy that they will receive over a long period. This encourages them to advance with a project without the uncertainty of future energy prices affecting the scheme's financial viability. This is particularly important in emerging renewable markets and high-cost construction projects such as nuclear power plants. Without these incentives, it is highly unlikely that companies would invest in these risky schemes as they could be unlikely to recoup the cost of their untested device. This would be the case if they were paid the actual value for the power that they would be generating.

Companies are encouraged to enter bids for the contracts during allocation rounds. Currently, there have been two rounds of funding specifically for renewable energy that has been finalised, with successful applicants having been notified (Crown, 2013) (Crown, 2016). The third round is currently at a draft stage, and hence the prices have yet to be finalised (Crown, 2018). The strike prices offered during each round are displayed in Table 3-1 with respect to their value of £/MWh in 2012 prices.

Table 3-1: UK Strike prices for renewable technologies specified in £/MWh with respect to 2012 prices

	Round 1					Round 2		Round 3	
	14/15	15/16	16/17	17/18	18/19	21/22	22/23	23/24	24/25
Offshore wind	155	155	150	140	140	105	100	56	53
Tidal stream	305	305	305	305	305	310	300	225	217
Wave	305	305	305	305	305	300	295	281	268

It should be noted that for comparison, in January 2019, the price for energy in the UK was around £35 per MWh. Accounting for inflation, this equates to around £30.17 in 2012 prices (Bank of England, 2019). When comparing this value to the contract allocations, it is clear that there is a substantial difference between the value paid and the value of the electricity generated. As previously mentioned, this is to encourage the development of renewable technology.

3.3. Life Cycle Assessment

LCA is a methodology for assessing a product or system with respect to the impact that it will have. In order to explain and expand on the procedure behind this methodology, the following subsections outline the philosophy of life cycle thinking, the historical development of the LCA methodology and regulations, current regulations and the methodology for conducting an assessment with respect to the four key stages. The subsections also explains; impact categories, functional units and the benefits and limitations of the methodology. A final subsection discusses LCA's application in the offshore industry, focusing on tidal power and wind.

3.3.1. Life Cycle Thinking

Life cycle thinking is a product-oriented philosophy that encourages users to think beyond the traditional focuses of singular product impacts. This can be achieved by exploring additional benefits of changes to a product's life cycle in areas such as the social, economic and environmental impact of the product. (Life Cycle Initiative, 2020). The philosophy draws from scientific methods of analysis such as LCA and life cycle costing methodologies, to create a holistic understanding of the overall impact of the product/process. The results of each of these are combined using an impact assessment to assess the findings. This can be used to provide insight to users in order to help determine the optimal course of action with respect to their requirements. Importantly the methodology sets out to reduce the impact of the product/process without shifting the burden between different segments of the lifecycle.

This is an important concept to consider owing to the current environmental impact reduction culture. Currently, there is a shift towards environmental consciousness with companies striving to do the right thing for the environment. As a result of this, they are looking to improve their environmental impact. This impact can be measured using the LCA methodologies, which can be used to quantify the environmental impact of a product/service. However, it should be noted that companies still have to make a profit to operate effectively, and as a result, there are several key stakeholders to consider when making decisions within a company.

3.3.2. LCA Development

Life Cycle Assessment, also known as Life Cycle Analysis, is a method of holistically examining a product or system with respect to a functional unit. It was first used by the Coca-Cola Company in 1969 when they commissioned the Midwest Research Institute to quantify the emissions and resource requirements for different beverage container materials for their soft drinks. Unfortunately, this report was unpublished (Guinée, et al., 2011); however, it established the idea which led to the modern regulations developed by the International Organization for Standardization (ISO).

During the 1990s, concern regarding the inappropriate use of LCA within product marketing prompted the development of the current 14000 standards series. This consisted of four separate standards: ISO14040: 1997, ISO14041: 1998, ISO14042 and ISO14043:2000, which when released, were widely adopted globally (ISO, 1997) (ISO, 1998) (ISO-A, 2000) (ISO-B, 2000).

In 2006 the standards were revised. During this revision, it was proposed that two new standards, namely ISO14040 and ISO14044, would replace the previous ones. The new standards focused on improving the wording of the standards and reducing errors. However, the technical core of the previous methods was largely incorporated directly into the new standards. As a result of the development of the new standards, the aforementioned standards were cancelled (ISO-A, 2006) (ISO-B, 2006). Further details of the current standards are provided in subsection 3.3.3, which discusses the current regulations.

It should also be noted that since its conception, the LCA methodology has developed for uses in a wide range of business /industry sectors. As a result of this, it is no longer just limited to the manufacturing industries and has been used as an analysis tool for both products and services.

3.3.3. **Current Standards**

Since its inception in 1996, the process of conducting an LCA has been refined and developed into the modern procedure that is widely used today. The current international standards, ISO:14040 E*nvironmental management - Life cycle assessment - Principles and framework*, have been adopted by a number of countries, including the UK (BS EN ISO 14040:2006), as the method of best practice for conducting an LCA (ISO-A, 2006).

The current ISO:14040 regulations outline the core principles and define the framework to which all LCAs should conform. Additionally, ISO:14044 *Environmental management - Life cycle assessment - Requirements and guidelines,* was introduced to further expand on the definitions of key stages of the framework and provided further guidelines for the undertaking of LCA (ISO-B, 2006). Both ISO: 14040 and 14044 were reviewed and reconfirmed in 2016 as part of the ISO review policy which takes place every five years. The next review is due in 2021.

3.3.4. Methodology

The framework set out by ISO 14040 outlines the four key phases for conducting an LCA. This can be seen in Figure 3-10. Due to the complexity of conducting an LCA, the process is considered to be dynamic, allowing information to flow between the four key stages and informing both the decisions made and the results of the assessment. The four key areas are further defined in ISO 14044 as:

Goal and Scope - Details the extent of the investigation being conducted by outlining the product/system being investigated. Additionally, the boundary conditions of the assessment are defined alongside the functional units that will be used.

Inventory analysis - Lists all the parts and processes in the system being investigated, providing data on inputs to the process such as material and energy and the outputs such as emissions and waste.

Impact Assessment - Collates all the information from the inventory analysis into the relevant impact categories with respect to the functional unit specified in the Goal and Scope.

Interpretation - Defines how the results are reported, ensuring that the process is fair, the method conforms to the regulations set out in ISO 14040, and the results meet the criteria set out in the Scope.

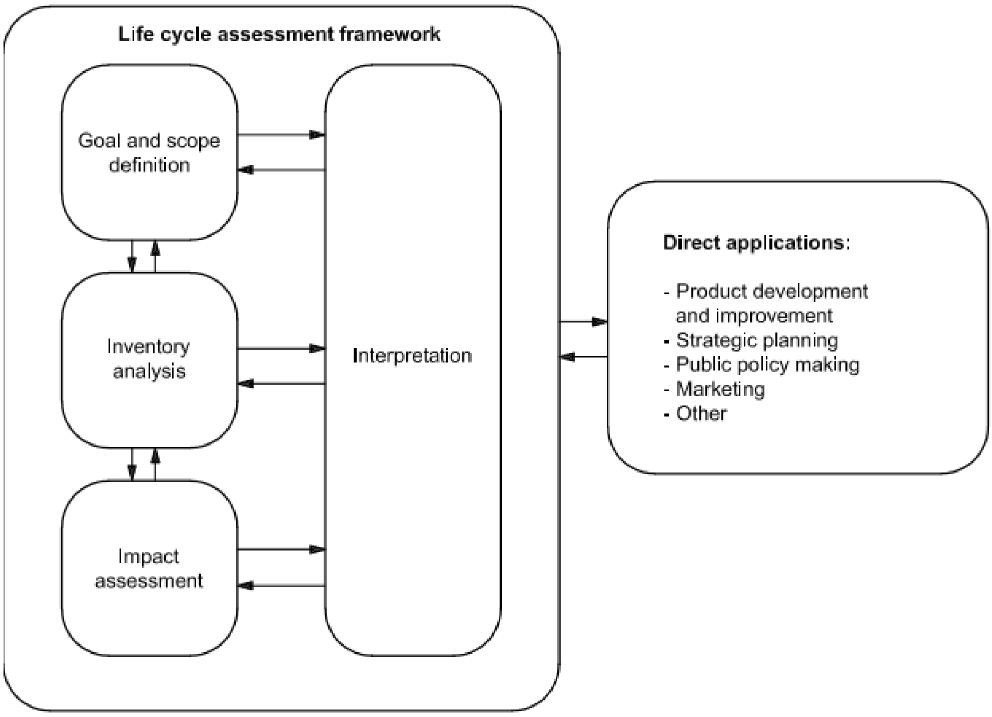


Figure 3-10: LCA Framework as defined by the ISO (ISO-A, 2006)

3.3.5. **Impact Categories**

The goal of the Impact categories is to create a base unit for comparison and collation of emissions with respect to a base unit that each impact category is assigned. There are a number of varying impact categories that can be analysed using the LCA methodology, from Global Warming Potential (GWP), acidification, eutrophication to human toxicity. Each impact category has characterization factors that can be used to combine different emissions that contribute into one easy to understand value. This process is further detailed in the explanation of GWP in the subsequent subsection.

Global Warming Potential

There are a number of different gas emissions that contribute to global warming. In order to collate these different emissions into one unit, it was proposed that carbon dioxide equivalents are calculated for each of the gases. These values can then be summed to provide an overall figure that quantifies the GWP for the released emissions. For GWP, the gas Carbon Dioxide (CO_2) is used as the baseline for the comparisons. As a result of this GWP values are specified in the unit of CO_2 equivalent (CO_2eq). Table 3-2 details some of the common GWP weighting factors specified over a 100-year life span.

Table 3-2: GWP of common Industrial designated emissions (Forster, et al., 2007)

Gas	Chemical symbol	GWP in CO_2eq (over 100 years)
Carbon dioxide	CO_2	1
Methane	CH_4	25
Nitrous oxide	N_2O	298
Chlorofluorocarbons	CFC's	10,000 +

These weighting factors can be applied to their respective emissions to calculate the equivalent value of the base unit. This process is highlighted in the case of the emissions of the following gases, 3.4kg-CH_4, 11kg- CO_2 and 0.2kg-N_2O. By applying the weighting factors detailed in Table 3-2, they can be incorporated into one easy to understand value. This is observed in the following equation,

$$(3.4 \times 25) + (11 \times 1) + (0.2 \times 298) = 155.6 KgCO2eq \qquad (3\text{-}3)$$

It should be noted that there are alternative methods that might be better suited to examine GWP, such as Global Temperature Change Potential. However the GWP is the simplest approach and has been widely used in the Kyoto Protocol, and for this reason, it will be used throughout this Thesis (Shine, Fuglestvedt, Hailemariam, & Stuber, 2005).

3.3.6. **Functional Unit**

The typical functional unit used in LCA's for power generation devices is the emissions per kWh of energy produced. For example, for the impact category of GWP, the results are typically displayed as gCO_2eq/kWh. This functional unit requires an understanding of the power generated from the device and the impact that it will have. This is a good metric for a comparison between different power generation methods. However, the value only accounts for the production of energy and the GWP of the device, it does not define or provide any financial information. Hence, in a commercial world, driven by financial success, other solutions may be better suited for defining a functional unit when conducting an LCA for power generation devices.

3.3.7. **Limitations and Benefits**

There are a number of advantages and disadvantages of conducting an LCA study. The results of an LCA investigation can be used both internally within a company/business to inform decisions on materials and processes but also, externally, as a method of comparison against competitor products. Additionally, by holistically analysing a product, instead of individual stages, areas of improvement can be identified.

Some of the major drawbacks to conducting an LCA includes the amount of data required to perform an assessment and the potential for lack of indicatory emissions. In the case of the former, the generation of this data is time-consuming and costly. In addition to this, any errors in the data can lead to large uncertainties in the results. In the case of the latter, the quantification of the release of emissions may be undefined in parts or entirety, especially when dealing with release rates or frequency. For example, CO_2 may be emitted over a long period of time or in a short but significant (and potentially damaging to the environment) burst. However, the LCA process, as it currently stands, does not give scope for indicating this.

The main benefit of an LCA study is in the way that it can be used as a decision-making tool, allowing users to identify ways of reducing their impact via identification of the preferred material, method or process. This is achieved by directing resources to address potential hotspots in the lifecycle of the device.

3.3.8. Previous Offshore LCAs

Due to the relative infancy of tidal power, only a limited number of LCA investigations have been completed for TSG's. The majority of these investigations focus solely on one device, and all have been completed with respect to a pre-situated turbine or a hypothetical location. As a result of this a number of different research areas were examined as part of the literature review, and are discussed further under the following headings: Tidal power LCA, wind power LCA, additional LCA investigations and LCA in site selection.

Tidal Power LCA

One such example is presented in the article L*ife Cycle Assessment of the SeaGen Marine Current Turbine* (Douglas, Harrison, & Chick, 2007). The study focuses on the SeaGen turbine located in Strangford Lough after its deployment. The report examined 21 of the most "significant components" that made up 96% of the total weight of the device. The objectives of the LCA were to determine both the embodied energy required to manufacture the device and their carbon intensity over the turbine's life cycle, accounting for transportation and deployment of the device. The results of this study calculated the emissions of 1,924t CO_2 and an embodied energy for the device as 25,903GJ with an estimated annual power output of 4,746MWh. This report found that the device had a rapid carbon payback period of just 14 months, confirming that tidal power is both a renewable and environmentally form of energy production.

Of particular note was the sole tidal device comparative study *Tidal energy machines: A comparative Life cycle assessment study* (Walker, Howell, Hodgson, & Griffin, 2013) which set about comparing four different types of turbines: the Deepgen, SR2000, Flumill and Open Hydro Centered turbine, positioned at the same hypothetical site. The functional unit for this study was the embodied energy and CO_2 emissions for each of the different devices. The report determined that the Open Hydro open-centred turbine was the optimal turbine for that specific location with respect to the embodied energy and CO_2 emissions of 41,131 tCO_2 and 534,677 GJ. However, over its life cycle, the device was credited with producing 7,546,585 GJ of energy and saving 1,099,705 tCO_2 with respect to the future energy scenario.

This report additionally detailed the high level of scrutiny, which comes when making comparisons between devices. This is mandated by ISO:14040 to make sure the results of the comparison are equal and fair. This process was detailed in an appendix under the heading of Sensitivity Analysis.

The aim of the paper *"Life Cycle Assessment (LCA) of marine current turbines for cleaner energy production"* was to develop an environmental assessment analysis of an innovative, 6m diameter, 160kW, horizontal axis turbine built by ADAG and deployed in the Strait of Messina. The methodology analysed the device against ten impact categories using the functional unit of one completed energy production system. In addition to this, a comparison was made between the electricity required to build the device and the power produced during its operation, showing a large net gain. This led to the conclusion that the environmental impact of the device was extremely low, therefore prompting further investigations into the technology (Cavallaro & Coiro, 2007).

In addition to this report, the paper "*Life cycle assessment of ocean energy technologies"* was examined. This paper discusses a generalized holistic assessment of 180 ocean energy devices by examining the material resources used by some of the major device components. The categories were as follows; structural elements, electrical elements, mooring/foundations and power take-off components. Data for each of these elements was provided from an in-house database. The report noted the wide variety of device designs owing to the early stage of device development and recognized the role that LCA could play to aid in the reduction of environmental impacts (Uihlein, 2016).

As a result of the limited number of tidal LCA studies, a number of additional fields were examined. Of particular interests are wind power devices, which share a striking similarity to horizontal axis TSG's, including key design components and in some cases offshore operating environments. While not completely 100% relevant, these studies provide a better understanding of the application of LCA.

Wind Power LCA

The article *"Life Cycle Assessment of Onshore and Offshore Wind Energy – From Theory to Application"* demonstrates a comparative assessment of the emissions between different turbines placed on and offshore, With a 2.3 and 3.2MW turbines positioned onshore and 4 and 6MW turbines offshore (Bonou, Laurent, & Olsen, 2016). The report identified the different infrastructure requirements to support the operation of the devices in each of the environments. In particular, the requirements to use large amounts of steel in the foundation monopiles during deployment offshore. The article detailed the impact assessment methodology, outlining the use of ReCiPe and a functional unit of kWh of power delivered to the grid to identify a preferred site. A number of limitations were highlighted in the article, particularly the lack of data regarding the end of life situations of the devices and additionally the inability to recycle some of the major turbine components, namely the turbine blades, which are made from composite materials and are not reliably recyclable.

Another article compares a 4.5MW and 250W device paying particular attention to the impact that distance and transportation methods have on the overall LCA investigation into the GWP of the devices. The article identified that boats and trains were preferable to the transportation of components compared to the environmental impact that trucks have due to their ability to move larger quantities of materials.

However, more importantly, the article identified the possibility that different devices could be better suited to different locations with respect to the environmental impact and local power requirements. For example, small rural communities were better served by smaller-scale 250W turbines, owing to the reduced power requirements of the local area, and the reduced environmental impact of moving a smaller turbine to these sites when compared to the large material mass associated with the 4.5MW turbine (Tremeac & Meunier, 2009).

Additional LCA Investigations

In addition to the aforementioned device-specific LCA's, additional investigations across alternative industries were also examined. These articles detail the processes for parametrization and decision-making within the field of LCA and will be highly pertinent to the development of a generic site selection tool.

The article *"The life cycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making"* discussed the application of LCC in regards to decision-making within the building industry. It identified and analysed ten existing environmental accounting tools, including LCA, before discussing the future development of decision support tools to bridge any shortcomings.

The conclusion of the article identified the need for the development of decision-making support tools, which combines the experience of researchers from different fields, to cooperate and develop the tool that appeals to multiple users. Importantly the article concludes that further research may lead to decision-making tools that involve people in the decision-making process (Gluch & Baumann, 2004).

Additionally, of particular note for this research is the methodology defining the parametrization of the model for analyzing wind converters. The approach behind this methodology demonstrated how 330 parameters were defined with respect to a number of different wind turbines and were then linked to nine key user-specified parameters that informed decisions within the model with respect to different converters. The results generated from this model were compared with respect to the functional unit of kWh of energy produced. In order to validate the findings from the model, the results were compared to data sources from literature. This showed that the results were similar to the other literature, which acted to validate the model (Till, 2012).

Another article discussing the positioning of a biomass power plant was also identified. The methodology detailed the application of Geographical Information Systems (GIS) to site select a biomass power plant with respect to two analysis methods: Suitability and Optimal analysis, where optimal analysis considered the location of the biomass fuel and the power plant identifying the effects of transportation logistics on the impact of the Biomass impact. During the process, GIS was used to identify the "least-cost transport pathways". This article recommended that every bio-energy project should include an LCA (Hiloidhari, et al., 2017). This particular article identified the importance of understanding site selection and its effect on environmental impact due to increased transportation distances.

LCA in Site Selection

Another key finding in the field of LCA research is the combined use of LCA and Geographical Information Systems (GIS) to conduct Spatial LCA's. These are critical findings for the development of a site selection tool, as they showcase the impact that geographical location can have on the environmental impact of a product/service. As a result, it confirms the rationale behind the thesis objective, which identified a perceived impact of the site selection process on environmental findings. The following provides a summary of the key findings in this area of research:

Seagate, an electronics manufacturer, has identified the effect of customer location on the environmental impact of its products using LCA. This process identified that in different regions of the globe, the company has different transportation requirements to reach their customers. This is with respect to the distance between their factories and the end-user. This inevitably resulted in a change in environmental impact with respect to changes in the distance. Additionally, it was observed that energy usage requirements varied between locations during operational phases of their device. Each of these elements affects the final results. This outlined the fact that whilst the components are built in the same plant, the environmental impact that the component will have is dependent on the customer's location (Seagate, 2020).

Additionally, the article *"Influence of site-specific parameters on environmental impacts of desalination"* proposed a three-stage methodology using environmental impact as the decision-making element for selecting a preferred desalination scheme (Maedeh P. Shahabi, 2014). This is achieved with respect to site-specific criteria and adopts a 3 stage methodology: Stage 1 - Identify feasible plant locations, Stage 2 - Develop a range of feasible scenarios for each of the sites identified, Stage 3 - Identify a preferred scheme from the scenarios based on their environmental impact as determined using LCA. The methodology developed was used to examine sites in Western Australia. While the methodology was used to select a feasible solution for desalination plants, the findings were purely based on the environmental impact, and it did not account for the financial effects of implementing and running the schemes.

Additionally, the article *"GIS-Based Regionalized Life Cycle Assessment: How Big Is Small Enough? Methodology and Case Study of Electricity Generation"* detailed a new methodology for performing regionalised LCAs, with particular focus on examining the impact of how an area's size can affect results. This methodology was showcased with the example of the impact of power generation in the United States. Typically in an LCA model, this is defined with respect to a global model for the power produced in that country. The paper proposed a separate model in the form of regional emission areas. These specifically examine the emissions of power generated with respect to the identified area, with the results providing a better representation of the emissions associated with power production in that region. (Mutel, 2011).

3.3.9. **Additional LCA Literature**

In addition to the previously mentioned literature, the book "The Hitch Hiker's Guide to LCA" provided additional insight into the LCA methodology. The book provides a useful guide for undertaking an LCA and provides specific detail on the application of the methodology using examples to illustrate the point. (Baumann & Tillman, 2004)

One key aspect identified in the book was the two distinct types of LCA; Accounting LCA (also known as attributional LCA) and Change-orientated LCA (also known as Consequential LCA).

Attributional LCA is used to determine the stand-alone impacts of the product or procedure being investigated. The results of this investigation can be used in studies to compare products/services and make environmental product declarations.

In contrast, Consequential LCA typically looks at the impact that a decision has on the findings. For example, this might involve examining the impact that two different methods of manufacturing a component have on the product's life cycle, and making a decision based on those findings. This approach could also be adopted when making decisions about site selection.

The type of LCA adopted by the proposed methodology is essential to consider as it will help define the process for conducting the LCA.

3.4. Software

The following section identifies and discusses the software chosen in order to complete the investigation aims. It was identified that three specialist software packages would be required; one for assisting in with the LCA analysis, a second for providing flow data for a site, and a third for processing and combining the results together.

3.4.1. LCA Software

The data produced when conducting an LCA can be expansive. In order to manage this, a number of software packages have been developed to simplify the process via computer-aided management of the data. This streamlines the process for the user allowing for more in-depth analysis to be carried out on large scale systems. There are a number of different software packages available each with its own benefits and limitations. The following is a shortlist of some of the well-known software packages,

- GaBi

- Open LCA
- SimaPro
- Umberto

Typically, the LCA software is combined with Datasets in the form of different databases. As the data is generated from measured values, the cost to obtain data can often be very expensive, and as a result, the databases are very valuable. Data sets have to be updated regularly and checked to ensure that the information provided is accurate. There are a number of different databases available for users; however, most software comes with inbuilt datasets. The chosen software for the undertaking of this project was GaBi, which along with the inbuilt database was purchased for the duration of the project via the Liverpool John Moores University Faculty of Engineering and Technology, Faculty equipment fund. The following subsection discusses the GaBi Software in further detail.

GaBi

GaBi is widely regarded as one of the best software packages to use when conducting an LCA. The name comes from the German words "Ganzheitliche Bilanzie" which translates to "Holistic balance sheet". The software was specifically developed by Thinkstep as a tool to ease the undertaking of an LCA. This is achieved in the software using three simple elements which are explained and illustrated in Figure 3-11 (Thinkstep, 2017):

Plans The basic worksheet that details the system that is being analysed providing basic information of the entire component.

Process Define stages in the production of the system being analysed outlining the process being carried out at each stage of production.

Flows Used to connect process and represent the flow of energy and material being moved/used throughout the lifecycle.

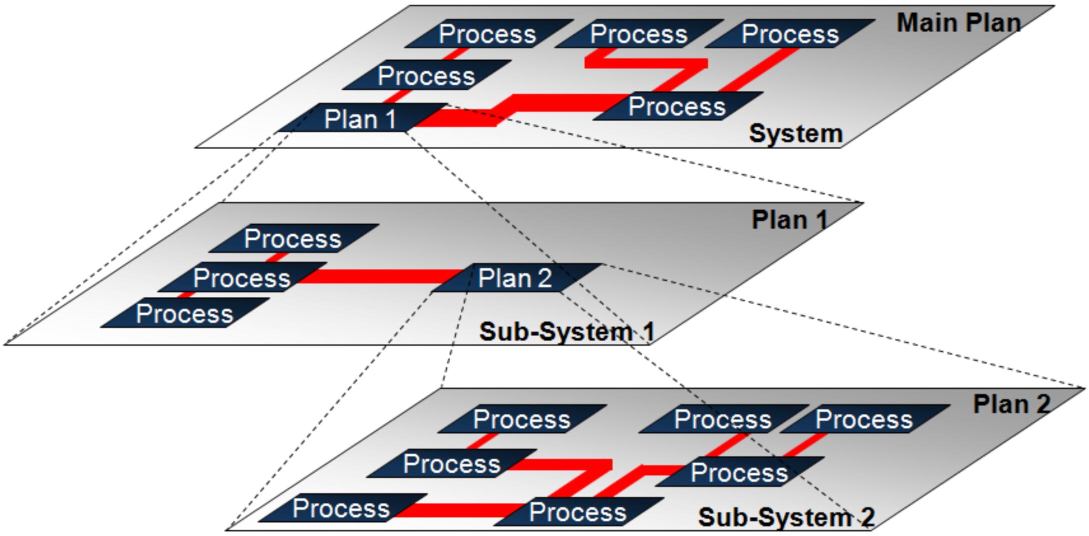


Figure 3-11: Hierarchical system of plans and processes in GaBi (PE International, 2013)

Whilst the software provides a simplistic interface for the user, the main component of the software is the GaBi databases. These have been rigorously put together to provide detailed information on a wide range of manufacturing processes that can be defined in the model. This information provides the backbone to conducting an LCA. The databases in GaBi are checked and updated yearly and built on six fundamental concepts (Thinkstep, 2017):

- Data gathered from real industrial processes and materials
- Data sets are refreshed annually
- All data is subjected to quality assurance checks
- An independent, critical review of all data is carried out by DEKRA
- Global datasets encompass different global regions
- Information is provided on how each of the individual data entries was gathered

These six concepts provide a very reliable and regulated source of data for the databases. This ensures users' confidence in data that they utilise in their models. As a result of these factors, GaBi is used by commercial companies in a wide range of industries.

3.4.2. Tidal Flow Software

Mike 3 Student Lab Kit

Mike 3 is a specialist 3D modelling software which is used widely in industry as a tool to simulate a wide variety of hydrodynamic conditions, allowing designers to determine operational conditions that their structures may face (DHI, 2017).

In order to assess a particular site, a bathymetry model needs to be produced. This is constructed using depth locations to map the seafloor. At a commercial level, this data originates from real-world measurements, such as accurate depth sounding. This data is typically a very realistic representation of the seabed for the area. However, alternative sources such as Admiralty Charts can be used to provide a basic analysis of the area, whilst still maintaining a fairly good degree of accuracy.

Once the model has been produced, it can be subjected to tidal shifts within the software. This generates flow simulations which flood and ebb into the model from along the inlet boundary edge as specified. This results in flow formation across the model as water level changes. Users can take specific flow data from an unlimited number of points throughout the model.

The Mike 3 software is produced by DHI and has previously been used to site select turbines in the river Mersey (Kelly, Blanco-Davis, Michailides, Davies, & Wang, 2018). In addition to this, the software is used by the EMEC. This was highlighted by the evidential support that the EMEC provided for the Marine Accident Investigation Branch report into the sinking of the Cemfjord in the Pentland Firth in January 2015 (Marine Accident Investigation Branch, 2015). This was showcased with the software being used to detail the expected tidal flow conditions during the disaster.

The software requires the construction of a model area that is subjected to tidal conditions based on the inbuilt global tidal model of the software. However, this process of modelling has to be validated extensively to ensure that the defined model area conforms to the examined site.

POLPRED

POLPRED is a specialist tidal flow prediction software used in offshore industries for analysing tidal currents at varying sites within UK waters. The software was developed by the National Oceanography Centre (NOC, 2019).

The software uses a grid layout and numerical modelling to interpolate data from harmonic constants between the grids with respect to a range of sources, including data from the UK tidal gauge network. One advantage of the software is the pre-built model that has been generated from a combination of data sources to define the bathymetry of the UK coastal area. The model has undergone a rigorous validation process with data from tidal gauges used to fine-tune the model (NOC, 2005).

3.4.3. Data Processing - Excel

Excel is a globally used spreadsheet program developed by Microsoft. The software consists of gridded cells that are arranged across 16,384 lettered columns and

1,048,576 numbered rows. The first version of the software was originally released in 1987 and has since been updated a number of times to the current office 365 version. Over the 32-year period of operation, Excel has become a household name that's user friendly and easy to understand (Microsoft, 2019).

Excel has previously been used to process large amounts of tidal data using the 484 functions built into the software (Kelly, Blanco-Davis, Michailides, Davies, & Wang, 2018). Excel allows the user to perform simple tasks such as calculations as well as solving complex mathematical problems. Whilst there are a number of other software packages that are capable of processing data better then Excel, Excel was chosen due to its commercial availability, which means that a user will already be familiar with the software and typically have it available to them reducing the requirement to purchase additional licences.

3.5. Conclusion

The completion of the Literature Review brings about the conclusions of the first two aims of the project. These outlined the requirement to investigate current literature in the fields of Tidal power and LCA. The following remarks, identified in bullet point form, highlight the most important findings in the chapter, and as specified in the research design methodology, this will be significant in the development of the proposed methodology for site selecting turbines.

- TSGs' modular design allows them to be deployed one at a time or en masse in arrays.

- Current TSG technology shows that it is reaching the point of commercial deployment with a number of schemes.
- It should be noted that currently, there is no obligation for a company to look at the environmental impact of the devices outside of the direct area of impact of the turbine.
- The philosophy of Life Cycle Thinking encourages users to assess multiple impacts of changes to a product's life cycle and their subsequent effects in different areas, promoting a greater understanding of the impact that a product or service might have and encouraging holistic decision-making to reduce its impact. The impact is typically assessed and quantified using LCA.
- The typical functional unit used to define power generation for the GWP impact categories is gCO_2eq/kWh. This functional unit accounts for the production of energy from a device; however, it does not define the financial costs associated with it.
- Parameters can be defined within an LCA methodology to create a generic tool that can then be tailored to the user requirements via the alteration of the specified values.
- LCA has previously been used in site selection. This frequently involves combining the assessment with geographical information to create a site selection methodology for identifying a preferred site with respect to the holistic environmental impact. Of particular note was the identification that changes in delivery distance and end-user energy requirements would impact the final results.
- There has yet to be a published paper looking at the environmental and financial impact of site selecting tidal turbine. Current TFS reports instead

focus on the immediate environmental impact at the site with respect to wildlife and LCA studies have been conducted post device deployment and with respect to hypothetical sites typically investigating environmental payback periods.

- The following software packages were discussed and sourced for the project, POLPRED, GaBi and Excel.

CHAPTER 4: DEVELOPED METHODOLOGY OVERVIEW

4.1. Summary

The following chapter provides an overview of the proposed methodology developed from the findings of the literature review. This is achieved by defining the initial concept with respect to the project objectives. The key stages of the developed methodology are then explained in detail in the following chapters with respect to each key work package identified. Namely: The Site and turbine specification, Technical Feasibility Study (TFS), Life Cycle Analysis (LCA), and Combination Tool.

4.2. Initial Concept

The completion of the first two aim of the investigation identified the emergence of tidal power as a renewable energy source, specifically highlighting the current interest in the commercialisation of TSGs due to their low capital cost and modular nature. This has presented the opportunity for smaller companies to develop and deploy their designs, generating interest in investment and commercialisation of the device. As a result of this, it is expected there will be increased deployment of these devices in the future, with companies looking to take advantage of their ability to generate predictable and renewable electrical power.

At this time, site selection techniques focus primarily on the known financial implications of the scheme. While there are requirements to assess the direct environmental impact on wildlife at an intended site, currently there are no requirements to assess the overall environmental impact that the device's life cycle has on the developer and, indeed, the planet. In a world tackling climate change companies are continuously striving to improve their carbon footprint. To achieve this, they are using tools such as LCA to assess impact. The Literature Review showed that tidal energy systems evaluated using LCA are typically assessed with respect to their GWP, in the unit of Emission of gCO_2eq/kWh. While this generates a standard unit for comparing different methods of energy production, it provides no direct information to the users about the actual emissions of the device, or more importantly, the financial implications.

These discoveries highlighted the need for the development of a methodology for a site selection tool in line with the 4th objective of the project. The tool will have to combine the results from a TFS with those of an LCA. This will help companies to better understand the impact that their devices will have. Whilst tidal power is already a renewable source of energy; it does not mean that the process of harnessing it cannot be improved environmentally. As a result of this, the developed tool will allow the user to make a site selection decision with respect to both the financial and environmental impact that site selection has. In order to facilitate the completion of objective 4, objectives 2 and 3 will have to be addressed. These objectives identify the necessity of developing methodologies for the LCA and TFS as follows:

- **Objective 2 -** An LCA will have to be conducted to assess the environmental impact of positioning a device at each site. However, in order to determine the true global impact that the device will have, a holistic analysis will be carried out. This will involve determining the impact across the entire lifespan of the device, from cradle to grave.

- **Objective 3 -** A TFS methodology will have to be developed, not only to identify the sites available for deployment but to scrutinise sites with respect to the financial impact that a device at a particular location will have. This can be used to determine if the scheme is financially viable - an important factor when dealing with commercial decisions.

It is expected that the process of site selection is going to affect a number of elements of each of the methodologies, and as a result, impact the findings of the combined methodology as follows:

- Changes in distance from the site to the grid connection point will affect both the financial cost and material mass of the cable. This will have a resulting effect on both the environmental impact and the initial installation cost of the turbine.
- The distance from the maintenance and construction port to the site will affect the fuel consumption of any vessel transiting between them. This will have both a financial and environmental impact associated with the fuel required to complete the journeys.
- There will be financial implications of the turbine operating at each of the different sites.

Some of the findings from each study can be used to inform decisions in other stages of the investigation. This results in the development of a methodology which requires data to be shared between the two studies. One example of data being shared is the distance data generated in the TFS. This data will also be useful to determine the fuel consumption of a vessel travelling these distances during the LCA.

Once the results from the TFS and LCA are generated, a normalisation methodology will be applied to combine the results. The resulting score for each of the specified sites will then be used to determine the optimum site for turbine deployment, with respect to both financial and environmental factors. In order to create this tool, the following methodology is proposed and developed further over the subsequent chapters 4, 5, 6 and 7.

4.3. Proposed Methodology

The proposed methodology for a combined LCA and TFS site selection tool for TSGs is depicted in Figure 4-1. This process is then further explained, with respect to the key stages identified.

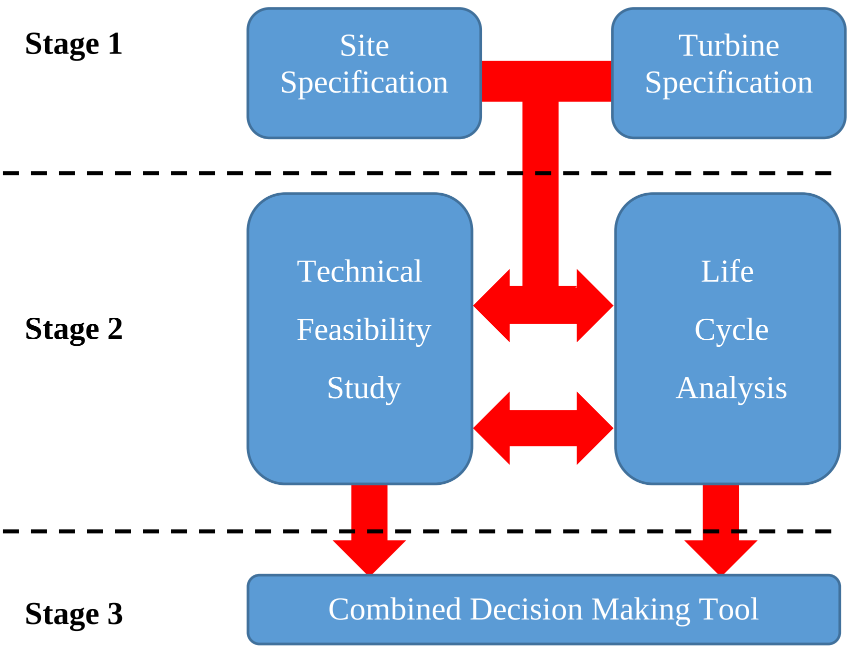


Figure 4-1: Stages of the developed methodology

Stage 1: Site and Device specified by the user and relevant data gathered.

Stage 2: TFS and LCA analysis to be carried out for the specified site and device. Data is allowed to flow between the two models, namely the distance information from the TFS to the LCA and fuel consumption from the LCA to the TFS, allowing calculations to be completed for both.

Stage 3: The results from the LCA and TFS are combined in the Decision-Making Tool. This tool combines, and ranks the sites, identifying the preferred site for deployment. The methodology will use a normalised weighting system. This allows the user to define their own weightings with respect to either the financial or environmental aspects of the site. This will allow the user to tailor this methodology to their specific requirements.

4.4. Data Sharing Arrangement

The defined methodology proposes that data will be shared between each of the key stages. As a result of this, it is important to understand the large volume of data that will be generated and shared. In order to visualise this movement, Figure 4-2 details the data expected to be generated at each stage, and shows how this will flow between stages. This data flow is particularly important to understand when data is used to inform calculations within subsequent stages. In the case of Stage 2 and 3 data “in” is situated on the left, and data generated by the independent methodologies, and hence “out”, is stated on the right.

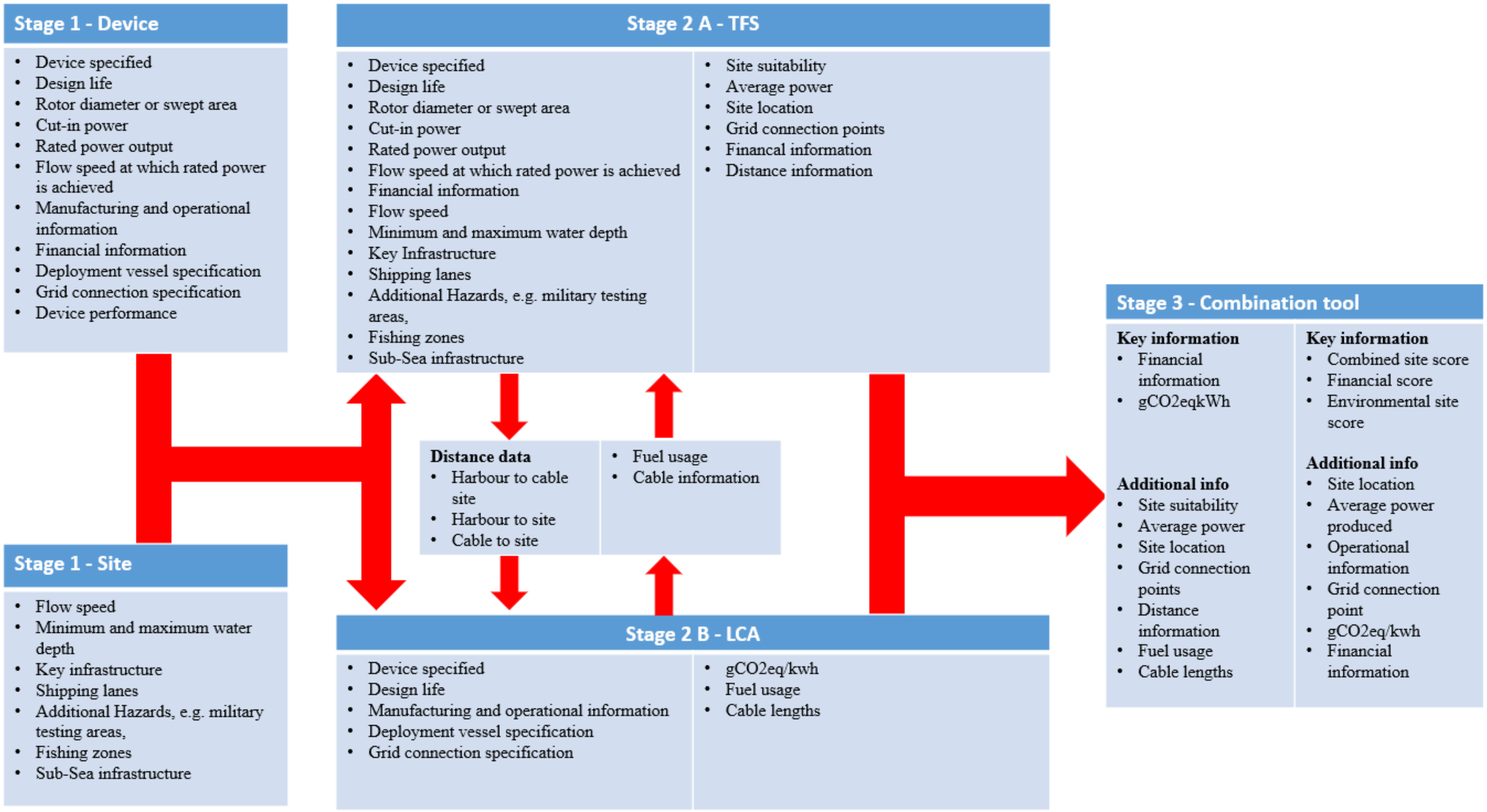


Figure 4-2: Data movement and sharing between stages.

4.5. Contribution to Knowledge

It is envisioned that the development of this unique, forward-thinking methodology, which assesses tidal power sites with respect to both financial and environmental factors, will be a key contribution to the pool of knowledge. However, the main contribution is expected to be the tool/methodology developed. This is because the tool will be able to provide decision support with respect to both financial and environmental factors. This is particularly important in the fledgeling tidal power industry as it has the chance to effect change as the industry grows and matures. The tool proposed in this chapter is further developed across the subsequent chapters.

4.6. Conclusion

It is expected that this methodology will result in the creation of a holistic decision-making tool. By encompassing the environmental results from the LCA alongside the financial findings of the TFS, the tool can be used to site select the optimal tidal turbine location with respect to both the environmental impact and financial costs. The following chapters go on to detail the development of this methodology, identifying and explaining the key stages identified in Figure 4-1. These are as follows:

Stage 1 CHAPTER 5: SITE AND TURBINE SPECIFICATION (STAGE 1)

Stage 2A CHAPTER 6: TECHNICAL FEASIBILITY STUDY (STAGE 2A)

Stage 2B CHAPTER 7: LCA STUDY (STAGE 2B)

Stage 3 CHAPTER 8: COMBINATION TOOL (STAGE 3)

CHAPTER 5: SITE AND TURBINE SPECIFICATION (STAGE 1)

5.1. Summary

The initial phase of the methodology is the selection of both the site and the turbine. Both of these elements will have to be identified by the user, and their characteristics will be unique to the study. As a result of this, any findings will inform the site selection with respect to these. In order to provide the data required to conduct the TFS and LCA a large amount of specific information will need to be sourced for each of them. This information is detailed in the following subsections.

5.2. Site-Specific Information

Once a site is identified, site-specific data will have to be gathered. This data might have to be collected from several sources, and will have to include information regarding the following elements:

- Flow speed data
- Minimum and maximum water depth data
- Key Infrastructure
- Shipping lanes
- Additional hazards, e.g. military testing areas
- Fishing zones
- Sub-sea infrastructure

A key source for this information is an Admiralty Chart. Admiralty Charts are specialist nautical charts published by the UK Hydrographic Office, a UK governmental department. These charts contain a range of information for specified nautical areas. This data includes flow speeds, water depth, sub-sea infrastructure and shipping routes. Therefore, it is recommended that the appropriate chart be sourced for the site selected.

5.3. Device Specification

Once a device has been identified for the site, information on the operation of the device will need to be defined. Typically, this is presented in the specification of the device. This outlines key operational information for the device including the following;

- Design life
- Rotor diameter (or swept area)
- Cut-in power
- Rated power output
- Flow speed at which rated power is achieved
- Manufacturing and operational information
- Device performance
- Financial information.

This information will be required for completing both the LCA and TFS elements of the methodology. As a result of this, the findings of each will be with respect to the device specified.

It should be noted that the site identified will likely have an effect on the turbine specified. This could be due to restrictions that apply to the site, such as water depth or flow speed. As a result of this, an initial assessment should be made with the limited data for the site to ensure that the device selected is suitable for deployment at the site.

CHAPTER 6: TECHNICAL FEASIBILITY STUDY (STAGE 2A)

6.1. Summary

The following chapter outlines the proposed TFS methodology. Firstly, an overview provides a brief outline of the TFS before the individual stages are defined for assessing the feasibility of a site. The subsequent subsections will outline the following stages; Site Information, Distance to Infrastructure, Inclusion/exclusion Criteria, Flow Data, Power Generation calculations and Optimal Positioning of the turbine before concluding with the Financial Assessment.

6.2. Overview

In power generation, a TFS is used to assess the potential of a site before development. This is accomplished by examining the strengths and weaknesses of the proposal against a technical and financial specification; therefore assessing the "feasibility" of the project. Typically, there are a number of key components that are used to assess the project's feasibility; these include:

- Site surveys – Identifies potential sites and discounts areas that cannot be developed due to specific constraints (e.g. shipping lanes, subsea wrecks, seabed conditions).
- Infrastructure requirements – Identifies grid connection points and site access routes.

- Predicted power generation – Provides an assessment of the power available at specific points across the site.
- Financial analysis – Determines the costs and potential earnings of the site accounting for material usage and the power generation.

In order to assess power availability at the site, a technical specification is required, containing information about the device being positioned at specific points at the site. This includes the device characteristics such as rated capacity, required operating area and swept area (for turbines). This information will have been sourced in the first stage of the methodology. Using this information, the site can be assessed to identify any points where the device cannot or should not be deployed. This could be due to breach of one of the specified criteria, such as incompatible water depths, shipping hazards or seabed conditions.

Once sites have been identified for development, potential power generation can be calculated using flow data for the site. Flow data can be obtained from specialist modelling software or on-site measurements. This data provides a reasonable assessment of the conditions expected at the site and hence can be used to calculate the power outputs of the device.

Once an average power output has been established the financial value of the project can be determined. In order to calculate this, the cost of the device has to be accounted for and then offset against the profits generated from the sale of power to the national electricity grid. Costs will include the initial capital cost of the turbine, the grid connection cable through to maintenance and decommissioning costs. Profits will be calculated considering the power output of the turbine, device life span, strike price and loss in earnings due to turbine downtime.

There are a number of different ways of displaying financial information. However, the two key methods are the Payback Period, the time taken for the project to break even, and the Cost of Energy production, which details the cost associated with producing electrical energy in (£/kWh).

The findings of the feasibility study naturally influence decisions on whether to proceed, redesign, or cancel a project. Typically, the sites identified will be subjected to further analysis using data gathered from on-site measurements. This is required to corroborate the findings of the initial feasibility study before a device is physically deployed at the site.

Once a site has been selected, and the relevant documentation sourced, the initial phase of the TFS can begin with the breakdown of the large site into smaller, more manageable sub-sections.

6.3. Site Breakdown

In order to holistically assess the site, the site identified will have to be broken down into subsections each with a known geographical location. These locations will be specified as grid points with respect to their Longitude and Latitude, providing a precise location for each site. The size of these subsections will depend on a number of variables, such as the availability of data or required separation distance between devices. By sub-dividing the site into sections, a comparison can be made between them to identify the optimal positions within the whole site. An example of how a site can be broken down is shown in Figure 6-1, which identifies 73, 1km by 1km sites off the east coast of Orkney near Yesnaby.

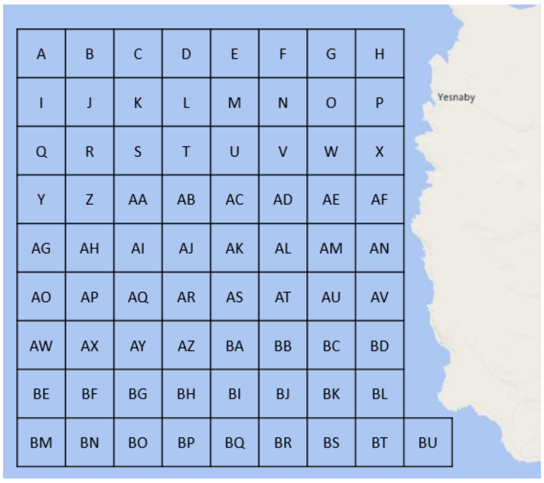


Figure 6-1: Illustration of how a grid can be used to divide a site (Google, 2020)

Whilst geographical coordinates such as Longitude and Latitude values can be used to define the location of each sub-sites, an alphabetical lettering system can be used to reference each of the sites identified as seen in Figure 6-1. It should be noted that the centre of each site is the point at which the individual site assessment will take place.

6.4. Distance to Infrastructure

In order to calculate the distance from key infrastructure points to each of the identified sites, key infrastructure points have to be determined. Infrastructure for tidal turbines will include ports, for construction and maintenance activities, as well as grid connection points. Once established, these sites can be mapped with the individual sites using the Longitude and Latitude values for their location.

In order to determine the distance from the site to the infrastructure points, a 2D representation of the site can be generated. This is achieved using the defined size of the site and the geographical values for each individual site and infrastructure points. By defining a 0,0-reference point for the site, the geographical Longitude and Latitude values can be converted to values of distance. This is achieved using the known distance of the site divided by the ratio of the difference between the geographical values to the reference point. For example,

The Latitude of site A is 53.0N, and site B is 53.5N. The distance between these two values (Y) is 55.6km. The infrastructure point, C, is located at a latitude of 53.17N and is the 0 reference value for the calculation. The distance from C to A is calculated as,

$$C\ to\ A = \frac{Y}{\Delta AB} \times \Delta CA \tag{6-1}$$

$$C\ to\ A = \frac{55.6}{53.5 - 53} \times (53.17 - 53) = 18.9km$$

And C to B as,

$$C\ to\ B = \frac{Y}{\Delta AB} \times \Delta CB \tag{6-2}$$

$$C\ to\ B = \frac{55.6}{53.5 - 53} \times (53.5 - 53.17) = 36.7km$$

This methodology can be applied in both the Latitude (N to S) and Longitude (E to W) directions. This allows the user to determine the X and Y components for the distance between the infrastructure point and each subsite. The straight-line distance, the distance travelled to the site (Z), can then be calculated using Pythagoras' theorem.

$$Z = \sqrt{(x^2 + Y^2)} \tag{6-3}$$

While this method determines the distance for straight-line travel from the infrastructure point to the site, it does not account for situations where this is not possible. An example of this is an obstruction due to coastal geography. In order to account for any such obstructions, a nodal approach will have to be adopted. This means that the journey from a point to the site will be broken down into separate stages. The results of each of these stages are then combined to calculate the actual distance travelled. Figure 6-2 displays one such example for when this additional step may be required.

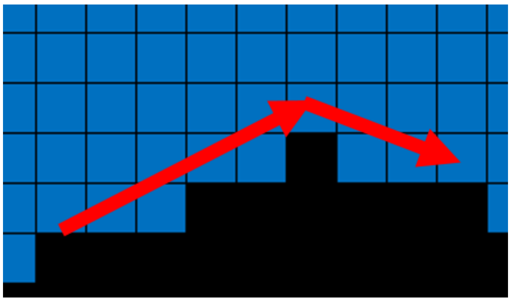


Figure 6-2: Annotation of the nodal approach to the distance to infrastructure

It should be noted that while this method is not completely precise as it does not account for the curvature of the earth, it provides a good approximation of the distance between sites. This is because the curvature of the earth has negligible effects over relatively small site distances.

In the event that there are multiple infrastructure points capable of serving the site, the method can be applied to each of the infrastructure points identified. The resulting distances can then be compared, with the shortest distance being used to determine the optimal infrastructure point for that particular site.

It should be noted that distance data generated from this process is shared with the LCA study. This will inform the results of the transportation phases of the device and the length of the grid connection cable required to connect the site.

6.5. Inclusion/Exclusion Criteria

Exclusion criteria are used to identify sites that are not suitable for turbine deployment. Sites can be excluded for a number of reasons relating to hazards or nonconformity to the device specification. As a result of this, information about the site and the device has to be taken into account at each sub-site. This ensures that the site is capable of hosting a device. Any site that does not meet the requirements or poses a hazard can be excluded from the analysis. Examples of exclusion criteria include the following;

- Shipping lanes
- Maximum water depth specified by the device
- Minimum water depth specified by the device
- Subsea infrastructure
- Fishing zones
- Wrecks
- Military firing ranges

It should be noted that additional exclusion criteria might be identified and applied to the site. In these cases, those considerations should also be included at this stage.

Each subsite will have to be analysed according to the exclusion criteria points identified. This will determine if the sites conform to the requirements or not. The results of this analysis can then be plotted using assigned numbers to detail if the site is excluded or included. For simplicity, a ‘0’ will indicate that a turbine can be deployed at the site, and other values can indicate excluded sites.

The results from these assessments are then amalgamated to identify the sites that are suitable for deployment. This process is seen showcased in Figure 6-3, which displays how two studies are combined into one. In this example, values of 1 indicate exclusion due to water depth requirements and 2 due to subsea cables. The results of these two studies can then be combined into one, with the sites having a common score of 0 being identified as capable of hosting a turbine. In this example, only 13 are available from the initial 45 sites identified. The remaining 32 sites have been excluded from the study as they are incompatible.

1	0	1	1	0
0	1	0	1	1
1	0	1	1	1
1	0	0	1	1
1	1	0	0	0
0	1	1	0	0
0	1	0	0	1
1	1	1	1	0
1	1	1	0	1

0	0	2	0	0
0	0	2	0	0
0	0	2	0	0
2	2	2	2	2
0	0	2	0	0
0	2	2	0	0
2	2	0	0	0
2	0	0	0	0
0	0	0	0	0

1	0	2	1	0
0	1	2	1	1
1	0	2	1	1
2	2	2	2	2
1	1	2	0	0
0	2	2	0	0
2	2	0	0	1
2	1	1	1	0
1	1	1	0	1

Figure 6-3: Example combination of exclusion criteria, from left to right, water depth requirements, subsea power cables and combined results.

It should be noted that additional exclusion criteria might also be specified later on in the project. This might include values for a minimum return on investment (ROI) or maximum device cost. These cannot be applied until after the results of the TFS are generated and can be used to influence the results of the combined decision-making tool.

6.6. Flow Data

The power equation for a TSG identifies that the velocity of flowing water has a substantial effect on the power generated by the device. Hence the flow speed at each site needs to be determined. Whilst it is possible to collect real-world measurements for each of the sites, this typically requires a large amount of time and resources to gather. As a result of this, specialist software packages can be used as an initial data source for identifying potential deployment sites. This means that an informed decision can be made with respect to the site.

Once a site is identified as the optimal deployment location, the specific area can be analysed further with real-world measurements to corroborate the findings. This process saves a substantial amount of both time and money that would be required to gather data for the entire area.

There is a wide range of specialist tidal power software, such as MIKE 3 and POLPRED. These allow the user to analyse a site to determine various elements such as flow speed (m/s), flow direction (deg) and tidal height (m).

Owing to the nature of tides, the flow rates at each site constantly change over time. This is caused by the gravitational interaction between the Sun, Earth and Moon. This typically results in higher flow speeds being generated a few hours either side of the high tide. In addition to this, the tidal phases affect the flow speeds with spring tides generating faster flow speeds and neap tides slower ones. This effect varies between these two periods and makes up the lunar cycle.

In order to account for these varying conditions and provide an overall analysis of the tidal flows at each site, the time frame for any analysis will have to cover at least one lunar month. This will provide an in-depth analysis of the flow conditions across an entire cycle from spring to neap and back again. The flow data generated from the software will then be used later to calculate the expected power output for a device at each site. In addition to the flow speed, data for the flow direction and height at each site will be generated during the analysis, which may also be required.

It is recommended that any results generated from the software are corroborated during a validation phase. This will help ensure that any data generated from modelling software corresponds to known values for the site. This validation can be achieved by comparing results from the model to other key sources of data such as the Admiralty Chart.

6.7. Power Generation

The flow rate at each site will change over time due to the aforementioned interactions between the Sun, Earth and Moon. In order to calculate a power output for the turbine, an iterative process will be required to determine the power output for each of the time step defined in the flow data. The average power calculated over this time can then be used to determine the power output of the turbine over longer durations with respect to the variable flow conditions. The standard equation for calculating the power from a TSG is:

$$P_t = \frac{\rho \times A \times {v_t}^3 \times C_p}{2} \tag{6-4}$$

Where ρ is the density of seawater (kg/m^3); A is the swept area of the turbine blades (m^2); v_t is the velocity of water flowing through the turbines at time step (t) (m/s); C_P is the turbine coefficient of performance; P_t is the power output at time step (t) (W). While some of the factors are defined by the site, such as the water velocity and density, a number of factors are limited by the specification of a turbine. These include the swept area and coefficient of performance of the device. Additionally, the specification of a turbine will typically outline a cut-in speed and flow speed at which rated power output is achieved. This will have to be considered when calculating power output from a device. This is because if these conditions are not met the device will not be capable of producing power. The following subsections look at these components detailing the individual steps to develop the power calculations for two different types of tidal devices; Fixed and Yawing devices.

6.7.1. **Power Ratings**

A turbine operates in three distinct power phase; Rated, Non-operation and Cut-in. These are typically specified by the turbine manufacture and are dictated by the design of the device. The following is a definition of each of the power phases:

- Rated power is the maximum power that the device is capable of producing
- Non-operational is where the flow speed of water through the turbine is inadequate for power generation to begin. Typically, most turbines require a flow speed of between 0.6 and 1m/s to begin power generation
- Cutting in – This stage covers power generation between the Rated and Non-operational phases as a result of there being sufficient flow to start power generation but not to reach the full rated capacity of the turbine. This leads to variations in power output between zero and the rated maximum of the device

In order to account for this, the power generated from a device has to be analysed, and the correct power phase identified. This then allows the appropriate restrictions on the power output to be applied. Table 6-1 shows the resulting power output at different stages; assuming P is the power calculated for the device. The different phases can also be used to analyse the turbine with respect to the amount of time it spends operating in each of the phases. Typically the goal is to maximise the time that the turbine is operating at its rated power.

Table 6-1: Power phases of a tidal turbine and power output

Analysis	Phase	Output
P > Rated	Rated	Rated Power
Rated > P > Cut in	Cut in	P
Cut in > P	No operational	0

This process is automated in Excel using the IF Function. The IF function checks whether a condition is met and returns a specified true or false value. This is achieved using three specified elements; a logic test, value if True and value if False. The function can be applied to the power phases of a turbine identified in Table 6-1 resulting in the equation where the actual power output of a device, P_A, can be determined with respect to the conditions. Where P is the calculated power output, R is the rated power of the device, and C is the cut-in power.

$$P_A = IF(P > R, R, IF(P < C, 0, P)) \quad (6\text{-}5)$$

6.7.2. **Swept Area**

The swept area of a turbine is outlined in the specification of the device and is defined as the maximum area in which that the blades rotate. For most tidal devices the area can be calculated using the standard equation for the area of a circle.

$$A = \pi r^2 = \frac{\pi d^2}{4} \quad (6\text{-}6)$$

Whilst this defines the swept area of the turbine, the swept area exposed to the oncoming flow is not always a constant. Vertical axis TSG's can be separated into two categories, Yawing and Fixed devices. These categories refer to the ability of the turbine to rotate/yaw. In the case of yawing turbines, the turbine has the ability to track the oncoming flow and rotate to compensate for changes in the flow direction. This ensures the maximum swept area is exposed to it. Fixed turbines do not have this ability. As a result, changes in flow angles result in a reduction of the swept area exposed to the oncoming flow. This change is with respect to both the flow direction and the directional placement of the turbine.

The following sections discuss Fixed and Yawing turbines further, and separate power equations are developed for each type of device.

Yawing

A Yawing turbine allows a manufacturer to maximise the device power output by controlling the yaw of the device. This is achieved by rotating/yawing the turbine in order to expose the maximum swept area to the oncoming flow.

Turbines such as Atlantis Resources AR1500, have active yaw control using a mechanical system (Atlantis Resources, 2016). The inclusion of these systems in a device design comes with increased mechanical complexity and cost. Alternatively, devices can be passively yawed. This is achieved using the flow of water to help position the device, much like a weather-vane, pointing into the direction of flow. This has the advantage of not requiring energy or complicated machinery to assist in the process. However, a specific device design is required, which can lead to an increase in cost. One example of a passively yawing system is the Scotrenewables SR2000 (Orbital Marine Power, 2019).

Typically, yawing systems are incorporated into larger devices, both in power and size, to optimise the power they produce. The cost of these systems is typically offset by the extra power generated over the systems lifetime.

Fixed

Alternatively, a number of tidal turbines are fixed. This means that they are unable to yaw, leading to a reduction in exposed surface area with varying flow directions. By excluding the ability of the device to yaw, the initial capital cost of the turbine is reduced. This is why the majority of test turbines are fixed, as developers look to refine the initial design before subsequently improving the device performance. Examples of fixed turbines include the aforementioned SeaFlow, SeaGen (Marine Space, 2016), Open Hydro (European Marine Energy Centre (EMEC) Ltd, 2018) and the Nova M100 (Nova Innovation Ltd, 2019).

6.7.3. Directional Placement Effect on Swept Area

Equation (6-4) is valid for all turbines that have the ability to yaw. This is because it can be assumed that the yawing device ensures that the maximum frontal area of the turbine is constantly being exposed to the oncoming flow. However, for fixed devices, the exposed area of the turbine changes with respect to both the turbine placement and flow angle. An example of the effects on the swept area is shown in Figure 6-4. This shows a representation of the exposed area at different angles between 0˚, head-on flow to 90˚, side-on flow.

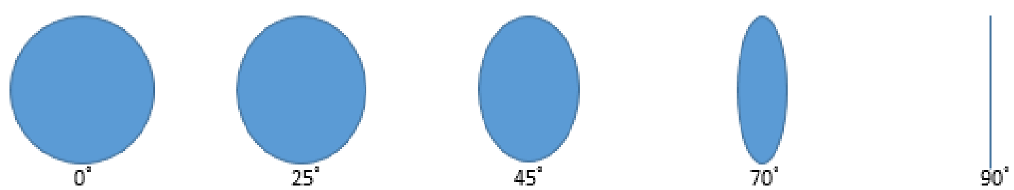


Figure 6-4: Representation of exposed swept area at different flow angles

In order to calculate the exposed swept area (Af), the following formula has to be used: Where A is the original area of the turbine (m^2) and Δθ is the difference between the angle of the turbine (θt) and the flow direction (θf). The value for Δθ should be an absolute value (a number without its sign) to ensure that a positive area is determined. This can be achieved using the absolute function (ABS) in Excel. Data for the flow direction is obtained from the flow data generated in the POLPRED model. It should be noted that angles are specified with respect to 0˚ equalling North, 90˚ East, 180˚ South and 270˚ West.

$$A_f = A \times \cos(ABS(\Delta\theta)) \quad \text{(6-7)}$$

This calculation is further demonstrated in a case study for a 10m diameter turbine seen in Figure 6-5.

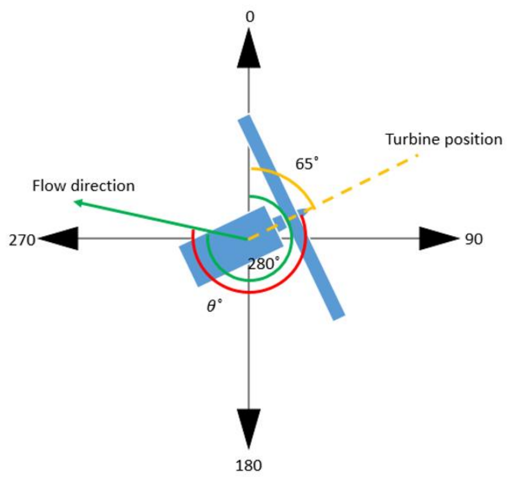


Figure 6-5: Turbine swept area example

The turbine has a specified swept area of 78.54m^2. Situated at an angle of 65˚ with respect to a flow angle of 280˚ the exposed swept area can be calculated to be as -64.33m^2, a loss of 14.2m^2.

$$78.54 \times \cos(ABS(65 - 280)) = 64.33$$

This new value of the exposed area is then used to calculate the power output of the device. This will result in a loss of power generated at the site due to the reduction in the exposed area. The loss in power can lead to a significant impact on the power produced by the turbine over its life. As a result of this, the optimum deployment angle becomes an important consideration when deploying fixed devices.

In addition to the loss of area, a fixed turbine is exposed to two directions of flow, through the front and back of the turbine. The front is clear of obstructions allowing the water to pass into the turbine easily. However, when water flows into the back, there can be an interaction between the flow and the structure of the device. As a result of this, the Cp of the device is likely to be impacted. This is not the case for yawing turbines where it can be assumed that the device will always point head-on into the flow.

In order to determine if the flow is into the front or back of the turbine, the difference between the turbine placement and the flow angle (Δθ) needs to be considered. This can be achieved using the AND function in Excel. The AND function works as a logic check to determine if multiple criteria are met, returning either a True or False value. By defining 0˚ as the front of the turbine, any value for Δθ that is larger than 90˚ but less than 270˚ indicates the flow is into the back of the turbine. As a result of this, the following equation was developed to indicate which Cp value should be applied.

$$AND(\Delta\theta > 90{,}270 > \Delta\theta) \times 1 \qquad (6\text{-}8)$$

Note that in the equation, the function is multiplied by one, this is to adjust output defined in Excel from True/False text into a number format. As a result of this, False outputs produce a 0 value, identifying flow into the front of the turbine, and True result produces a value of 1, indicating a flow into the back of the turbine. This function can then be used to define which Cp value to apply to the power equation for flow into the front or back of the turbine.

6.7.4. Combined Power Calculation

The following subsections identify the combined power calculations accounting for the Power ratings, swept area and directional placement for both a fixed and yawing TSG.

Yawing

The equation for a Yawing turbine only has to account for the power rating of the turbine. This is because it can be assumed that the maximum frontal area is constantly exposed to the oncoming flow. This equation can be developed by combining the standard equation for power from a turbine with the equation developed for the power rating. This results in the following equation:

$$P_A = IF\left(\left(\frac{\rho A v^3 C_p}{2}\right) > R, R, IF\left(\left(\frac{\rho A v^3 C_p}{2}\right) < C, 0, \left(\frac{\rho A v^3 C_p}{2}\right)\right)\right) \quad \textit{(6-9)}$$

Where P_A is the actual power produced in watts, ρ is the fluid density (kg/m^3), A is the swept area of the turbine (m^2), v is the flow velocity (m/s), C_p is the coefficient of performance for the turbine, R is the rated power of the turbine and C the cut in power.

Fixed

The calculation for a fixed turbine is more complicated to define. This is because it has to account for the varying flow direction. As a result of this, the equations identified in the previous section are displayed in Table 6-2 in the format that they are used in Excel.

Table 6-2: Equations used to calculate power from a Fixed turbine

Name and denotation	Equation
Flow direction ($\Delta\theta$)	(ABS(θ_f- θ_t))
Swept area (A)	(ABS(A*COS(RADIANS($\Delta\theta$))))
Power in kW (P)	((0.5*ρ*A*v^3)/1000)
C_p Indicator (C_PI)	((AND($\Delta\theta$ >90,270>$\Delta\theta$))*1)
Power including C_p (P_C) in kW	P*IF(C_PI, C_pB, C_pF)
The power generated (Pa) in kW	(IF(P_C >R,R,IF(P_C <C,0, P_C)))

When combined, these equations create the complete equation for power from a fixed turbine. Where, θ_f is the water flow angle, θ_t is the turbine placement angle, ρ is the water density, v is the flow velocity, R is the rated power of the turbine, C_pB is the value for the Cp when the flow is into the back of the turbine and C_pF is the Cp when the flow is into the front.

$$Pa = IF((((0.5 * \rho * (ABS(A * COS(RADIANS((ABS(\theta f - \theta t)))))) * v^3)/1000) * IF((AND((ABS(\theta f - \theta t)) > 90,270 > (ABS(\theta f - \theta t)))) * 1), CpB, CpF)) > R, R, IF((((0.5 * \rho * (ABS(A * COS(RADIANS((ABS(\theta f - \theta t)))))) * v^3)/1000) * IF((AND((ABS(\theta f - \theta t)) > 90,270 > (ABS(\theta f - \theta t)))) * 1), CpB, CpF) < C, 0, (((0.5 * \rho * (ABS(A * COS(RADIANS((ABS(\theta f - \theta t)))))) * v^3)/1000) * IF((AND((ABS(\theta f - \theta t)) > 90,270 > (ABS(\theta f - \theta t)))) * 1)\ CpB, CpF)))) \quad (6\text{-}10)$$

Note that additional functions have been used in this equation due to the way that Excel operates. Namely the ABS function, which returns the absolute value and the RADIANS function, which converts an angle from degrees into radians. This is required to use the COS function in Excel. In addition to this, it should be noted that the C_p Indicator (C_pI) equation identified in Table 6-2 acts as the logic check for the Power including C_p equation hence there is no separate logic component defined in the final equation.

It should also be noted that it is possible to use this equation to calculate the power from a yawing turbine. This can be achieved by defining the angle of the turbine (θt) as the angle of the flow (θf) if required.

Optimal Directional Placement of Fixed Turbines

As previously discussed, the directional placement of a fixed device affects power output. In order to account for this, the optimal direction will need to be identified and then specified for the turbine as part of the feasibility study. This can be achieved using the power calculated from the device situated at different angles at each site. The results from each angle will have to be analysed with respect to the average power produced at each angle, with the maximum average power output indicating the optimal turbine angle. This will allow for the identification of the optimal angle for the turbine placement. This can be achieved using the power equation developed for a fixed turbine and iteratively calculating the average power at varying angles over the specified period, in this case, a lunar month.

An example of how the angle of the turbine affects the power output is seen in Figure 6-6. This figure showcases the average power output of a 9m diameter, 100kW rated turbine over a single tidal period of 12 hours and 20 minutes, with respect to different angles of placement in one-degree increments. In this example, the optimal angle for this turbine is determined to be at 94˚ when the maximum average power output of 48.05kW is achieved.

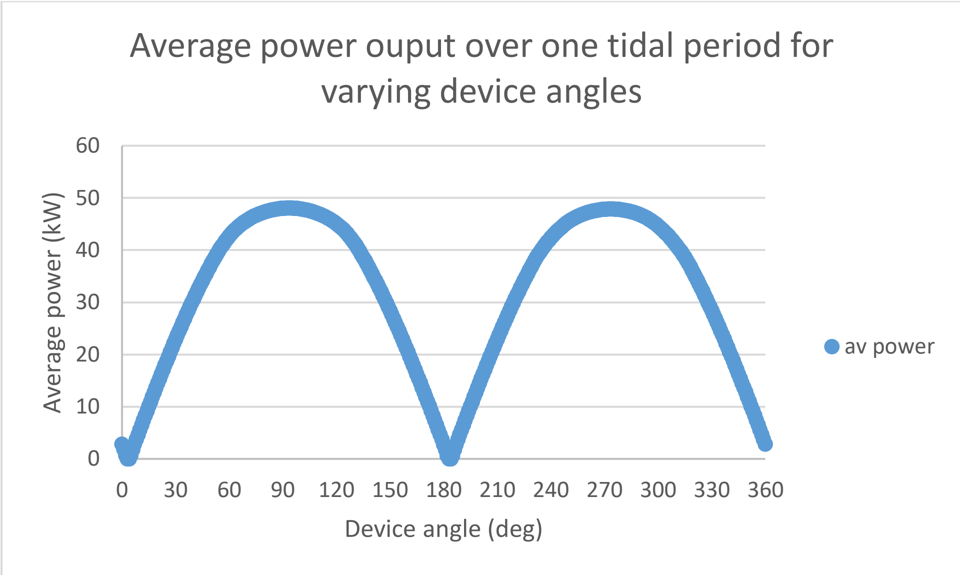


Figure 6-6: Average power output of a tidal turbine over one tidal period at varying angles of device placement.

By analysing each site using this methodology, the optimal angle can be determined and then specified for the turbine at that site. The optimal angle is the point at which the maximum average power output over the specified period is achieved. In the example shown in Figure 6-6, this is for one tidal period; however, for the full analysis, it will be across the lunar month.

In order to showcase the difference in power generation between a yawing turbine and the optimally placed fixed device, the power outputs over a single tidal period can be plotted against one another. The results of this process can be seen in Figure 6-7, which shows a slight loss in power generation between the two devices on the inflow. This is due to the water entering the back of the fixed turbine which has been specified with a lower value for the Cp due to the interaction of the water and the nacelle, as detailed in the development of the equations.

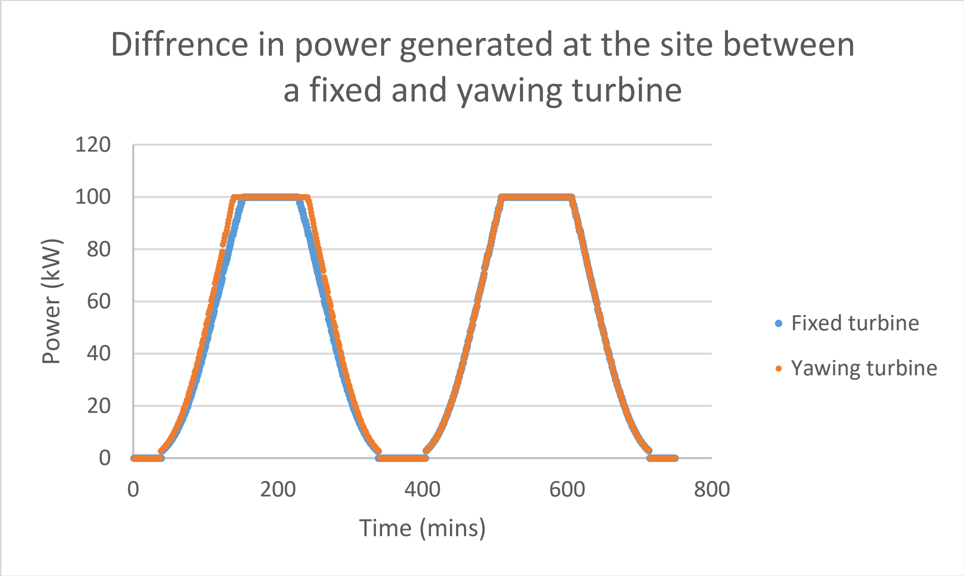


Figure 6-7: Difference in power generated from a yawing and optimally placed fixed turbine over a single tidal period

6.7.5. Power Output

Using the two equations developed, the average power output of a tidal device can be calculated with respect to the varying tidal conditions and device specification. This average can then be used to determine the power output of the device over its life span. This is accomplished using the following equation to calculate the power output of the device in kWh.

$$Pl = LS \times 365.25 \times 24 \times P \qquad (6\text{-}11)$$

Were Pl is the power generated over the lifetime of the turbine (kWh), Ls is the life span of the device (years) and Pa is the average power output calculated for the device (kW).

This equation determines the power output of the device if it operates 100% of the time. However, downtime for maintenance activities will have a resulting impact on power production over the life of the device. In order to account for this, the equation can incorporate these factors in the following equation; where Mt is the number of maintenance trips over the device's lifespan, Dt is the time in days that the turbine will be offline due to maintenance and Pl is now the power produced by the turbine during its lifetime accounting for the maintenance activities (kWh).

$$Pl = ((Ls \times 365.25 \times 24) - (Mt \times Dt \times 24)) \times P \qquad (6\text{-}12)$$

The resulting calculation allows the user to determine the power output of the turbine in the standard unit for power generation during its expected life span.

6.8. Finance

The final phase of the feasibility study is a financial analysis of the scheme accounting for profits and expenditures. In order to simplify the analysis of the sites for site selection purposes, the effects of inflation can be removed from the financial analysis. This can be achieved by accounting for all costs with respect to the 2012 strike price of electricity paid via a contract for difference. This method will provide an initial assessment of the financial impact of each site and allow for sites to be identified.

It is envisioned that once a site has been identified by the combined methodology, further investigation using a full financial analysis will be carried out for the site selected site. This additional assessment can draw upon additional data generated from further investigations into the site identified, such as the addition of real-world flow measurements and detailed financial information to guide the project cash flows.

With this in mind, the financial results can be displayed in a number of different ways, including, the Profits, Expenditures, Revenue, Cost of Energy and Payback Period. Each of these points is discussed further in the following sections.

6.8.1. **Profits**

Profits are generated directly from the sale of electricity to a national grid. Typically, companies will sell their electricity at a prearranged strike price, which is set for a specified time period. As identified in the literature review, the current strike price for TSG's is £305 per MWh (Crown, 2018). This value is with respect to the 2012 prices, adjusting for inflation between 2012 and 2018; this would be valued at approximately £353.79 per MWh (Bank of England, 2019).

In order to simplify the process of conducting a financial investigation for site selection purposes, the effects of inflation can be excluded from the assessment by defining all costs with respect to 2012 prices. As a result, profits generated at each site can be calculated with respect to 2012 prices, removing the uncertainty of the effects of inflation over prolonged periods of time.

This can be achieved using the following equation; where AVp is the average power output calculated (kW), Sp is the current strike price per kWh (£0.305/kWh), and OpT is the number of hours the turbine is operational. This is a simple conversion that takes the average power output (kW) and the operational time (h) to determine the power produced in kWh. This value can then be converted to a financial value using the price of electricity specified in the strike price.

$$AVp \times Sp \times OpT \tag{6-13}$$

In order to account for the loss of earnings due to downtime, the OpT is calculated assuming there are 8,760 hours in a year, by multiplying this by the lifespan of the device (Ls), minus the downtime in days (Dt) which can be converted to hours by multiplying by 24 and the number of Maintenance visits (Mv) over the turbine's life.

$$OpT = ((8760 \times Ls) - (Dt \times 24 \times Mv)) \quad (6\text{-}14)$$

6.8.2. **Expenditures**

Expenditures account for any financial expenditure on the project. This will cover multiple phases of the project from construction, deployment, maintenance and decommissioning. Included in these phases will be the following major expenditures,

- Device cost
- Grid connection cable cost
- Fuel prices
- Decommissioning costs
- Maintenance costs
- Number of maintenance trips.

The summation of all of these elements will allow the user to calculate the total expenditure of the project. Note that some of these elements will be affected by the site selection process, such as the length of the grid connection cable and the cost of travelling to the device to perform maintenance tasks. As a result, the following equation is used to calculate the cost at each site; where F_{con} is fuel consumption (kg), Fc is fuel cost (£/kg), Grid_to_site is the distance between the grid connection point and site (km), Cc is the cable cost (£/km), Idc is the initial device cost (£) Dc is the decommissioning cost (£), Mc is the maintenance cost (£), and Mv is the number of maintenance visits over the life of the device.

$$(F_{con} \times Fc) + \left(Grid_{to_{site}} \times Cc\right) + Idc + Dc + (Mc \times Mv) \quad (6\text{-}15)$$

By defining these elements in 2012 prices, a direct comparison can be made between the profits and the expenditures to calculate the expected revenue of the device.

6.8.3. **Revenue**

The revenue of the device can be defined by the profits minus the expenditures. By defining all of the financial elements with respect to the 2012 value of electricity specified by the strike price, a direct comparison can be drawn without the requirements of including estimates on inflation. This value provides a clear picture of the expected profits or losses of the scheme. As a result of this, it will be used as the key decision-making component for the TFS in the combination stage of the methodology. However, in addition to this, there are a number of additional metrics that can be calculated to investigate the financial impact of the device further. These included the cost of energy and the payback period. These can be calculated to provide additional assessment but are not mandatory for the methodology.

6.8.4. **Cost of Energy**

Cost of energy is a key metric that specifies the financial cost of producing electrical energy. This metric allows the user to compare the cost of power generation between different power schemes. It is calculated using the following formula; where CC is the installed capital cost (£), FCR is the fixed charge rate (%), Co&M is the annual Cost of operations and Maintenance (£), and EA is the annual energy production (kWh) (Afework, Lyndon, Hanania, & Donev, 2018).

$$COE = \frac{(CC \times FCR) + Co\&M}{EA} \quad (6\text{-}16)$$

6.8.5. Pay-back Period

The pay-back period is the time taken for the device to cover all the expected costs associated with the device. It is calculated by dividing the total cost of the device by the expected annual revenue. The result of this output is typically measured in years for large scale projects.

The value determined is then compared to the expected life of the device to determine if the scheme is going to make a profit or a loss (Aggarwai, 2019). By dividing the payback period by the lifespan of the device, a ratio of the payback period can be generated. Higher ratios indicate higher profits to costs and values below ‘1’ determine that the scheme will cost more than the profits it will bring in. This process can be used to inform decisions regarding whether or not to proceed with the scheme or to invest in alternative schemes.

CHAPTER 7: LCA STUDY (STAGE 2B)

7.1. Summary

The following subsection outlines the proposed LCA methodology. Initially, an overview is provided as an introduction to the LCA methodology before the development of the generic tool is defined. The structure of these subsections conforms to the four stages of conducting an LCA as guided by ISO 14044 (ISO-B, 2006), namely the Goal and Scope definition, Inventory Analysis, Impact Assessment and Interpretation.

7.2. Overview

As previously identified in the Literature Review, the LCA methodology has been developed over a number of years into two official standards, ISO 14040 and ISO 14044 (ISO-A, 2006). These standards define the requirements for conducting an LCA and have been adopted internationally. In order to develop the new methodology, these international standards allow the tool to be developed for a generic global setting. As a result, the methodology developed will use these ISO standards as the basis for the development of a generic LCA tool, with information obtained from the literature review being used to help define modelling choices to create the new methodology for assessing tidal power schemes. In order to achieve this, the following subsections are defined by the four key stages for the analysis as set out in the standards, with each stage being defined and applied to generate a generic LCA for a TSG.

7.2.1. **Defined Life Cycle Overview**

Within the context of site selection for tidal turbines, the objective of the LCA study will be to determine the environmental impact of a TSG positioned at each of the separate sites identified. As a result, the main aim of the LCA will be to attribute the impact associated with placing a turbine at each site (Baumann & Tillman, 2004).

It should be noted that there is a comparative element defined in the 3rd stage of the site selection methodology being outlined. As a result, there may be some elements of the LCA that could be considered as part of a consequential analysis, especially if a standard turbine is being assessed. This is because the user will effectively be comparing results between sites in the third stage of the methodology, to identify a preferred site with respect to the environmental and financial impact.

However, because this comparison does not take place using purely the LCA data generated at this point and is not conducted during this stage of methodology, the LCA was considered to be purely attributional. This is in line with the goal of the developed methodology which identifies that the primary purpose of the LCA is to generate data for each of the sites identified for subsequent processing in the site selection methodology.

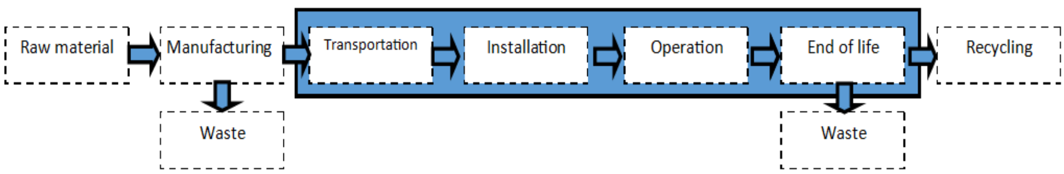


Figure 7-1: Highlighted life cycle phases affected by site selection

In order to generate a holistic LCA, a number of the key life cycle phases for the turbine will have to be explored. These are identified in Figure 7-1. Whilst a holistic analysis will be carried out, the impact of site selection for a modular device will most likely be limited to the stages highlighted in this figure. As a result of this, the remaining stages could be assumed to be common to each site, as site selection will not impact these phases. This is because the processes occurring at these stages will be the same regardless of the site selected. This concept is highlighted in the example of the manufacturing stage, where it can be assumed that a modular turbine will be constructed in exactly the same way regardless of the site at which it will be deployed.

As a result of this assumption, it would be possible to complete a Gate-to-Gate analysis for modular turbines, focusing solely on the identified areas that site selection impacts. However, it should be noted that the environmental impact of site selection might affect the manufacturing of some devices, specifically devices that are bespoke. This can be seen in the case of the SeaGen turbine. This turbine requires a steel monopile to be driven into the sea bed (Atlantis, 2017). If the site selected was to change, the length and structural makeup of the monopile would be affected by the water depth at the site, with more material required to support the turbine at greater depths. This will inevitably have an impact on environmental emissions over the life cycle of the device.

In order to account for this, the developed methodology will require the undertaking of a holistic LCA (cradle to grave assessment), examining the impact from raw material extraction to the end of life decommissioning of the turbine. This will allow the user to ascertain the entire environmental impact that a device at each site will have over its lifespan.

However, as identified in Figure 7-1, the most common effects of site selection are expected to be the transportation, installation operation and end of life stages of the device. This is because site selection will affect the following key elements of the LCA:

- Distance travelled from embarkation Port to the Site – changes in distance will affect the fuel consumption of any vessel travelling this distance during the installation, maintenance and end of life stages.
- Distance from Port to Grid connection point - changes in distance will affect the fuel consumption of any vessel when grid connecting the device during the installation and end of life stages.
- Distance from the Grid connection point to the Site – changes in distance will affect the fuel consumption of any vessel travelling this distance during the installation and end of life stages. In addition to this, the distance between the grid connection point and the site will affect the length of the grid connection cable required. As a result of this, there will be an effect on the manufacturing of the cable, which will affect both cost and material usage. This will be determined in the installation stage.

As a result, a holistic LCA will be conducted to allow the findings from the LCA to inform decisions with respect to the environmental impact of positioning the device at each site. The following subsections go on to define the development of a generic LCA methodology for a TSG with respect to the four key stages defined in the ISO standards.

7.3. Goal and Scope Definition

The initial phase of the LCA is to outline the purpose of the study effectively. This is achieved by defining key elements of the LCA, including the goal, scope, methodology, assumptions and data collection methods. The act of defining each of these elements allows the user to detail the extent of the analysis, helping to focus the investigation during the other stages. Due to the dynamic nature of LCA, the goal and scope can be changed and updated throughout the project to reflect decisions or changes made in other stages.

The goal and scope effectively act as an outline guiding the LCA and providing users with a complete overview of the process. The following elements of the goal and scope are discussed and defined;

- The **Target Audience** for the project will be industrial partners and other key stakeholders who have an interest in the deployment of a TSG at the site. As a result, the values will be presented as a single impact per turbine deployed. This decision is further detailed when specifying the functional unit. Additionally, since the primary user will be stakeholders in the project, it is expected that a large amount of data for the device will be provided.
- The **Scope**, as previously identified in the Defined Life Cycle Overview, the impact of the turbine will be attributed to each site. As a result, the scope of the LCA is to conduct a holistic analysis from cradle-to-grave for a single TSG deployed at the site. This will be with respect to the sites identified within the specified location and, as a result, the outcome will be specific to that site. However, as previously discussed and depicted in Figure 7-1, some sections of

the assessment might be common across all sites. This could be accounted for in the assessment in order to simplify matters if required.

- **Assumptions** made during the LCA have to be stated, enabling a user to understand the effects that this will have on the results. The following assumptions are applied to the Generic LCA methodology used to assess the impact of tidal turbine deployment:
    - The manufacturing of any modular turbines will be common to all sites and hence not be affected by the site selection.
    - The end of life phases of modular turbines will be common once the device has been returned to port.
    - Cable manufacturing will be specified per metre of cable, and their construction will be standard for all turbines using the same cable.
- The **Functional Unit** for the analysis will be the emissions per deployment of tidal device at the specified site and will be presented in kg CO_2eq per turbine at each of the sites. This value will allow the user to holistically understand the entire impact of situating the device at each site by presenting an easy-to-understand value for the target audience. This decision was made in order to remove the need for the user to have additional knowledge of the power generation of the device and is therefore different from the typically presented gCO2eq/kWh found during the literature review. The specification of this functional unit allows direct comparisons to be made across the site with respect for purely the environmental impact in stage three of the developed methodology, where the lowest impact device being identified as the preferred site.

- Primarily, **Data Collection** will be obtained directly from the industrial partners for each specific process where applicable. This data may come in the form of onsite measurements or as results from pre-existing assessments. This will result in data being specifically relevant to the life cycle impact of the TSG, and as a result, it will provide a robust base for the LCA. If primary data is not available, secondary data can be used. This data may be in the form of publications, specification or literature. All efforts should be made to use secondary data that is specifically relevant to the TSG; however, this might not always be the case. As a result, generic secondary data might have to be used. It should be noted that the uses of any secondary data may impact the clarity of the final results.

  It should also be noted that as detailed in the proposed site selection methodology and depicted in Figure 4-2, some data will be obtained from findings generated during the TFS.
- **Data Parametrisation,** in order to generate a generic and adaptable model, appropriate data will be parametrised thought the LCA model. This is required in order to allow user-specified parameters to determine the impact of the turbine specified for investigation, allowing multiple sites to be investigated within the methodology and the subsequent LCA findings calculated.

7.4. Inventory Analysis

The Inventory Analysis, also referred to as the Life Cycle Inventory (LCI) is the stage where data is gathered and compiled into the model. In this case, the generic tool is developed in the specialist LCA software, GaBi, using the process of parameterisation.

This is achieved firstly by defining generic processes which are then parametrised, allowing user-specified data to be defined at a later date for each process. This has the benefit of determining the impact of each process with respect to these values. The parameterisation process is defined in detail in subsection 7.4.3.

The processes modelled in GaBi have specified material flows in and out, which can be defined by inputs and outputs. An example of this is seen in Figure 7-2, which details the washing and drying of Polypropylene (PP) scrap. The example details the material input and output flows. Note that these typically balance across a process so inputs equal outputs specifically when dealing with material flows. These flows can be defined using parameters to create generic manufacturing and distance processes that vary with respect to the parameters.

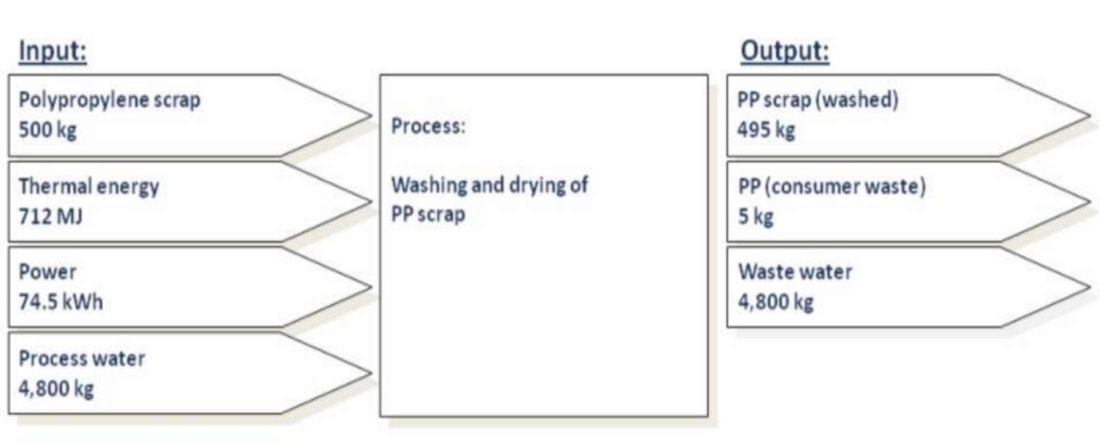


Figure 7-2: Example of material and resource flows in and out of a process (PE International, 2019)

7.4.1. **Generic Manufacturing Processes**

It can be assumed that there are a number of generic manufacturing processes used in the construction of a TSG. These are likely to include: bending, cutting, welding, abrasive blasting and painting. These generic processes can be defined in GaBi and then applied to the manufacturing of components that make up the TSG. This will require the use of parameterisation, which is detailed in section 7.4.3.

The generic manufacturing processes identified and their corresponding material flows are defined in the Generic LCA. These are detailed for each process in Table 7-1.

Table 7-1: Material and resource flow for the generic manufacturing processes

	Material/resource Flow	
Process	In	Out
Bending	Steel part Electricity	Steel Part
Cutting (Plasma arc cutting)	Steel part Shield Gas (Argon (Ar)) Electricity	Steel part Shield gas Scrap steel Heat
Welding – Gas metal arc welding	Steel part Shield gas (Mix of Argon (Ar) and Carbon dioxide (CO_2)) Electricity Welding wire	Steel part Shield gas Heat
Abrasive blasting	Steel part Compressed air (14 Bar) Blasting abrasive	Steel part Dust Waste
Painting	Steel part Paint Compressed air (7 Bar)	Finished component

It should be noted that for any process requiring a compressed air input, this flow is detailed in a separate process defined within GaBi. Theses process requires electrical power to run a compressor and generate the specified compressed air.

7.4.2. **Generic Distance Processes**

As previously discussed, there are a number of processes that are uniquely influenced by the site selection process. These are directly linked to the distance between the specified key locations. This process can be visualised in Figure 7-3 which identifies the key locations and the defined distances between each as; A - distance from Port to the site, B - distance from Port to the grid connection point and C - distance from the grid connection point to the site. Data for each of these distances will have been generated in the TFS and will be used in this stage of the methodology.

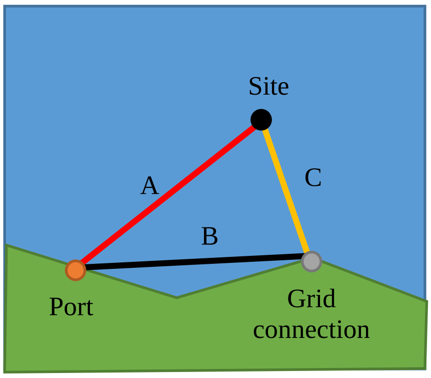


Figure 7-3: Travel distances between the Site, Port and Grid connection point.

Each of these elements will have an impact on the following processes during the LCA analysis. This is due to the distances that have to be overcome. These processes are further defined below, alongside the distance that affects them and a description of the process:

- **Turbine Deployment and recovery** – Distance A - The distance that a boat has to travel to and from the site for deployment and maintenance activities.
- **Cable deployment and recovery** – Distance A, B and C is the distance that a boat laying cable to the site has to cover; this includes the distance travelled to reach the grid connection point, the laying of the cable and then returning

to port. It should be noted that the cable laying process will likely be conducted at a reduced speed.

- **Cable manufacturing** – Distance C – the distance specified determines the length of the cable that is required to be manufactured.
- **Maintenance** – Distance A - The distance that a boat has to travel to and from the site.

These generic distance processes are defined in GaBi as Cable Manufacturing and Ship Transporting. Each of these processes is defined with respect to material flows in and out of the process. In the case of the cable manufacturing, the process this is defined per metre of cable, and for the ship transporting process it is per kg of fuel used. The flows in and out of each of these processes are:

Cable Manufacturing (per m of cable)

In: Copper, HDPE, PP fibres, PP granulate, steel, electrical energy, thermal energy

Out: Heat, grid connection cable

Ship Transporting (per kg fuel)

In: Fuel, Cargo

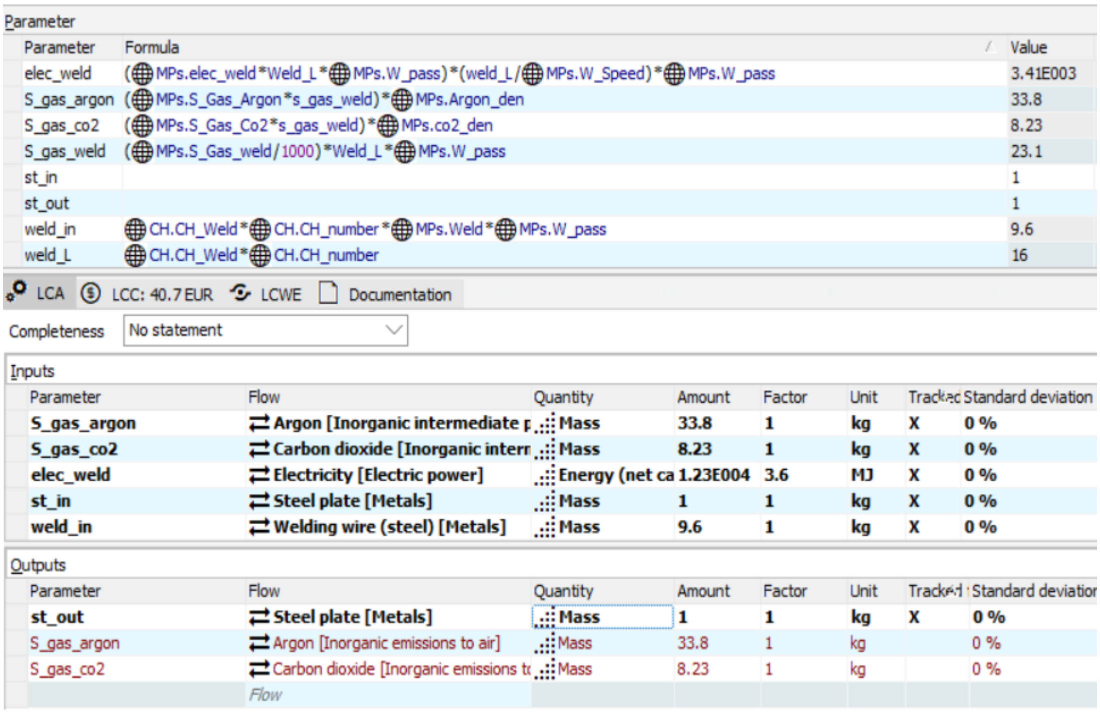
Out: Carbon dioxide (CO_2), Carbon monoxide (CO), Dust (particles to air), Methane (CH_4), Nitrogen oxide (NO), Sulphur dioxide (O_2S).

By defining the ship transporting process with respect to kg of fuel used, a calculation for the fuel consumption needs to be performed to determine the mass of the fuel used. This can be achieved using the parameterisation of the model to present different scenarios.

7.4.3. **Parameterisation**

The process of parameterisation was identified in the literature review as being a simple way of creating a generic model, that can then be used to investigate a specific device/service. This is achieved by altering specified parameters (Till, 2012) (Maedeh P. Shahabi, 2014). In order to create this generic model, each of the processes identified have been parameterised. This is a key part of the development of a generic LCA model for site selecting tidal turbines, as it allows users to define their own input values that affect the result generated. In order to achieve this, parameters are used in conjunction with formulas to create calculations. These calculations are used to determine variable outputs that change with respect to the inputted parameters.

The process of parameterisation can be demonstrated with a simple function such as 100 – X=Y. The parameter X is defined by the user, and any changes in its value affect the resulting output of the function. In order to generate generic processes, parameterisation was applied to each of the processes previously specified. An example of how this is carried out in GaBi is shown in Figure 7-4, which details the parameters used in the welding process. The figure is then further explained by expanding one of the parameter formulae for the mass of welding material added to the component. This shows how the parameters within the function are used to determine input and output flows in the process, with respect to the user-defined parameters. The values used to specify the welding process were obtained from the article "*Environmental and Social Life Cycle Assessment of Welding Technologies*" (Ya-Ju Chang, 2014)



Parameter

Parameter	Formula	Value
elec_weld	(MPs.elec_weld*Weld_L*MPs.W_pass)*(weld_L/MPs.W_Speed)*MPs.W_pass	3.41E003
S_gas_argon	(MPs.S_Gas_Argon*s_gas_weld)*MPs.Argon_den	33.8
S_gas_co2	(MPs.S_Gas_Co2*s_gas_weld)*MPs.co2_den	8.23
S_gas_weld	(MPs.S_Gas_weld/1000)*Weld_L*MPs.W_pass	23.1
st_in		1
st_out		1
weld_in	CH.CH_Weld*CH.CH_number*MPs.Weld*MPs.W_pass	9.6
weld_L	CH.CH_Weld*CH.CH_number	16

LCA | LCC: 40.7 EUR | LCWE | Documentation

Completeness: No statement

Inputs

Parameter	Flow	Quantity	Amount	Factor	Unit	Tracked	Standard deviation
S_gas_argon	**Argon [Inorganic intermediate p**	**Mass**	**33.8**	**1**	**kg**	**X**	**0 %**
S_gas_co2	**Carbon dioxide [Inorganic interr**	**Mass**	**8.23**	**1**	**kg**	**X**	**0 %**
elec_weld	**Electricity [Electric power]**	**Energy (net ca**	**1.23E004**	**3.6**	**MJ**	**X**	**0 %**
st_in	**Steel plate [Metals]**	**Mass**	**1**	**1**	**kg**	**X**	**0 %**
weld_in	**Welding wire (steel) [Metals]**	**Mass**	**9.6**	**1**	**kg**	**X**	**0 %**

Outputs

Parameter	Flow	Quantity	Amount	Factor	Unit	Tracked	Standard deviation
st_out	**Steel plate [Metals]**	**Mass**	**1**	**1**	**kg**	**X**	**0 %**
S_gas_argon	Argon [Inorganic emissions to air]	Mass	33.8	1	kg		0 %
S_gas_co2	Carbon dioxide [Inorganic emissions t	Mass	8.23	1	kg		0 %
	Flow						

Figure 7-4: Parameters of the welding processes in GaBi

The process for welding, depicted in Figure 7-4, shows the inputs and outputs of the process with respect to the parameters defined in the upper section of the figure. Each of these parameters is then linked to either input, output or one of the other equations in the process. It should be noted that in this example, the functions for defining the St_in and St_out are left blank in this process. This is because they are parameterised on the plan in the layer above to ensure that they can be adjusted with respect to the other processes that are defined in the manufacturing stages.

$$Weld_{in} = CH.CH\_Weld \times CH.CH\_number \times MPs.Weld \times MPs.Weld \qquad (7\text{-}1)$$

The formula that has been defined to calculate the mass of the weld added in the welding process is identified in equation (7-1). By applying the parameters specified in Table 7-2, the calculation determines that 9.6kg of mass is added to the component during this process. This value would change with respect to the parameters defined, altering the flow in and out of the process.

Table 7-2: Defined parameters for the Welding Formula

Parameter	Description	Unit	Value
CH.CH_Weld	Length of welds on the components	(m)	6
CH.CH_Number	Number of components being welded	(#)	4
MPs.Weld	Mass of material added per welding pass	(kg)	0.1
MPs.W_pass	Number of welding passes per each component	(#)	4

7.4.4. Distance Parameterisation

In the case of the cable, the manufacturing emissions are defined per metre of cable. The resulting outputs from this process are then calculated by multiplying the defined emissions per metre by the length of the cable in metres. Similarly, the emissions from shipping can be calculated with respect to the mass of the fuel used. This requires the mass of fuel to be calculated with respect to the distance travelled in order for the emissions to be determined.

However, it should be noted that the ship is likely to travel at different speeds during different operations. For example, during cable deployment and recovery phases, the ship will likely travel to the Grid connection point at cruise speed and then slow down to lay the cable. This will have to be accounted for by adding the results of the fuel used during the cruise to the grid connection point and the cable laying to calculate the total fuel used during this phase. The calculated fuel consumption can then be used to determine the emissions from the vessel. As a result of this, the fuel used across the life of the turbine will need to be calculated with respect to a number of factors.

The fuel calculations and cable parameters are defined further during the application of the developed methodology in the case study. This can be seen in subchapter 9.4.5. GaBi Modelling.

7.4.5. **Parameterisation Summary**

In total, the generic model contains 102 parameters that pertain specifically to the device and manufacturing processes. Of these, only four of these will be altered between defined sites if a common turbine is being assessed. These are the distance between the grid connection point and the site (Cable_to_Site), harbour/port to grid connection point (Harb_to_Cable) and harbour/port to site (Harb_to_Site). In addition to these distances, the average power generated by the turbine at the site (Elec) was also specified. These values are defined during the TFS, which determines the distance between points and the average power produced at each site. The remaining parameters were defined in the event that a bespoke turbine design was being assessed for deployment at the different sites or in the event that alternative construction methods were to be assessed.

A full list of the parameters defined in the generic methodology can be found in Appendix G - GaBi Parameters, which details the parameters alongside the values allocated to them during the case study in CHAPTER 9: CASE STUDY. The parameters defined in the generic model provide input values to 287 formulae. These formulae are spread throughout the model and are used to determine the material and resource flow across plans and process with respect to the input parameters.

7.4.6. **Data Collection**

With the use of parameters throughout the model, data will have to be collected for each of the parameters specified. The quality of this data will depend on its availability, with primary data being provided through industrial collaboration being preferable. However, secondary information may have to be sourced from literature for some of the processes identified. One key source of information will be the specification of the ship that will be used to deploy, maintain and recover the turbine. This is because it will define fuel flow rates and speed required to calculate the fuel consumption for deploying a TSG at each site. This is critical because it is conceived as being one of the key impacts that site selection will have on the LCA findings.

7.5. Impact Assessment

The impact assessment stage defines the impact of the device with respect to the selection of impact categories and classification. During this stage, the results from the inventory analysis are collated and assigned to their respective impact categories. These categories are defined by the different effect that emissions have on the environment.

The main aim of this methodology is the identification of the environmental impact of deploying a TSG. As a result of this, the impact of GWP is the main focus of the results from the LCA for the device.

Within GaBi, there are a number of different characterisation methodologies that can be applied for assigning impact categories. Seeing as none of the previous LCA studies focusing on TSG's defined which methodology was used, CML2001-Jan. 2016 Global warming potential (GWP, 100 years) will be applied.

CML is a database that comprises of characterisation factors developed by the Institute of Environmental Sciences at the University of Leiden in The Netherlands. The factors were last updated in 2016. The characterisation factors defined in this methodology effectively weigh each of the elements to a standard characterisation factor. In the case of GWP, CO_2eq is used to define the impact, and the characterisation factors defined by CML are applied to any gases that contribute to GWP. (CML - Department of Industrial Ecology, 2016)

This methodology will be applied to the inventory analysis in GaBi, allowing all the material flows to be assessed and assigned their relevant impact. The result of this analysis is a holistic overview of the impact of the device with respect to the functional unit defined in the scope. In this case, kg CO_2eq per turbine deployed.

7.6. Interpretation

The final phase of the LCA is the interpretation and reporting of the results. An important part of this process is ensuring that the results generated to conform to the Goal and Scope of the project. As a result of this, the findings have been compared to the initial goal and scope outlined to ensure that they conform with respect to the scope, data quality, functional unit, target audience and the assumptions made. This is an important phase as it provides a check for the project to ensure that the process has been conducted properly.

In order to report the results from the LCA study, they have to be with respect to the functional unit specified in the goal and scope of the project. In this case, the functional unit is emissions per deployment of the device at the specified site. Using this methodology, the emissions can be determined for each site identified during the site specification. These results are then compared against one another to determine the optimal placement of the device with respect to the findings.

This comparative process will not be bound by the additional requirements specified in ISO 14040, which are required for comparing different products. This is because the target audience specifically identifies the industrial clients and key stakeholders in the project. As a result of this, the comparisons are being made internally and not provided to the greater public. In addition to this, the comparison is being made against the same device, and hence there is no bias towards or against different companies.

The final phase of the LCA will be the undertaking of a Sensitivity Analysis. This is required to check the results generated.

7.6.1. Sensitivity Analysis

Owing to the use of parameters in the model, it is good practice to ensure that all values are correctly specified. In order to achieve this, it is recommended that a sensitivity analysis is conducted to ensure that changing parameters does not have an adverse effect on the results/findings of the method. This can be achieved in GaBi using the in-built sensitivity analysis tool. This tool can be used to assess the impact of changing parameters within user-defined variations to ensure that the resulting findings are as expected.

On completion of the sensitivity analysis, the results generated from the LCA are used in the final stage of the developed methodology, Stage 3 - Combination Tool.

CHAPTER 8: COMBINATION TOOL (STAGE 3)

8.1. Summary

The final stage of the methodology is the development of an analysis tool that combines the results from the TFS (£) and LCA (kgCO_2eq). This subsection details the development of the combination tool by first introducing the idea of combining the results before detailing the use of normalisation and user-defined weighing systems. The methodology established can then be used to identify the optimal location for the turbine with respect to the environmental and financial factors accounting for those user-defined preferences.

8.2. Introduction

There are a number of different methodologies for combining results. In this case, the simplest method would be to combine the results of the TFS and LCA achieved by dividing. This could be by dividing the TFS by the LCA results to generate a unit of £/kgCO_2eq or dividing the LCA results by the TFS findings to generate units of KgCO_2eq/£. Whilst this methodology would allow the identification of a preferred site with respect to these findings, the results cannot be adjusted with respect to user preferences. As a result of this, the adopted approach for this methodology makes use of normalisation.

8.3. Normalisation

Normalisation is a process that linearly transforms a result with respect to a data set. There are a number of different methods for normalising data; however, in this case, Min-Max normalisation is used. This methodology creates a dimensionless value which is directly related to the data set.

Min-Max Normalisation is capable of defining a score between 0 and 1, with a score of 0 identifying the minimum and a score of 1 indicating the maximum value in the data set. The score is determined using the following equation, where x indicates the result for the respective site and min and max indicates the minimum and maximum values found in the data set (KRAJ Education, 2019).

$$y = \frac{(x - \min)}{(max - \min)} \qquad (8\text{-}1)$$

The resulting score can be used to determine the position of the result with respect to the other results across the site. Whilst this formula can be used in cases such as the TFS, where it is desirable that a higher profit generates a higher score, this outcome is not always preferable. In situations such as with the LCA results, it is preferable that the lower value of emissions receives a higher score. This is achieved simply by subtracting one from the calculated score, effectively flipping the order of scoring. This creates a hierarchy where the lower values receive higher scores and are determined by the following equation.

$$y = 1 - \frac{(x - \min)}{(max - \min)} \qquad (8\text{-}2)$$

It should be noted that for the financial score if the minimum net return is negative, the value will be assigned as 0. This will act as a method of ensuring that unprofitable sites will receive a reduced score.

Once these two normalised scores have been calculated, they can be combined to create a Site Score. This value will be based on the results of both the LCA and TFS. Whilst this method could be used to identify the optimal site, this process lends equal weighting to each of the studies. This, however, might not be the desired outcome of the user.

8.4. **Weightings**

In order to generate a user-friendly tool that can be used to inform decisions, a weighting system can be applied to the normalised scores. This weighting system can be influenced by the user to define the outcome with respect to their objectives, allowing the tool to be used by multiple stakeholders from both the private and public sectors. Whilst it is currently envisioned that the focus of the private sector will be on the financial impact, the public sector may be more interested in the environmental impact.

This could be of particular interest with the uptake of the concept of life-cycle thinking, which promotes decision-makers to think about the environmental impact that their choices have. This could encourage the use of this system, as decision-makers are encouraged to think about the environmental impact that site selection has. Further down the line, it could even be public policy that drives the weightings to determine the balance between profits and environmental impact of the site selection process.

In order to develop the weightings, a sliding scale between 0 and 100 percent is defined for the LCA and TFS results. The specification of the weighting of one of these then impacts the other in the form of a ratio. For example, if the TFS is assigned a weighting of 70%, the LCA will have a resultant weighting of 30% (100-70). This ratio can then be applied to the normalised result scores previously determined.

The overall weighted site score is defined in the following equation; where L is the site results from the LCA study, F is the site results from the TFS, F_{min}, F_{max}, L_{min} and L_{max} are the minimum and maximum results from the corresponding data sets respectively, and Lw is the user-assigned weighting for the LCA component in the Combination tool. Note that, as previously mentioned, the assigned weighting for the TFS is dependent on Lw and can be calculated by 100 – Lw.

$$\left(\left(1-\frac{(L-L_{min})}{(L_{max}-L_{min})}\right)\times\frac{L_w}{100}\right)+\left(\left(\frac{(F-F_{min})}{(F_{max}-F_{min})}\right)\times\frac{100-L_w}{100}\right) \qquad (8\text{-}3)$$

The weighted score calculated can then be used to compare each of the sites together to determine a preferred site. This will be indicated by the highest score, with the results calculated with respect to both the user-defined weighting for the environmental and financial impacts of the device at each of the locations.

8.5. Results

With the optimal location determined from the weighted score, the final stage of the combination tool is the effective reporting of these results to the user. In order to achieve this, an overview of the site will be provided to the user with respect to the initial site breakdown. Results from the studies can then be plotted on to this breakdown providing a visual representation of the results to the user. In this method, the area excluded from the study and the optimal sites for the placement of the device can be easily identified. This is showcased in Figure 8-1 which clearly identifies the ten optimal sites (in green) with respect to their weighted score along with exclusion information for subsea cables (purple), land (black) and water depth requirements (red).

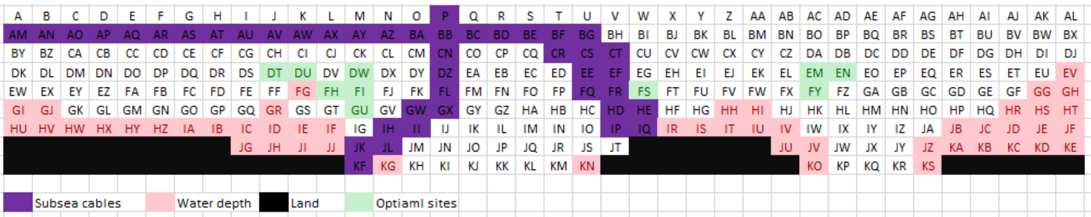


Figure 8-1: Example of the result overview

Whilst this provides a quick overview to the user, it does not provide specific information regarding the sites identified. This additional information will have to be displayed alongside the findings from the model in a technical results section. This will allow the users an in-depth understanding of the results. Information that will have to be provided to the user will include the following:

- User-defined weighting for the LCA and TFS
- Site Score
    - Finance score
    - Environmental score
    - Combined score
- Site Location in the form of longitude and latitude

- Findings from the TFS; including average power generation, time spent in each operational phase, financial information and the directional placement of the device (if appropriate)
- LCA results

In addition, the standard unit for comparing the impact of the turbine of g CO_2eq/kWh can also be determined and displayed for the site. This can be calculated from the known data in the model by converting the total emissions associated with the device from kilograms to grams and then dividing it by the power generated over the lifetime of the device. This will allow rudimentary comparisons to other power generating devices and can act as a check to ensure that the methodology has been carried out effectively.

The results generated from the methodology will give the user an in-depth understanding of the findings from the analysis. This provides additional information for them to make an informed choice regarding the deployment of the turbine.

8.6. Conclusion

The methodology developed fulfils the requirements of the aims of the project to develop a site selection tool for TSG's with respect to both the environmental and financial elements. The methodology developed conforms to three key stages that need to be undertaken during the methodology. As previously identified, data is allowed to flow between the methodologies allowing informed decisions to be made with respect to the findings.

The use of the weighting system provides the user with the ability to define the impact that each of the studies has on the site selection process. It should be noted that, with this methodology, a weighting of 100% for either the LCA or TFS will result in the identification of the optimal site purely with respect to that particular methodology.

The next step outlined in the Research Design Methodology is to test and refine the developed methodology by applying it to a case study situation. This is a major step in completing the final aim of the project, which requires that the methodology is tested in order to be evaluated in a 'real world' setting. This will validate its use as an industrial decision-making tool.

CHAPTER 9: CASE STUDY

9.1. Summary

The following chapter demonstrates how the developed methodology is applied in a practical setting using a case study. The case study is the third phase in developing the new methodology and acts as a "real-world" test of the proposed procedure by demonstrating its application. This is achieved by applying the methodology to position a turbine, the Nova M100, at a site off the north coast of Devon. The chapter follows the structured stages of the developed methodology, discussing the site and device specification (Stage1) before detailing the TFS, LCA (Stage 2A and 2B) and combination tool (Stage 3).

9.2. The site and Device Specification

9.2.1. The Site

The target site for analysis is a 53.8 km by 26km area off the coast of North Devon extending from Ilfracombe to Minehead, and across the water to Llantwit Major in Wales. The site is identified in Figure 9-1, with further details of each of the reference coordinates provided in Table 9-1. In order to calculate the size of the site, the distances between each point have been measured using the Google maps measuring tool. These findings were then corroborated using an online latitude/longitude calculator (Williams, 1997).

The North Devon coast site has long been of interest for the prospects of tidal power generation, hosting both the SeaFlow turbine and the North Devon Demonstration Zone. This established track record is one of the leading reasons for the site being selected as the case study site to test the methodology, as the successful operation of a TSG' deployed at the site has previously been achieved.

Figure 9-1: Boundaries of the North Devon site (Microsoft, 2019)

Table 9-1: Reference values for Figure 9-1

Letter	N-S	E-W
A	51°25′30″N	4°14′15″W
B	51°25′30″N	3°27′45″W
C	51°11′30″N	4°14′15″W
D	51°11′30″N	3°27′45″W

Site Information

The site is covered by Admiralty Chart 1165, which details the area of the Bristol Channel from Worms Head to Watchet (Crown, 2015). The current edition, April-2015, is a key source of information for ships navigating the area providing; Water depth data, current speeds and additional notes on the area. This data is particularly useful for the TFS as it provided the backbone for the exclusion criteria, and provides known data that can be used to corroborate results from software packages in order to validate the data.

Identification of Key Infrastructure

In order to site select potential key infrastructure points, appropriate infrastructure has to be identified. This includes locations for the construction, maintenance and grid connection of devices across the site. The original plans for the North Devon demonstration zone identified both Lynmouth and Ilfracombe as a potential base for the deployment and maintenance of devices in the area. An assessment of the port facilities showed that Ilfracombe had a good-sized harbour with dockside facilities. This resulted in Ilfracombe being selected as the base of operation for all deployment and maintenance activities. Lynmouth was considered as a second base of operation. However, it was discounted due to the reduced port facilities and the assumption that only one maintenance/deployment port would be required for each site.

In order to connect the device to the UK National Grid, grid connection points needed to be identified. It was assumed that any populated area along the coast would be an acceptable grid connection point. This was based on the assumption that there would already be infrastructure at these sites for connecting the local community with supply from the National Grid and hence energy could be fed back into the grid at these sites.

Four grid connection points were identified within the site. Three are situated along the coast of North Devon at Ilfracombe, Lynton and Minehead with the fourth at Llantwit Major in Wales. The key infrastructure points are all identified in Figure 9-2.

Figure 9-2: Infrastructure points identified (Google, 2019)

9.2.2. **The Device**

The site selected had formerly been home to the world's first offshore tidal generator, the 300kw SeaFlow test turbine (Tidal Energy, 2003). Whilst this indicated the possibility of generating power at the site, the relatively small power output of the turbine indicated a potential limit of power generation at the site. This could be due to a number of restrictions such as device size or current speeds but prompted further investigation before the turbine was specified.

Initial analysis of the sites' water depth using the Admiralty Chart showed that only 10% of the sites were deeper than 35m at the lowest astronomical tide. This indicated that a relatively small turbine would be required in order to maximise the number of sites that could be assessed. As a result, the Nova M100 turbine was specified.

The Nova M100 turbine was a clear candidate for the site as it is one of the world's leading small-scale tidal turbines. The turbine has been successfully deployed in the

Bluemull Sound since 2016 in an array configuration, a world's first at the time (Nova innovation Ltd, 2017).

9.2.3. Nova M100 Specification

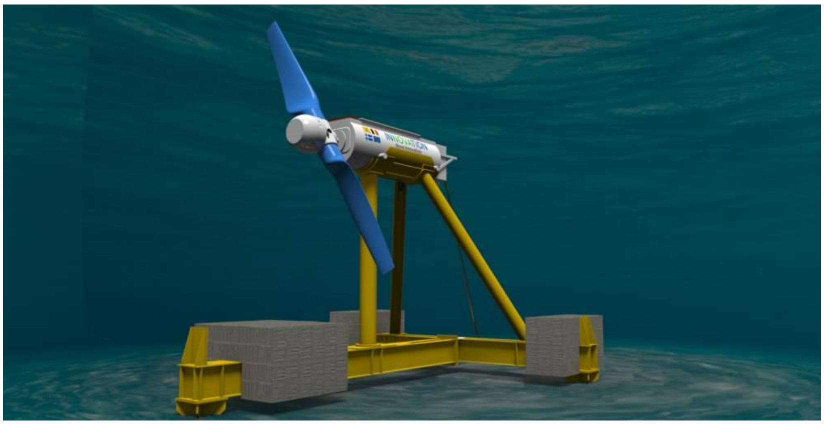


Figure 9-3: Nova M100 Turbine (Born to Engineer, 2016)

The Nova M100, identified Figure 9-3, is a horizontal axis, fixed, gravity-based turbine consisting of two modules, a base unit of steel and concrete and the turbine nacelle and rota assembly. The modular design allows the turbine to be easily split into two modules. This means that the nacelle and turbine blades can be recovered without difficulty, for maintenance activities.

The Nova M100 is a 100kW rated fixed based bi-directional turbine. This means that the turbine cannot rotate to orientate itself into the water stream. To compensate for this, the blades are designed to operate bi-directionally, generating power from both flows into and out of the turbine. As a result of this, the directional positioning of the turbine will be an important part of the site selection process. Table 9-2 provides the technical specifications for a typical configuration of the turbine.

Table 9-2: Specifications for the Nova M100 turbine (Nova Innovation Ltd, 2019)

Rated power	100	kW
Expected lifespan	20	Years
Rotor diameter	9	m
Swept area	63.62	m^2
Cut in speed	0.6	m/s
Rated power speed	2.0	m/s
Draft	15	M
Weight in water	80	Tones

The specification provided for the turbine does not detail a Cp or a cut-in power for the turbine. Both of these values can be calculated by rearranging the power equation for a TSG (3-2) and substituting the known values provided in the specification. In the case of the Cp, when the turbine is operating at its rated power, the power output is 100kW at the specified flow speed of 2m/s. Rearranging the equation results in a calculated mechanical efficiency of 38.34% for the device, assuming the density of seawater is 1025kg/m^3.

$$100{,}000 = 0.5 \times 1025 \times (\pi \times 4.5^2) \times 2^3 \times C_p$$

$$C_p = \frac{100{,}000}{0.5 \times 1025 \times (\pi \times 4.5^2) \times 2^3} = 0.3834$$

Similarly, once the Cp is determined, the Cut-in power of the device can be calculated for the cut inflow speeds of 0.6m/s using the now established value for Cp. The cut-in power of the device is calculated to be 2,700W or 2.7kW.

$$0.5 \times 1025 \times (\pi \times 4.5^2) \times 0.6^3 \times 0.3834 = 2{,}700$$

Owing to the device being fixed, it was likely that the Cp value would vary between the flow into the front and back of the device. Unfortunately, there was no data available regarding flow into the back of the turbine, so in order to account for this, it was assumed that the Cp of flow into the back of the device would be 5% less than that of the front. This defined the Cp value for the back of the turbine as 0.3334.

9.3. Feasibility Study

The following subsection details the process of conducting the Feasibility study with respect to the specified site, off the North coast of Devon and the device, the Nova M100. The methodology follows the structure of the feasibility study set out in Chapter 6.

9.3.1. Site Breakdown

The site was broken down into a 32 x 15 grid identifying 480 individual sites within the defined area. Each site measures 1,681m x 1,733m. A distance corresponding to a change in the longitude of 1.5 minute and latitude of 1 minute across each site. As a result of this, each site covers an area of 2.91km^2. These measurements correspond to the resolution of the POLPRED modelling software, which was later used to generate flow speed data. This meant that the site break-down matched the available data set, allowing for easy data transfer into the site selection tool.

By overlaying the sites on a map, it is clear to see that of the original 480 sites, 91 of them fall onshore. This resulted in these sites being excluded from further analysis. Each of the remaining 389 sites has been assigned an alphabetical nametag as a quick reference with values from A to NY. An overview of the sites being considered in the study is provided in Figure 9-4, which identifies all the sites with their alphabetical nametags. A full list of the precise location of each site is supplied in Appendix C - Case Study - Site Information.

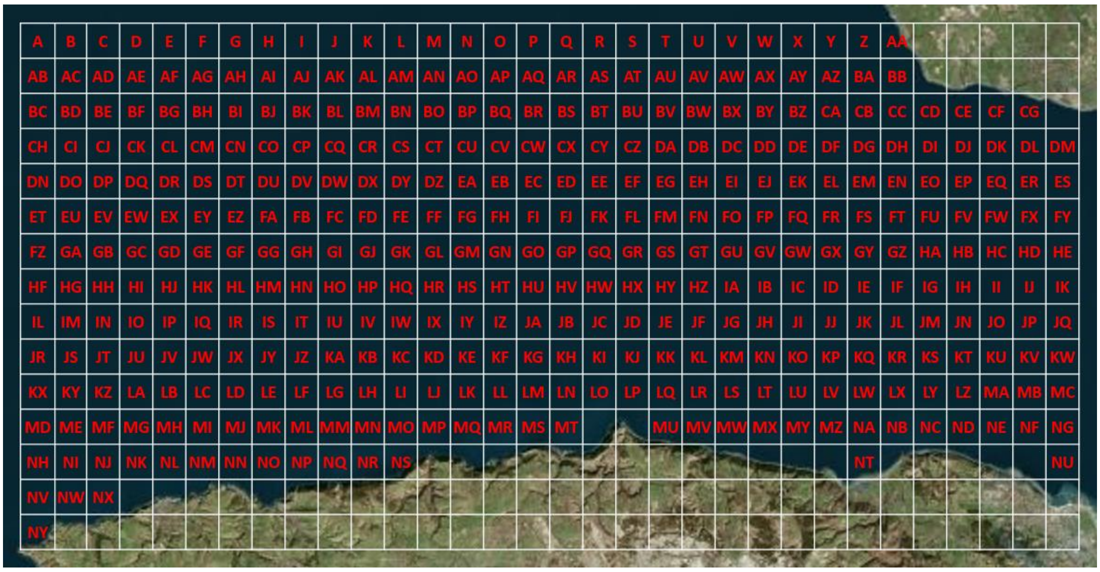


Figure 9-4: Site overlaid with individual sites for assessment (Microsoft, 2019)

9.3.2. **Distance to Infrastructure**

In order to determine the distance between the key infrastructure points, the methodology defined in subchapter 6.4 – "Distance to Infrastructure has been applied. As a result, the following distances can be calculated; from port to sites, sites to a grid connection point and port to grid connection point. The following subsections outline the results from this process. A full set of the results can be seen in list format for each site in Appendix C - Case Study - Site Information. It should be noted that this data is shared between the TFS and the LCA study to help inform the fuel flow calculations.

Port to Site

The port of Ilfracombe was identified for the maintenance and deployment of the device at each site. As a result of this, the distance from the port to each of the sites was calculated. This process determined the longest journey from the port would be 47km to site DM, and the shortest to site NM at 1.7km. A full set of results can be viewed with respect to the sites in Appendix D - Distance from Port to Sites (km)

Site to Grid Connection Point

Grid connection points were identified at Lynton, Minehead Llantwit Major and Ilfracombe. This provided multiple connection options for each of the sites identified. As a result, the optimal grid connection point had to be determined. This was achieved by assuming the optimal grid connection point would be the shortest distance between the site and the grid connection. This would result in the shortest length of cable, which results in cost savings for the project. This assumption then allowed the optimal grid connection point to be determined for each site.

Figure 9-5 identifies which grid connection point optimally covers each section of the site. In total, 140 sites are covered by the Ilfracombe point, 131 by Lynton, 30 by Minehead and 88 by Llantwit Major. The calculated distances from each site to the optimal grid connection point can be seen in Appendix E - Distance Between Grid Connection Points and Sites (km), with reference to the optimal grid connection point.

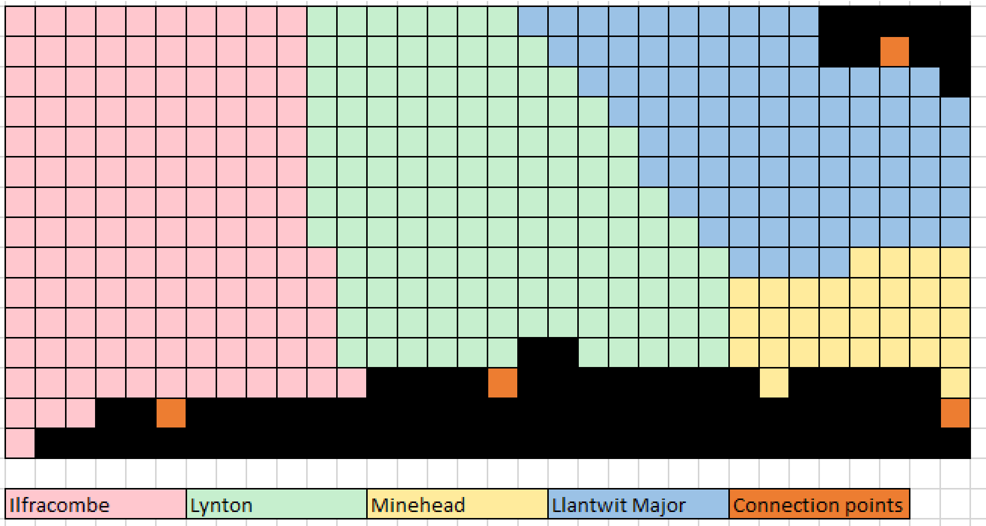


Figure 9-5: Identification of optimal grid connection point for each site

Port to Grid Connection Point

This accounts for the distance that a vessel would have to travel from the port at Ilfracombe to reach each of the grid connection points. The results of these calculations are displayed in Table 9-3. Seeing as Ilfracombe is both a port and grid connection point, the distance between them is calculated as 0.

Table 9-3: Distance from Ilfracombe to each grid connection point

Grid Connection Point	Distance (km)
Ilfracombe	0
Lynton	18.8
Minehead	44.6
Llantwit Major	44.5

9.3.3. **Inclusion/Exclusion Criteria**

Of the exclusion criteria identified in section 6.5, only four were identified at the site. These were; Shipping lanes, Subsea infrastructure, Water depth restrictions and Wrecks. Each of these elements is discussed further in the following subsection before the combined results of the exclusion criteria are defined and applied for the case study. It should be noted that the other exclusion criteria were discounted from the study for the following reasons;

Military firing ranges - No active military firing ranges are present in the area being assessed.

Fishing sites - There are currently no defined fishing areas around the site. However, some fishing activities can be observed from marine traffic data of the area, seen in Figure 9-6. It was assumed due to the relatively low volume that these activities could be redistributed around any turbines deployed at the site. Hence this was discounted from the exclusion criteria.

Shipping Lanes

The Bristol Channel is a major waterway for marine traffic. It is home to a number of large port facilities such as Cardiff, Newport and Avonmouth. In addition to this, the area is popular with smaller recreational pleasure craft. Figure 9-6 displays a density map of marine traffic in the area in 2017. The map clearly identifies the shipping routes taken by larger vessels in red and the less-well-travelled routes in dark blue.

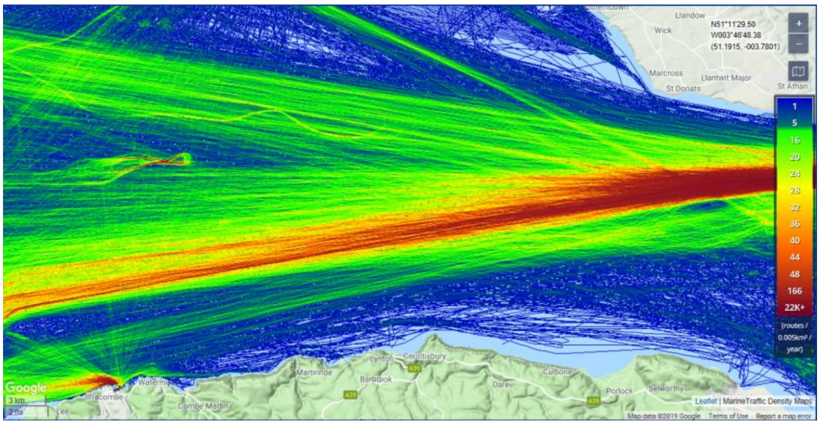


Figure 9-6: 2017 marine traffic density map for the Bristol Channel (MarineTraffic, 2017)

In order to avoid disrupting the major shipping lanes, it was assumed that any site that sits in the path of heavy marine traffic would be excluded from the study. The results of this can be seen in Figure 9-7, which identifies the sites excluded due to the shipping lanes in red.

1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1
0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0														0						0
0	0	0																													
0																															

Figure 9-7: Excluded sites due to shipping lanes (Red 1)

Subsea Infrastructure – Pipes and Cables

The Bristol Channel is home to a number of subsea cables and pipes. Owing to the critical nature of subsea infrastructure, a 500m exclusion zone typically applies to the surrounding area. This is in order to protect the structure and ensure that maintenance vessels can access them in the event of a failure. Any site that contained a cable/pipe was discounted from the study due to these constraints.

The Admiralty chart was a key source of information on the subsea infrastructure in the area, providing mariners with information to ensure that maritime vessels do not anchor at these points. As a result of the data gathered from the chart, the sites excluded due to the subsea infrastructure are identified in Figure 9-8 in red.

0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	1	1	1	1	1	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	1	1	1	1	0	0	0	0	0	0	1	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			0	0	0	0	0	0	0	1	1	1	1	1	1
0	0	0	0	0	0	0	0	0	0	0	0														0						0
0	0	0																													
0																															

Figure 9-8: Subsea infrastructure exclusion zones (Red 1)

Ship Wrecks

According to the Admiralty chart, there are a total of 29 shipwrecks charted within the identified site. Owing to the Protection of Wrecks Act (1973) (Maritime and Coastguard Agency, 2018) and other considerations such as the historic and dangerous nature of these sites, any site containing a wreck were excluded from the site selection process. These sites are identified in Figure 9-9 in red.

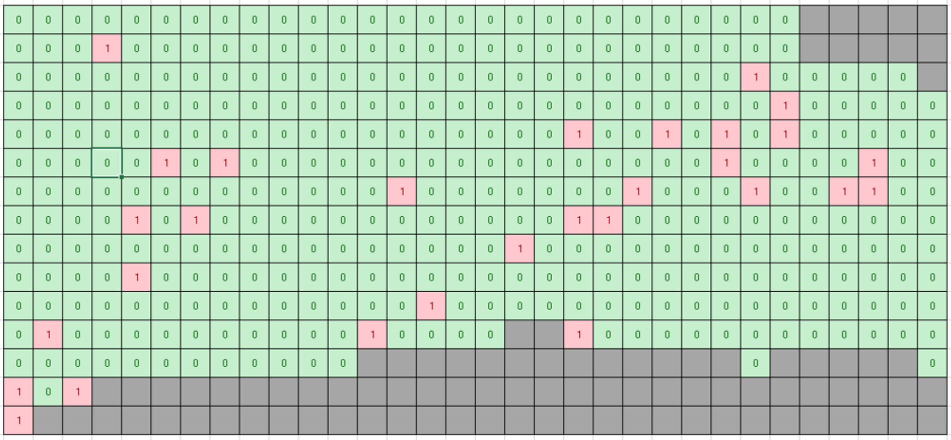


Figure 9-9: Locations across the site that contain shipwrecks (Red 1)

Water Depth

The minimum water depth at each of the sites was obtained from the Admiralty chart. The Admiralty chart provided water depth with respect to chart Datum, an approximation of the lowest astronomical tide. This corresponds to the absolute minimum water depth that will be observed due to astronomical tidal conditions at the site. Figure 9-10 shows the minimum water depth within each of the sites in metres. The water depth across the site varies from 0.2m at the shallowest site to 49m at the deepest.

36	37	34	34	34	35	32	32	30	28	28	21	23	22	25	19	18	16	14	13	12	10	15	3.2	10	12	1					
35	39	31	35	32	32	31	33	30	22	22	23	28	24	22	22	20	19	18	15	16	14	13	14	13	12	0.2					
37	39	34	35	34	31	30	34	31	30	31	30	23	21	21	20	20	18	17	17	19	17	16	15	13	12	11	11	9	7.5	2.5	
37	34	33	30	33	36	32	33	30	31	32	30	29	30	29	27	26	23	23	15	15	19	17	17	18	18	13	13	19	16	13	20
39	40	35	40	43	39	37	30	31	29	28	29	30	33	27	26	29	23	22	20	21	20	17	18	16	14	15	16	21	16	21	18
40	38	35	36	37	39	35	39	36	31	30	29	28	26	25	28	25	24	30	25	25	27	21	20	20	19	16	20	22	31	20	27
39	35	32	35	40	42	36	40	47	49	49	47	40	33	41	36	26	24	23	22	31	25	29	30	24	21	20	16	30	19	15	20
35	34	33	37	32	34	32	33	42	34	31	31	29	30	32	31	42	40	36	40	26	30	30	31	33	32	33	32	21	20	18	28
38	34	34	34	34	31	30	30	30	30	39	39	37	32	25	25	25	24	23	22	22	23	33	32	31	23	21	21	30	22	21	22
35	36	36	31	32	32	31	31	28	28	27	26	26	25	24	25	23	23	17	36	20	30	19	17	16	20	18	20	21	16	20	22
31	32	32	30	31	30	30	29	27	26	26	27	26	23	17	21	20	12	7.5	7.4	21	20	17	16	15	15	16	20	18	15	15	19
28	13	31	29	25	24	24	24	23	25	23	22	18	11	12	14	9			7.5	12	21	14	16	15	14	15	15	16	19	19	15
31	30	21	18	28	25	20	21	22	1.8	12	12														4						11
30	20	14																													
9																															

Water Depth Key					
0 to 10m	10 to 20m	20 to 30m	30 to 40m	+40m	Land

Figure 9-10: Water depth at each site (m)

The Minimum water depth required to host the Nova M100 is 15m. This corresponds to the draft of the turbine provided in the specification. By accounting for this, 47 sites are automatically excluded from the analysis. These sites are identified in Figure 9-11. It should be noted that the minimum water depth can be specified by the user as required, and the specified value will need to be compared against the known values to determine if the site is included or excluded.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R					W									
AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT		AV											
BC	BD	BE	BF	BG	BH	BI	BJ	BK	BL	BM	BN	BO	BP	BQ	BR	BS	BT	BU	BV	BW	BX	BY									
CH	CI	CJ	CK	CL	CM	CN	CO	CP	CQ	CR	CS	CT	CU	CV	CW	CX	CY	CZ	DA		DC	DD	DE	DF	DG			DJ	DK		DM
DN	DO	DP	DQ	DR	DS	DT	DU	DV	DW	DX	DY	DZ	EA	EB	EC	ED	EE	EF	EG	EH	EI	EJ	EK	EL		EN	EO	EP	EQ	ER	ES
ET	EU	EV	EW	EX	EY	EZ	FA	FB	FC	FD	FE	FF	FG	FH	FI	FJ	FK	FL	FM	FN	FO	FP	FQ	FR	FS	FT	FU	FV	FW	FX	FY
FZ	GA	GB	GC	GD	GE	GF	GG	GH	GI	GJ	GK	GL	GM	GN	GO	GP	GQ	GR	GS	GT	GU	GV	GW	GX	GY	GZ	HA	HB	HC	HD	HE
HF	HG	HH	HI	HJ	HK	HL	HM	HN	HO	HP	HQ	HR	HS	HT	HU	HV	HW	HX	HY	HZ	IA	IB	IC	ID	IE	IF	IG	IH	II	IJ	IK
IL	IM	IN	IO	IP	IQ	IR	IS	IT	IU	IV	IW	IX	IY	IZ	JA	JB	JC	JD	JE	JF	JG	JH	JI	JJ	JK	JL	JM	JN	JO	JP	JQ
JR	JS	JT	JU	JV	JW	JX	JY	JZ	KA	KB	KC	KD	KE	KF	KG	KH	KI	KJ	KK	KL	KM	KN	KO	KP	KQ	KR	KS	KT	KU	KV	KW
KX	KY	KZ	LA	LB	LC	LD	LE	LF	LG	LH	LI	LJ	LK	LL	LM	LN				LR	LS	LT	LU	LV	LW	LX	LY	LZ	MA	MB	MC
MD		MF	MG	MH	MI	MJ	MK	ML	MM	MN	MO	MP									MW		MY	MZ		NB	NC	ND	NE	NF	NG
NH	NI	NJ	NK	NL	NM	NN	NO	NP																							
NV	NW																														

Figure 9-11: Sites excluded due to minimum water depths of 15m

The maximum water depth for this site was not considered in the exclusion criteria. This was because the maximum water depth observed at the site was just 54m on a high tide. It was assumed that this relatively shallow depth would be well within the specified operating parameters of the chosen turbine and hence have no restricting effect on the placement of the turbine at the site.

Combined Exclusion Results

The combined exclusion results account for the findings from each of the individual exclusion criteria. In this case, the shipping lanes, subsea infrastructure, wrecks and the minimum water depth. In this example case study, a minimum water depth of 25m is specified to allow ample depth for the turbine to operate; these assumptions are used throughout the remainder of the case study.

Applying these exclusion criteria to the site, of the original 389 sites identified 300 are excluded. As a result of this, 89 sites were identified as potential sites for deployment of the turbine. Figure 9-12 displays the results from the combined exclusion criteria with respect to the key in Table 9-4. (Note that some sites are excluded due to multiple breaches of the exclusion criteria but this is not reflected in the figure).

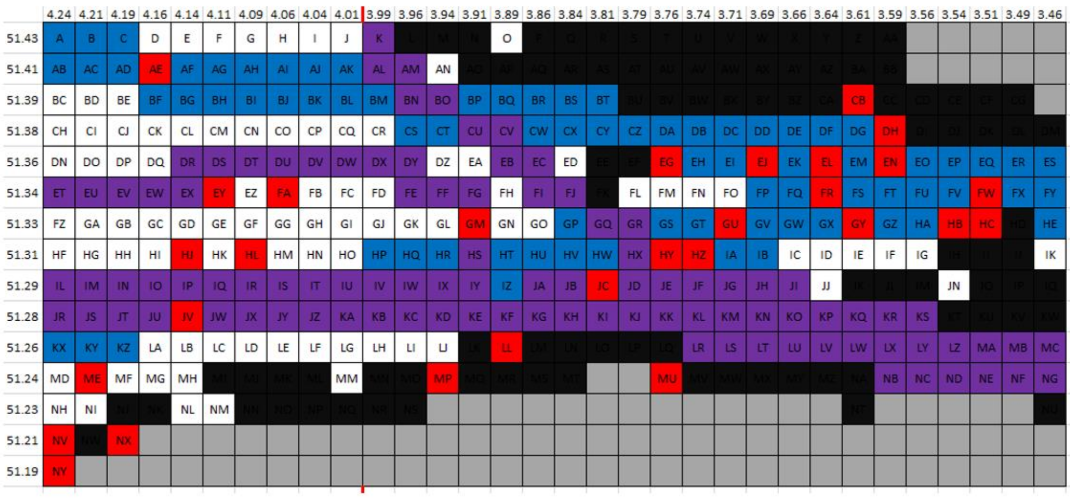


Figure 9-12: Exclusion criteria for the case study

Table 9-4: Key for Figure 9-12

(black)	Water depth requirements not met
(purple)	Subsea infrastructure
(blue)	Shipping routes
(red)	Shipwrecks
(grey)	Land
(white)	Sites for consideration

Despite identifying excluded sites, the exclusion criteria are not applied to the results of the LCA or TFS until their combination. This means that results and data are generated for all the sites. This is required in case of the event that the user wants to change the exclusion criteria at a later date.

9.3.4. Flow Data

The next stage of the TFS was the generation of flow data for the site. Initial studies typically use data generated from tidal models to predict areas of interest. As a result of this, the specialist software package POLPRED was used, specifically the High-Resolution UK-CS model (CS20-15HC3). The POLPRED software is capable of running two different types of analysis; spatial and time series. The following sections discuss the findings of each type of analysis before discussing the validation of the data generated from the model.

Spatial Analysis

The spatial analysis tool in POLPRED allows the user to visualise the tidal flows across the entire site, with respect to the model resolution of 1,681m x 1,733m. This allows the user to make some initial observations regarding the general condition at the site. Figure 9-13 shows four separate images from the spatial analysis of the site, identifying the flow speed and direction at varying tidal conditions across the site. It should be noted that the POLPRED model resolution was used to specify the resolution of the site break down in section 8.3.1. As a result, the site identified in the site break down matched the available data set. This allowed for data to be easily transferred into the site selection tool.

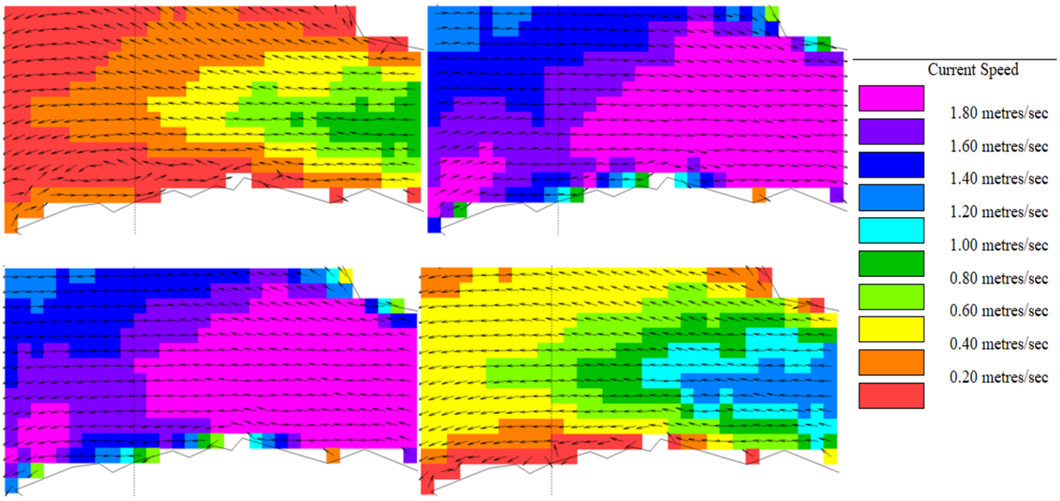


Figure 9-13: Range of Tidal conditions at the site, Top left –slack water, Top right – tide running in, Bottom left – tide running out and Bottom right – approaching slack water (NOC, 2019)

The following initial observations were made from the spatial analysis of the site:

- Water is faster flowing in the areas where the channel narrows between Devon and Wales.
- The flow direction on the inflow is mainly easterly and, on the outflow, westerly. This is due to the geography of the North Devon Coast restricting the flow.
- Water speed at the site reaches around 2 m/s, enough to hit the rated power output of the Nova M100 turbine specified.
- Flow rates are consistently above the specified 0.6m/s cut-in speed of the turbine.

The initial observations identified that power production is possible at the site for the specified turbine. This meant that a full in-depth analysis to determine flow speeds at each site could now be carried out using the time series analysis.

Time Series Analysis

The time series analysis provides in-depth information for a single point within a model with respect to a specified time step. This allows the user to generate precise information regarding this point, providing a realistic picture of the tidal flow conditions at the point. By modelling a time period of one lunar month in conjunction with time steps of 1 minute, a complete understanding of the flow conditions could be generated.

The analysis period chosen started on the 2/12/2018 at 1:32 and ended at 31/12/2018 at 13:15. In between these two points, there were 42,464 timesteps. The data generated via the software included: Date, Time, Water level (m) with respect to the Mean Sea level, Flow speed (m/s) and the Direction of flow (˚). An extract of this data is seen in Figure 9-14 for Site A.

Data computed from High Resolution UKCSModel (CS20-15HC3)				
Location:51˚25'30.0"N 4˚14'15.0" W		Time Zone: GMT		Datum: MSL
Date	Time	Level	Speed	Direc'n
		m	m/s	deg
02/12/2018	01:32	2.46	0.17	71
02/12/2018	01:33	2.46	0.17	71
02/12/2018	01:34	2.46	0.16	70
02/12/2018	01:35	2.46	0.15	70
02/12/2018	01:36	2.46	0.15	69
02/12/2018	01:37	2.46	0.14	68
02/12/2018	01:38	2.46	0.14	67

Figure 9-14: POLPRED time series results

It should be noted that a time series analysis was conducted for each of the 389 sites originally identified. This would allow for the event that the user wanted to adjust the exclusion parameters previously defined. As a result of this, a total of 16,518,496 time step iterations were generated across all of the sites identified across the investigation area. This data could then be used to calculate the power output of a turbine at each site.

Data Validation

The POLPRED model has already been tested, refined and validated against the tidal gauge network around the UK coast (NOC, 2019). As a result of this validation process, it is reasonable to assume that the results are reliable. However, it is an important part of the study to ensure that the results are validated for this application.

In order to validate the data obtained from the model for the North Devon sites, it has to be corroborated against known values. The Admiralty Chart 1165 provides specific tidal flow information for marine traffic in the area in the form of 'tidal diamonds'. These diamonds are used to indicate sites on the chart that have been physically monitored to determine the flow speed (knots) and direction (deg). This information is provided in one-hour increments either side of a spring and a neap tide. This indicates the maximum and minimum tidal flow situations that will be experienced at the point.

There are three tidal diamonds lying in the area of study identified. These are detailed in Table 9-5 alongside the data provided. It should be noted that the data is provided for six hours each side of the high water time, which for this chart is the time that high water occurs at Swansea.

Table 9-5: Tidal diamond data from Admiralty Chart 1165 for points within the identified site

	Tidal Diamond	L			N			K		
	Latitude Longitude	51˚ 16' 00" N 3˚ 47' 24" W			51˚ 19' 18" N 3˚ 32' 24" W			51˚ 20' 6" N 3˚ 50' 18" W		
		Direction (deg)	Speed spring tide (knots)	Speed neap tide (knots)	Direction (deg)	Speed spring tide (knots)	Speed neap tide (knots)	Direction (deg)	Speed spring tide (knots)	Speed neap tide (knots)
-6		225	0.4	0.2	280	0.9	0.4	244	0.5	0.3
-5		87	2.1	1.0	60	0.5	0.2	130	0.8	0.4
-4		97	3.3	1.6	78	2.4	1.1	89	2.3	1.1
-3		93	4.0	1.9	94	3.0	1.4	93	3.3	1.6
-2		92	3.6	1.7	96	3.2	1.5	97	3.3	1.6
-1		94	2.6	1.2	102	2.6	1.2	101	2.3	1.1
0		92	1.0	0.5	94	1.2	0.6	122	0.9	0.4
1		239	1.3	0.6	269	0.4	0.2	207	0.6	0.3
2		271	3.7	1.7	276	2.2	1.0	286	2.7	1.3
3		276	4.6	2.1	272	2.9	1.4	291	3.3	1.6
4		275	3.9	1.8	271	3.2	1.5	272	3.2	1.6
5		278	2.5	1.2	272	2.5	1.3	281	2.3	1.1
6		275	1.3	0.6	271	1.4	0.7	265	0.9	0.4

In order to compare the POLPRED analysis with the Admiralty Chart data, both flow speed and directional data have to be obtained from the model at each of the specified tidal diamond sites. As a result, a direct comparison can then be drawn with respect to the high tide occurring at Swansea. For the chosen analysis period, the spring and neap high water conditions occurred at Swansea on the following dates; the Springtide on the 8/12/2018 at 6:44 at 9.35m and the neap tide on the 17/12/2018 at 00:53 at 7.07m. This information was sourced from the Swansea Tide Tables (Dolby, 2019). The following are the validation results for the flow speed and directional component of the flow.

It should be noted that whilst data sourced from POLPRED can be used to help select a site, further work would have to be undertaken to corroborate the flow results before a device is deployed. This can be achieved by physically monitoring the site identified and comparing real-world measurements to the data generated. This step will typically be undertaken after a site has been identified due to the large costs associated with the collection of onsite data.

Flow Speed Validation

The flow speed from the POLPRED model is in metres per second (m/s). In order to compare the admiralty chart data to this, the chart data needs to be converted from knots to the SI unit of metres per second. A knot is calculated from the geographical latitude travelled during a set time. A speed of one knot, if maintained for one hour, would produce a change of 1 minute in the geographical latitude a distance of 1.852km. As a result of this Knots can be converted to m/s using the following equation, Where V is the velocity in m/s and Kn is the speed in knots.

$$V = Kn \times \left(\frac{1852}{3600}\right) \tag{9-1}$$

This conversion allows for a direct comparison between the results for both the spring and neap tides for each of the tidal diamonds. The results of this can be seen in the graphs presented in Figure 9-15.

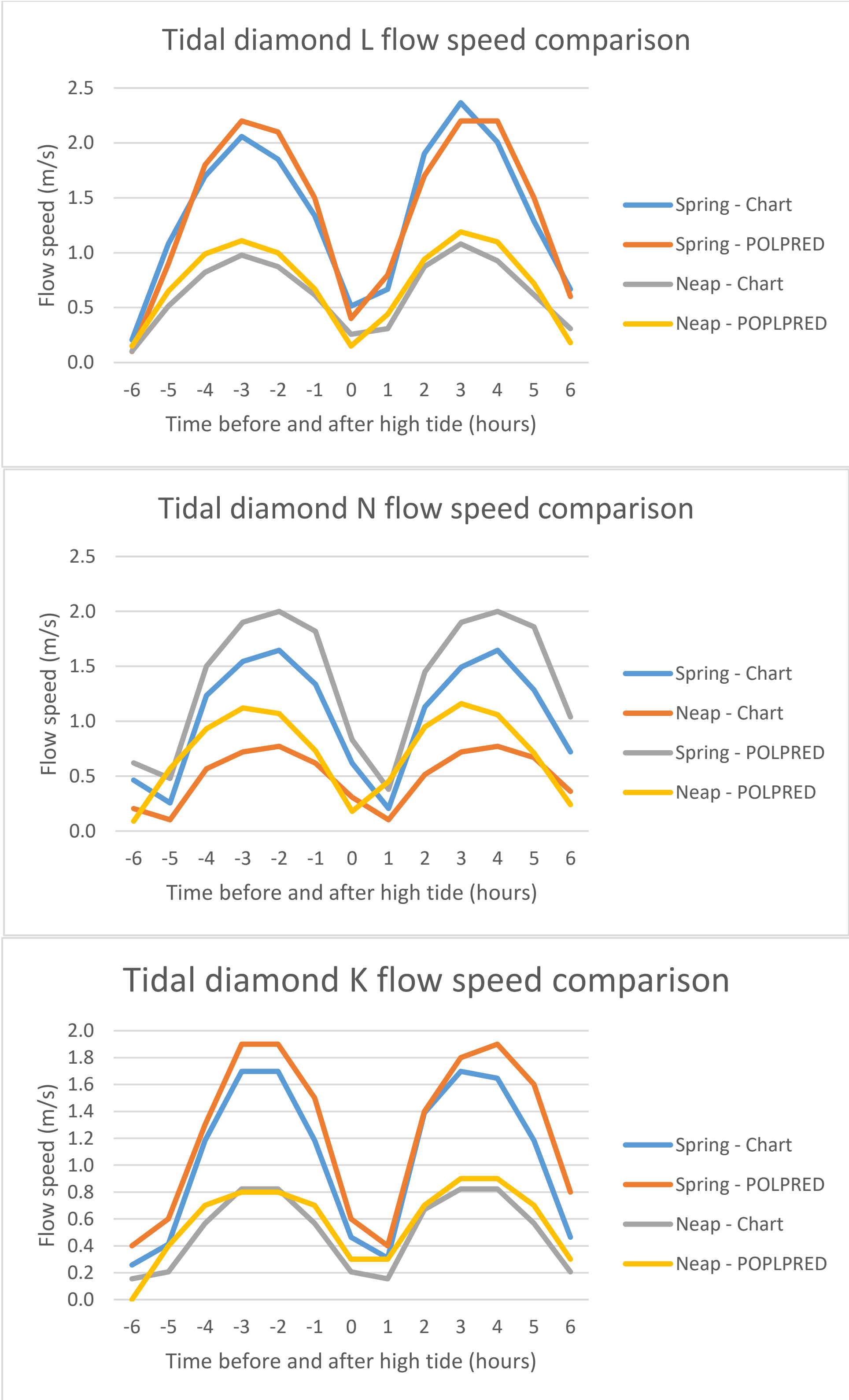


Figure 9-15: Validation of flow speeds obtained from the POLPRED model against the Admiralty Chart data, during Spring and Neap tidal conditions at sites; L (top), N (middle) and K (bottom)

Overall the flow data from the POLPRED model matched the data provided by the Admiralty Chart. However, it should be noted that there is a variation between the flow speeds at site N. Further investigation of the chart showed that this area had not been updated since 2008 when it became a “reported zone”. This is an area where vessels are required to request up-to-date water depth data due to constantly changing conditions. The difference between the values could be attributed to this. With respect to these findings, it was assumed that the flows across the site were valid.

Flow direction validation

In addition to the flow speed, the direction of the flow could also be used to validate the directional flow element of the model. This is particularly important due to the specification of a fixed turbine at the site, which means that the directional flow has to be considered in the analysis. The results of the analysis for each site can be viewed in Figure 9-16.

It was noted that there are some discrepancies between the flow directions across the three sites; however, they are close enough to validate the model. Overall the validation process determines that the results obtained from the model were within acceptable limits; as a result, the data from the POLPRED model could be used to assess the power output of each of the sites.

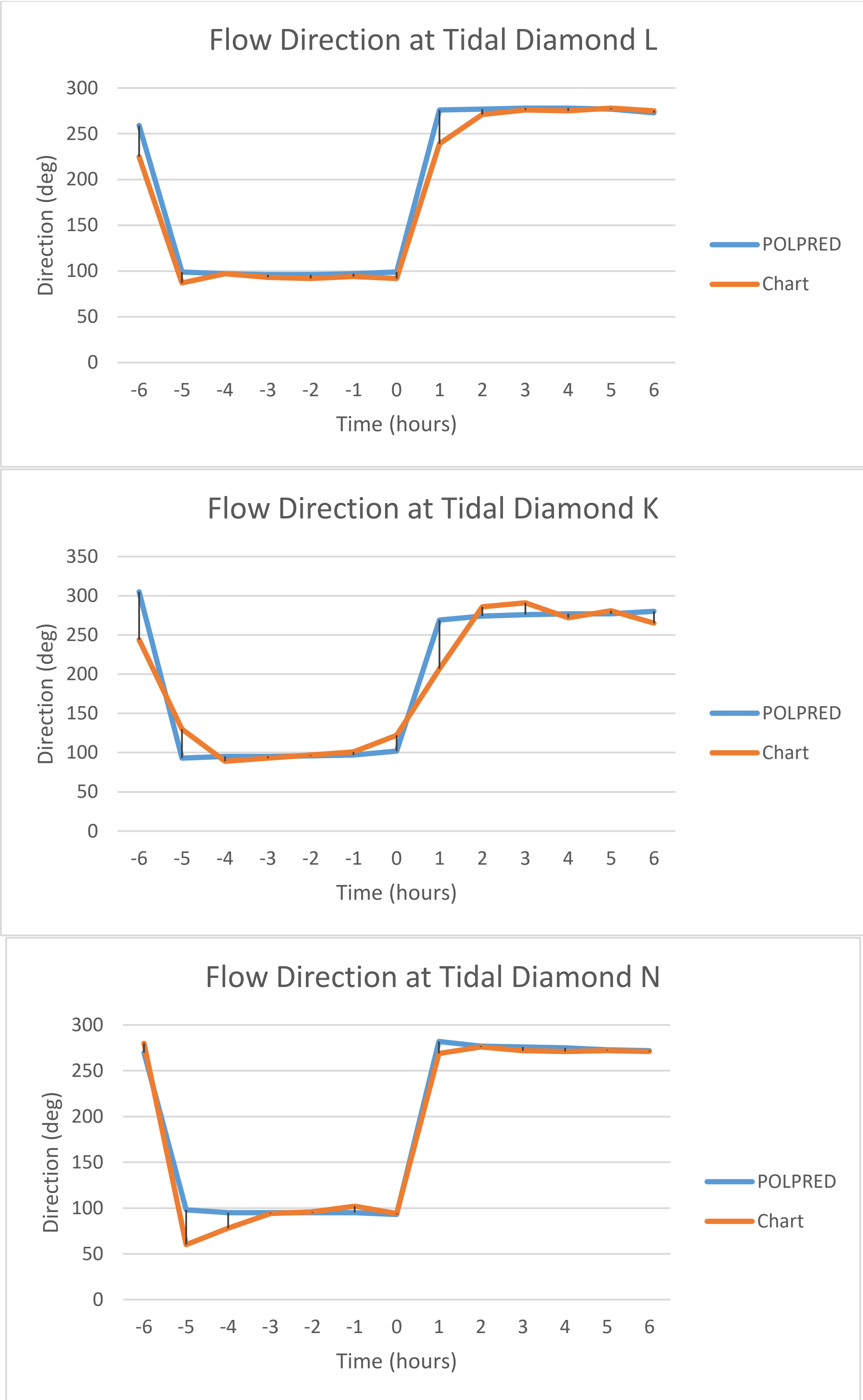


Figure 9-16: Validation of flow direction obtained from the POLPRED model against the Admiralty Chart data for sites; L (top), N (middle) and K (bottom)

9.3.5. **Power Calculation**

Owing to the specification of a fixed turbine, the power output is affected by the directional placement as previously identified. This meant that the power output of the device has to be calculated with respect to the optimal placement using the power equation (6-10) previously developed.

In order to determine the optimal position, the average power over the lunar period was determined with respect to this process. This was achieved by varying the angle of the turbine placement in increments of one degree to determine the power output over the lunar month at each of the potential 360 degrees of orientation. The maximum power determined was then used to specify the optimal direction of the turbine.

An example of this process is provided for site JG with the average power outputs generated shown in Figure 9-17 at varying device deployment angles. The optimal device placement is determined to be at 93 degrees, the point at which the maximum 32.359 kW is produced.

Additional analysis of the data from this process shows that the turbine reached rated power 9% of the time and was non-operational for 23% of the time. The remaining 68% is the time where the turbine is cutting in. This information was determined from the power generated at each time step for the specified 93-degree angle. By using the known number of time steps (42,464) and subtracting the number of occurrences of rated and non-operational power outputs, the time steps where the turbine was cutting in could be calculated. These results were then presented as a percentage of time spent operating in the defined power phases.

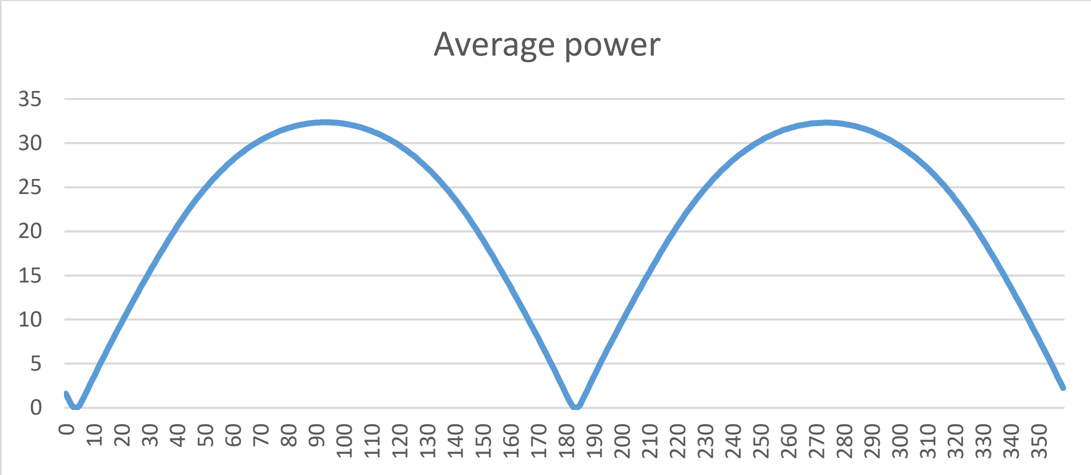


Figure 9-17: Average power output of the Nova M100 turbine at varying deployment angles at site JG

Figure 9-18 shows the average power produced at each site over the lunar month for the entire area under consideration. The optimal angle for the directional placement of each of these turbines is then detailed in Figure 9-19. Further results specifying the percentage of time that each of the optimally placed turbines spent operating in the different power phases (Rated, non-operational and cutting in) can be seen in Appendix F.1: Percentage of Time Spent at Rated Power (%), F.2: Percentage of Time Turbine is Non-Operational (%) and F.3: Percentage of Time Spent Cutting in (%)

4.63	4.56	4.76	5.22	5.86	5.35	4.91	5.71	6.59	6.32	6.22	6.80	6.56	6.36	7.02	7.47	8.31	8.16	7.44	9.48	13.31	10.51	7.88	5.68	6.17	4.33	1.20					
5.08	4.89	4.81	5.44	6.28	5.71	5.61	5.86	6.24	7.24	7.24	7.36	7.14	7.44	7.78	8.24	8.80	9.89	10.40	11.69	14.17	15.92	12.65	11.02	9.92	5.97	6.14					
5.47	5.68	5.29	5.74	6.25	6.00	6.22	6.59	6.91	7.40	7.93	8.33	8.39	8.58	9.09	8.95	9.27	11.21	11.21	14.07	18.55	18.44	15.26	14.23	13.93	15.21	20.42	14.66	10.35	2.95	0.39	
6.00	6.11	6.38	6.55	6.71	6.11	6.31	7.56	8.10	7.97	8.37	8.81	9.72	10.58	10.46	10.28	11.84	12.50	13.51	17.28	21.10	17.53	15.91	17.19	17.82	20.88	25.05	24.62	16.19	10.02	9.91	5.27
6.43	7.38	7.06	7.15	7.58	6.38	6.13	7.76	8.04	8.94	9.17	8.98	10.94	11.18	11.21	12.46	13.70	15.08	15.97	20.45	22.16	18.92	18.79	17.63	19.25	24.24	25.90	25.09	21.89	18.66	18.81	19.41
6.60	8.28	8.00	8.27	8.28	7.18	7.01	7.73	7.92	9.09	10.67	10.70	11.54	12.11	12.38	14.21	15.86	17.12	19.13	22.92	23.58	22.28	22.30	18.64	20.41	26.84	27.97	29.06	22.21	20.14	24.09	28.34
7.22	8.54	9.39	9.64	9.41	8.83	8.53	8.32	8.62	9.80	11.39	12.20	13.06	15.05	15.11	14.98	17.01	19.28	21.09	25.02	24.02	24.53	23.90	22.53	22.79	26.24	29.94	32.30	21.71	19.49	28.78	28.63
7.84	9.08	10.22	10.69	10.85	10.43	10.58	9.52	8.63	9.73	10.84	12.70	15.42	16.22	16.88	16.97	19.34	20.84	19.57	25.14	27.83	26.32	28.33	25.93	28.52	28.52	27.54	32.59	30.32	25.63	28.22	27.02
8.96	9.94	10.40	10.90	11.58	11.05	11.45	11.06	9.10	9.35	10.99	13.17	15.15	14.96	15.71	19.73	21.32	19.65	18.80	19.62	26.40	32.36	27.57	24.77	27.51	29.91	27.91	30.62	33.28	28.81	26.25	25.20
9.82	11.53	12.12	12.11	12.47	11.74	10.99	11.25	10.85	9.89	11.14	12.87	14.16	14.13	14.30	18.00	24.08	21.45	21.12	21.01	20.92	26.17	25.27	23.55	24.59	26.04	28.13	25.28	27.06	29.71	25.70	25.63
10.60	12.59	14.67	14.76	14.01	12.66	10.50	10.19	10.49	9.71	10.54	11.86	12.58	13.52	11.39	10.44	17.49	27.27	26.17	19.16	12.87	13.39	19.45	22.62	21.79	23.02	23.33	21.02	21.94	29.42	27.21	25.95
11.88	14.25	16.93	16.80	16.10	11.96	10.29	9.88	8.50	7.73	7.26	10.45	15.07	8.43	5.82	3.02	0.84			12.17	4.58	7.51	11.59	16.11	19.17	17.74	20.35	14.34	15.75	23.77	34.85	22.95
14.19	12.95	19.17	23.69	12.92	9.87	9.20	8.68	6.52	4.22	2.60	1.31														6.42						20.60
14.50	9.05	0.92																													
8.12																															

Figure 9-18: Average power in kW produced by the turbine over the Lunar month

83	83	83	83	85	87	87	89	89	88	92	95	96	99	101	100	101	103	109	113	108	104	103	109	122	317	133					
81	84	83	84	85	85	88	89	89	90	92	93	95	97	99	103	102	102	105	106	107	110	114	115	113	120	323					
81	81	82	86	87	87	87	89	92	91	89	92	94	97	99	99	102	103	104	106	109	109	108	109	109	112	117	299	276	266	293	
79	80	82	84	86	87	86	87	88	91	94	93	92	95	98	100	101	102	104	104	104	105	104	285	286	285	284	282	280	281	287	288
76	80	83	84	86	87	88	89	88	87	89	92	95	95	95	98	100	102	103	283	282	101	283	283	280	281	281	280	279	282	282	283
78	80	80	84	86	86	89	90	89	90	90	92	91	91	94	274	276	278	281	282	282	282	281	280	278	96	96	99	280	275	276	101
76	77	79	81	82	85	87	88	90	90	88	88	90	93	96	277	276	276	276	277	278	277	278	280	281	280	96	95	275	277	97	97
73	75	76	78	78	79	82	85	86	87	88	90	92	93	94	96	279	279	275	270	91	274	97	279	102	102	99	93	94	280	99	94
72	74	76	77	77	78	79	79	83	85	87	89	90	90	88	89	271	93	277	277	271	93	99	277	96	97	102	103	98	95	95	275
70	72	76	77	79	82	80	80	83	86	88	87	85	84	85	85	266	90	275	281	286	274	268	274	279	279	98	279	99	100	281	282
68	70	72	76	78	82	84	87	87	85	84	83	82	85	84	79	72	82	282	112	287	103	97	273	273	275	278	276	276	98	103	287
70	68	72	76	81	84	84	86	86	85	79	73	83	88	85	270	237			113	99	96	94	272	271	273	274	276	274	274	102	293
63	63	67	80	89	88	89	90	88	85	88	235														273						293
52	71	236																													
31																															

Figure 9-19: Optimal directional placement of the turbine specified in degrees, with green denoting an Easterly direction and yellow a Westerly direction.

9.3.6. **Finance**

Unfortunately, due to the commercial sensitivity of the data, no financial information is provided publicly for the costings of the turbine or cable. As a result of this, a number of assumptions had to be made regarding the expected costs of a TSG. These assumptions are made with respect to the exclusion of inflation from the analysis. Hence, these values are specified in 2012 prices, in line with the 2012 prices specified in the contract of difference for the sale of any generated power (Crown, 2018). The assumed values can be seen in Table 9-6.

Table 9-6: Assumed device expenditures

Expenditure	Cost in 2012 prices (£)	Variables
Initial device cost	£250,000	Idc
Decommission cost	£50,000	Dc
Maintenance cost	£25,000	Mc
Cable cost	£10,000	Cc

In addition to these assumptions the following additional financial elements were determined from literature and the specification of the turbine;

- Fuel cost 400$ per T (£0.32 per kg) (Ship & Bunker, 2018)
- Strike price £305/MWh (£0.305 per kWh) (Crown, 2018)
- The number of maintenance visits was specified by Nova to be four over the 20 - year lifespan of the device. As a result of this, maintenance, trips will take place every four years (Nova Innovation Ltd, 2019).

Using site JN as an example, the net profits can be calculated using the previously developed formulas for the profits and expenditures (detailed in section 6.8.1. and 6.8.2.). These equations require the values for the average power and grid cable connection distance previously determined during earlier stages of the TFS (33.276kW and 10km respectively). In addition, it is assumed that the maintenance downtime (Dt) is 14 days. Using these figures, the following calculations can be performed.

Profits

$$AVp \times Sp \times ((8760 \times Ls) - (Dt \times 24 \times Mv)) \quad \textit{(9-2)}$$

$$33.276 \times 0.305 \times \left((8760 \times 20) - (14 \times 24 \times 4)\right) = £1{,}764{,}495$$

Expenditures

$$(F_{con} \times Fc) + \left(Grid_{to_{site}} \times Cc\right) + Idc + Dc + (Mc \times Mv) \quad \textit{(9-3)}$$

$$(33{,}708 \times 0.316) + (10 \times 10{,}000) + 250{,}000 + 50{,}000 + (25{,}000 \times 4)$$

$$= £510{,}651$$

It should be noted that the values for the Fuel consumptions (F_{con}) come from the calculations during the LCA modelling. These calculations are detailed in the GaBi modelling process in subsection 9.4.5.

In this particular example, the net profits of a turbine located at site JN will be £1,253,844. This process was carried out for all of the sites identified and used as the metric in the final stage of the combination tool.

In addition to the net profits, both the payback period and cost of energy were calculated at this stage. The results for these studies can be found in the overview document presented in Appendix I - Combination Tool Overview, which details the results for the top 10 sites identified. These calculations were used to provide additional information regarding the financial elements of the project. However, they are not fundamental to the methodology, as the decision-making element focuses on the net profits.

9.4. LCA

The following subsection details the extent of the LCA study carried out for each of the sites at which the Nova M100 turbine will be deployed. This process follows the structure defined in Chapter 7.

9.4.1. Goal and Scope

The goal and scope of the LCA analysis have previously been outlined and defined in subchapter 7.3. However, owing to the iterative process of the LCA methodology, where data is allowed to inform decisions made in other key stages, the following additional assumptions had to be made. These additions are detailed during the subsequent subsections. However, in keeping with the methodology, are listed as follows.

- The generator housed in the TSG nacelle was omitted from the analysis due to a lack of available data.
- A number of assumptions were made regarding the operation of the deployment and maintenance ship. These assumptions were based on the specification of the vessel and are clearly stated and justified in subchapter 9.4.4. Distance Data, under the subsection heading Voe Earl.
- Only secondary data was sourced from literature and other methods due to the lack of available primary data.

- The Nova M100 turbine is a modular device; hence it would be possible to conduct a Gate to Gate analysis to determine the impact of site selection. This is based on the assumption that the manufacturing of the device would be independent of the site selection process. However, it should be noted that this would require initial information regarding the environmental impact of the manufacturing that was not available. As a result, a Cradle to Grave analysis was carried out.

9.4.2. Inventory Analysis

The following subsections define the inventory analysis for LCA of the Nova M100. Initially, the Device data requirements are discussed and defined before the parameters affected by the site selection process are detailed. Finally, an overview of the key life cycle stages of the model is provided in the form of images from the GaBi software, alongside key equations which are defined with respect to the specified parameters.

9.4.3. Device Data

In order to generate an accurate LCA model, specific device data has to be obtained for the Nova M100 turbine. Unfortunately, the turbine development company Nova Innovations were not able to provide this information. In order to inform decisions and help generate realistic assumptions for the LCA model, a Computer Automated Design (CAD) model of the M100 was generated in SolidWorks. This model was generated using images of the device alongside information provided from the technical specifications of the device. The model can be seen in Figure 9-20 alongside a conceptual image of the turbine for comparison.

The development of the CAD model helped define individual key components in the turbine, namely the Front Block, Back Blocks, T-Base, Feet, Concrete Holders, Front Pillar, Back Pillars, Turbine Holder, Turbine Nacelle, Rotor hub and Turbine Blades. These components are identified in Figure 9-21 and further detailed in Table 9-7.

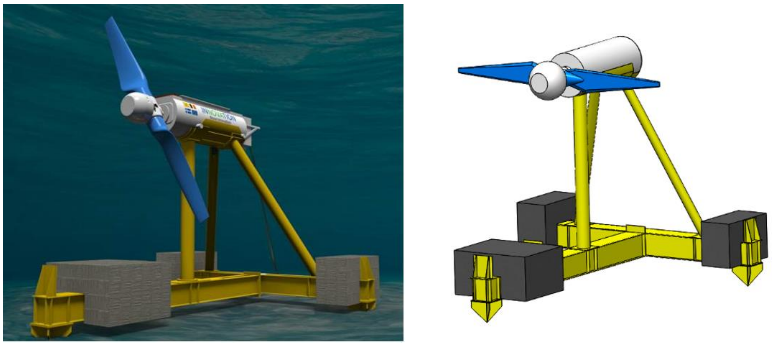


Figure 9-20: Nova M100 turbine (Nova Innovation Ltd, 2019) alongside Solid Works CAD Model

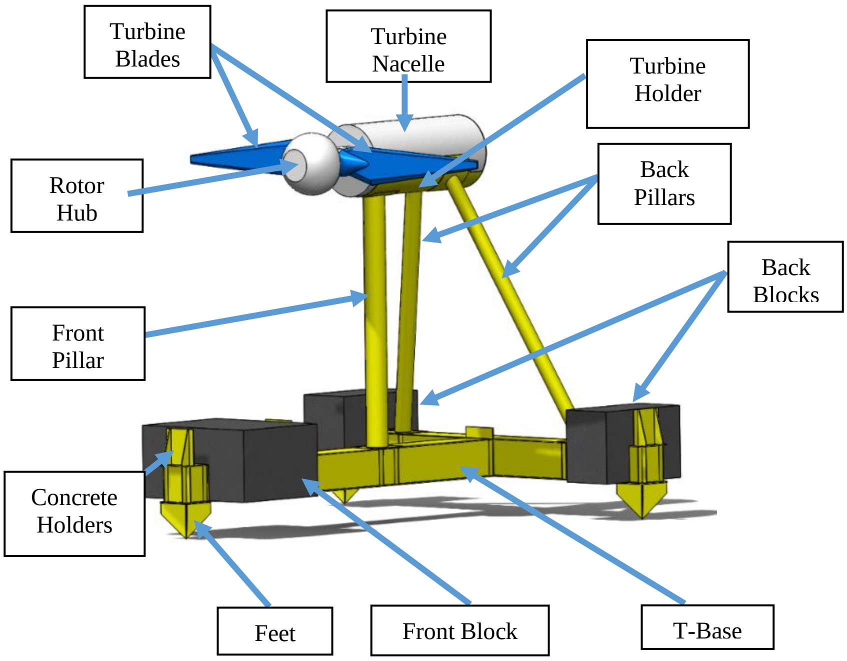


Figure 9-21: Key Turbine components

It should be noted that all of the steel components in the CAD model were assumed to be cut from a ¾ inch steel plate (19.05mm). This is a standardised size for a steel plate and is readily available. This had the added benefit of being under the maximum 20mm sheet thickness defined in GaBi for the generic sheet steel manufacturing process.

Owing to the difficulty in obtaining data for the device, the generator, which would normally sit inside the nacelle, was omitted from the LCA study at this point. This decision was made due to the lack of information regarding the component and the assumption that it would be manufactured off-site. As a result of this, the initial goal and scope of the LCA were updated to include this assumption.

It is later determined in the

CAD Validation section that this assumption results in a reduction of material mass of 6.009t. Approximately 7.5% of the wet weight of the turbine. Whilst this will have an impact on the overall LCA results of the turbine because it is a common component, it will not affect the findings with regards to the site selection process.

Material Mass and Surface Area

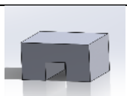
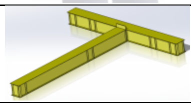
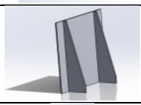
The individual models of each of the components provided detailed information. This data included the surface area and volume, which could be used to calculate the mass of material in each component. This was determined using the relationship between mass, density and volume, and was used to define values in GaBi.

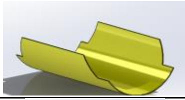
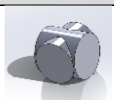
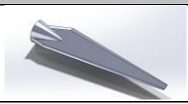
$$Mass\ (kg) = \frac{Density\ (\frac{kg}{m^3})}{Volume\ (m^3)} \qquad (9\text{-}4)$$

Three main materials were identified in the device: Concrete with a density of 2400kg/m^3– used to add mass to the turbine in the form of the front and back block, steel with a density of 7750kg/m^3 – used in the supporting structure of the device and drive hub and, fibreglass, with a density of 3.5 kg/m^3 – used in the blades and rotor hub cover.

The results of the mass calculations can be viewed in Table 9-7. These results established the finished mass of each of the components after manufacturing. In the case where there were mixed materials such as the rotor hub, these were broken down into separate sub-components. The mass of each individual component is calculated and combined to define the mass of the component. This data is used in conjunction with the parameters developed in the generic LCA model to specify the output weight of specific components. In addition, the total mass of the device was calculated by summing all the component masses and specified as 116,591.05kg (116.59 metric tonnes).

Table 9-7: Breakdown of turbine components detailing total mass and volume of components

			Total		
Main Components Name	Image	Number of components	Volume (m^3)	Material density (kg/m^3)	Mass (kg)
Front block		1	19.35	2400	46440.0
Back block		2	14.55	2400	34920.0
T Section		1	2.01	7750	15579.3
Feet		3	0.16	7750	1263.4
Concrete holders		4	0.11	7750	812.0
Front pillar		1	0.29	7750	2255.7
Back pillars		2	0.22	7750	1739.2

Turbine holder		1	0.23	7750	1788.5
Turbine nacelle		1	0.75	7750	5823.8
Rotor Hub		1			3474.5
Drive hub		1	0.45	7750	
Composite cover		1	2.21	3.5	
Blades		2			784.7
Composite part		0.9	0.92	3.5	
Steel reinforced component	Internal component	0.1	0.1	7750	

Manufacturing process

The development of the CAD model also helped to determine the details of specific manufacturing processes that would be required to construct individual components. This is illustrated in the case of the concrete holder.

The concrete block holder is a steel component that ensures that the concrete blocks sit on the base section correctly and restrict them from shifting in strong tidal currents. The CAD model for the concrete holder can be observed in Figure 9-22. The figure clearly shows that the component is assembled from three key parts, identified in separate colours. In order to manufacture the part, the individual components will have to be cut from a steel plate before being welded together to form the component. The surface will then have to be prepped for painting using sandblasting to clean the surface before a coat of paint is applied to finish the component and protect it from the saltwater.

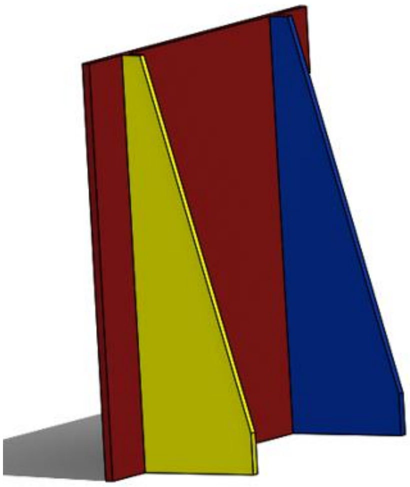


Figure 9-22: Concrete holder CAD model

Using the CAD drawing files, specific information can be gathered. This includes information such as the length of cut required to manufacture the component. This can be visualised in Figure 9-23, which shows how the three components could be cut out of one sheet of material. In addition to this, the length of the welds required to secure the components together can be measured. All of this information is important as it feeds into the Generic LCA process previously developed and used to conduct a realistic assessment for the device. Additional information determined for each of the steel components is displayed in Table 9-8.

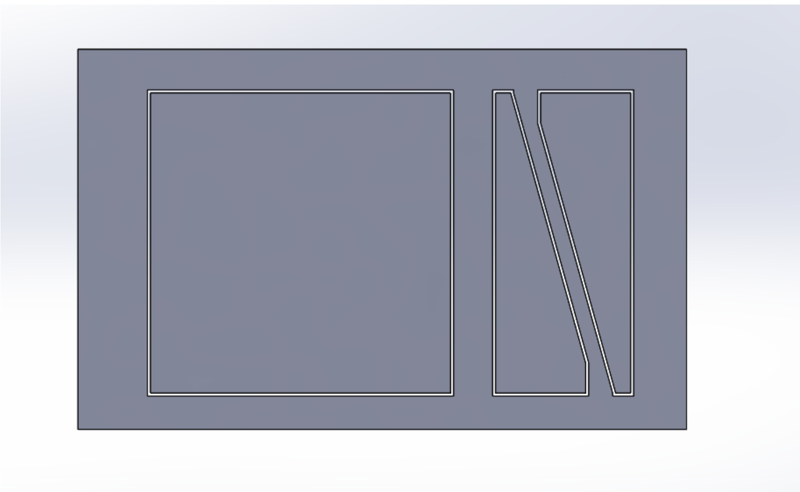
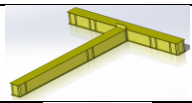
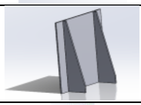
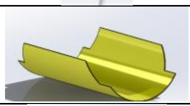


Figure 9-23: Visualisation of cutting the concrete holders out of a Steel sheet

Table 9-8: Steel component manufacturing information

Main Components Name	Image	Number	Cutting length (m)	Welding length (m)	Surface area (m^2)	Bending
T Section		1	304.7	300.4	209.7	No
Leg		3	15.8	9.5	5.7	No
Concrete holders		4	8.8	4	2.84	No
Front pillar		1	8.2	3.7	29.6	No
Back pillars		2	8.3	3.6	24.8	no
Turbine holder		1	15.9	0	24.5	Yes
Turbine nacelle		1	16.3	12.3	62.2	Yes

CAD Validation

In order to validate the CAD model of the turbine, the total mass of the turbine excluding the generator was calculated to be 116.59t. The specifications for the turbine do not provide a dry weight for the device. However, a wet weight of 80t is specified. This is the weight of the device when immersed in water (Nova innovation Ltd, 2017). This meant that a direct comparison of weight could be made by calculating the wet weight of the CAD turbine, using the Archimedes principle.

$$wet\ weight = weight - weight\ of\ fluid\ displaced \qquad (9\text{-}5)$$

$$\gamma_w = \gamma_o - (\rho \times V)$$

Where V is the volume of 41.56m^{3,} obtained from the CAD model, and ρ is the density of seawater as 1025kg/m^3 the calculated wet weight (γ_w) of the CAD turbine is 73.991t.

This is relatively close to the specified 80t. The missing 6.009T could be attributed to the generator, which normally sits inside of the nacelle, but was omitted from the study. As a result of this calculation, it was concluded that the CAD model provided a realistic estimate for the mass of the specified components and the manufacturing methods validating its use in the LCA.

9.4.4. **Distance Data**

The distance data determined during the TFS in Section 9.3.2 affects a number of components of the LCA, namely the cable and ship operations. As a result of this, they are discussed further in the following subsections. An example of the distance data previously generated during the TFS for site JN can be seen in Table 9-9.

Table 9-9: Examples of distance parameters defined in GaBi for site JN

Distance parameters	Distance (m)
Harb_to_Cable	44,600
Harb_to_Site	39,600
Cable_to_Site	10,000

Voe Earl

The Voe Earl is the multi-cat offshore service vessel that was chosen as the transportation vessel for deploying, maintaining and grid connecting the turbines at each site. The Voe Earl has previously been used for the deployment of the Nova

M100 in the Bluemull Sound, making it a logical choice (The Shetland Times Ltd, 2016). For reference, the vessel can be seen in Figure 9-24.

Figure 9-24: The Voe Earl (Offshore WIND, 2016)

Extracts from the specification of the ship (Delta Marine, 2012), engine (Caterpiller, 2009) and generator (Caterpillar, 2007) can be found in Appendix H - Voe Earl - Fuel Consumption Specifications. These documents provided specific information regarding the speed and fuel consumption of the vessel. The appropriate findings from these specifications were then parameterised and are detailed in Table 9-10. It should be noted that the following assumptions were made for different operational phases of the ship based on the information specified.

- It is assumed that one generator is always running during normal transit to power machinery aboard the vessel. This was due to there being no capacity for the ship to generate power from the main engines. A second generator is used to provide power when performing activities such as cable laying or deploying the turbine.

- Cruising speed (19.6km/h) is achieved when both main engines are running. Each engine consumed 376.5L/h of fuel. In addition to this, one generator will be running to provide power to the ship consuming 24.6L/h.
- Laying cable speed (10km/h), both main engines are assumed to be running at reduced power consuming 200L/h each, in addition to this, both generators are running consuming 24.6L/h each.
- Time on site (stationary), both engines are running at reduced power consuming 100L/h to hold the ship on site. It is assumed that both generators are running to power machinery to deploy turbine consuming 24.6L/h each.

Table 9-10: Ship specific parameters defined in GaBi

Parameter	value	notes
Cable_laying_speed	10,000	Ship cable laying speed (m/h)
Cable_fuel_con	200	Ship cable generator fuel consumption rate (L)
Generator_num	2	The number of generators on the ship
Generator_fuel_con	24.6	Ship generator fuel consumption (L)
Main_vist	4	Number of maintenance visits (#)
T_on_main	0.5	Time on site per maintenance visit (h)
Speed	19,600	Ship speed (meters per hour)
Fuel_Rate	376.5	Main engine fuel consumption rate (L)
Num_engins	2	Number of main engines (#)
Onsite_fuel_con	100	Ship main engine fuel consumption on site (L)
F_density	1.194	Fuel volume to mass ratio (L to kg)

Using the parameters defined, the fuel consumption at each stage can be calculated. This is further discussed in subsection 9.4.5 GaBi Modelling, where the fuel consumption is detailed in the GaBi model, during the varying stages of the device life cycle.

Cable

The Nova M100 turbines that are currently deployed are served by a dedicated, independent subsea cable (GREBE, 2017). However, no information was provided regarding the sizing of the cable used. As a result of this and other difficulties sourcing information regarding the cables, the cable manufacturing process was parameterised, allowing the user to define specific elements. This would then allow for the calculation of the material used to manufacture the cable. In order to achieve this, it was assumed that the materials used in the cable would be the same as others specified in the literature. With respect to this, the cable was designated as a three-phase power cable consisting of three copper cores wrapped in an outer protection system (Walker, Howell, Hodgson, & Griffin, 2013). The material make-up of the cable can be seen in Figure 9-25.

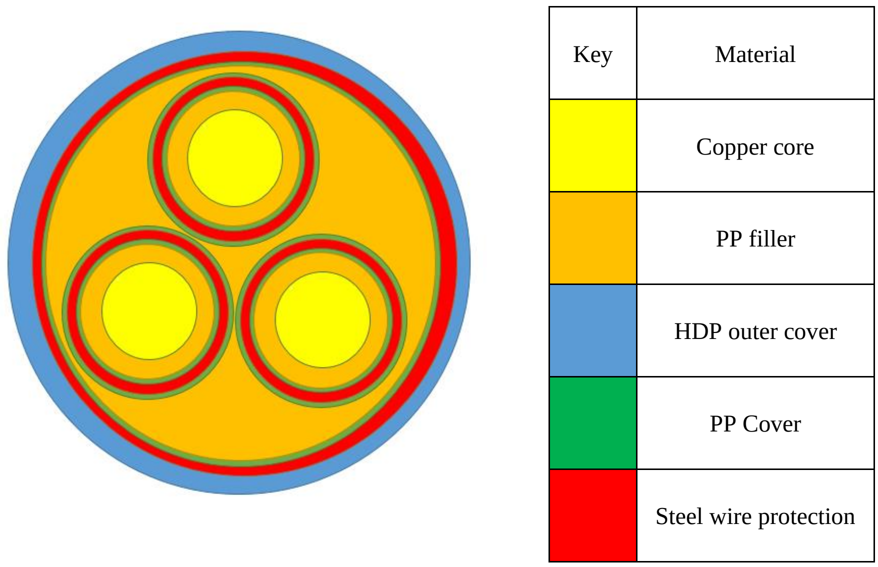


Figure 9-25: Cross-section of the specified materials in the cable

As previously mentioned in order to determine the mass of materials in the cable, the cross-sectional area of each component has to be defined by the user with respect to their diameters. It should be noted that the outer diameter defined for a material informs the inner diameter of the next material out from the centre. This can then be used to calculate the area of the material.

The cable can be split into two parts, the internal three cores, and the outer cable protection system. The total mass of the cable can be calculated based on the mass of the individual materials. The area of each of the internal three cables is calculated in Table 9-11 and the external protection system in Table 9-12. It should be noted that the area of the internal pp filler is the outer diameter area minus the combined area of the three internal cables (763.407mm) which also occupy this space.

Table 9-11: Area of inner cable components

	Diameters in mm		Areas (mm2)		The total area of cable sections	
	inner	outer	inner	outer		
Copper	0	11	0	95.03318	95.03318	mm2
pp filler	11	14	95.03318	153.938	58.90486	mm2
pp cover	14	15	153.938	176.7146	22.77655	mm2
steel	15	17	176.7146	226.9801	50.26548	mm2
pp cover	17	18	226.9801	254.469	27.48894	mm2

Table 9-12: Area of the external protection system

	diameters in mm		areas (mm2)		the total area of cable sections	
	inner	outer	inner	outer		
PP filler	0	41	0	1320.254	556.8473	mm2
PP cover	41	42	1320.254	1385.442	65.18805	mm2
steel	42	44	1385.442	1520.531	135.0885	mm2
HDPE outer	44	48	1520.531	1809.557	289.0265	mm2

The total mass of the cable can now be calculated per metre of the cable by using the density of each of the materials in conjunction with the volume calculated. To achieve this, the area is converted from mm^2 to m^2 and then multiplied by the length of the cable that was calculated for the distance between the Grid connection point and the

Site; this is defined in the parameter "Cable to site". Table 9-13 shows the resulting calculations per metre of cable. In total, the combined mass of the cable is defined as 5.582kg per meter. This calculation is automated within the GaBi model using the defined parameters.

Table 9-13: Mass of material per meter of cable

	mm2	m2	density (kg/m3)	Mass per meter of cable (kg/m)
PP filler	733.5619	0.000734	860	0.630863221
PP cover	147.6549	0.000148	860	0.126983175
Steel	285.8849	0.000286	7000	2.00119452
HDPE outer	289.0265	0.000289	930	0.268794667
Copper	285.0995	0.000285	8960	2.554491818

9.4.5. GaBi Modelling

With the completion of the data gathering, the appropriate parameters were defined within the generic model. The following subsections detail the GaBi model, initially providing an overview LCA plan before delving into each of the elements identified to display the model further. The following images are all screenshots from GaBi and depict material flows between processes and plans.

Overview

The overview plan, seen in Figure 9-26, identifies the four key stages of the turbine life cycle; namely the Manufacturing, Installation, Operation & Maintenance and End of life of the turbine. This effectively details the mass flow of the turbine between these stages with each of the sub-plans being defined with additional information.

Figure 9-26: Top plan of the LCA process modelled in GaBi

Manufacturing

The first stage of the turbine life cycle is manufacturing. This plan, which can be seen in Figure 9-27, details the manufacturing and assembly of the turbine. In total, nine major components were identified and defined within the model as sub-plans. It should be noted in situations such as the Leg; the turbine assembly requires three components. Hence the mass flow between the leg manufacturing and turbine assembly accounts for the combined mass of these three 421kg components.

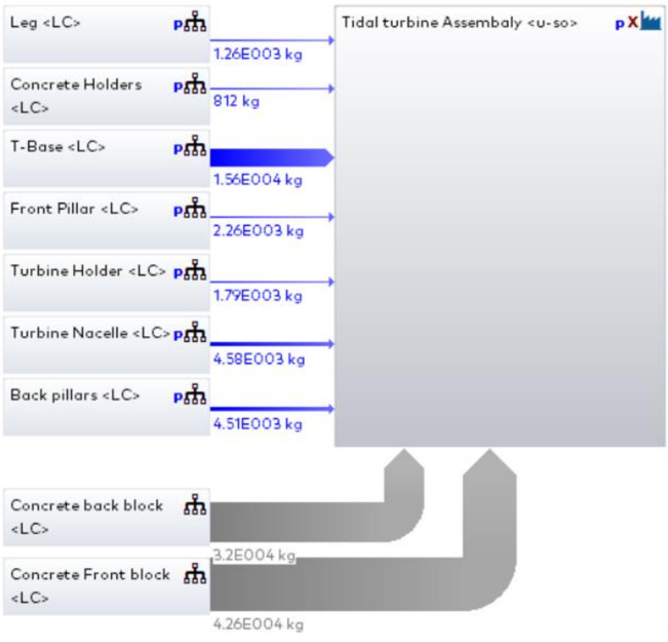


Figure 9-27: Manufacturing Sub-Plan

Each of the components manufactured is defined in more detail in additional sub-plans. This is demonstrated in Figure 9-28, which shows the sub-plan for the manufacturing process of the turbine Leg, from plate steel to finished component.

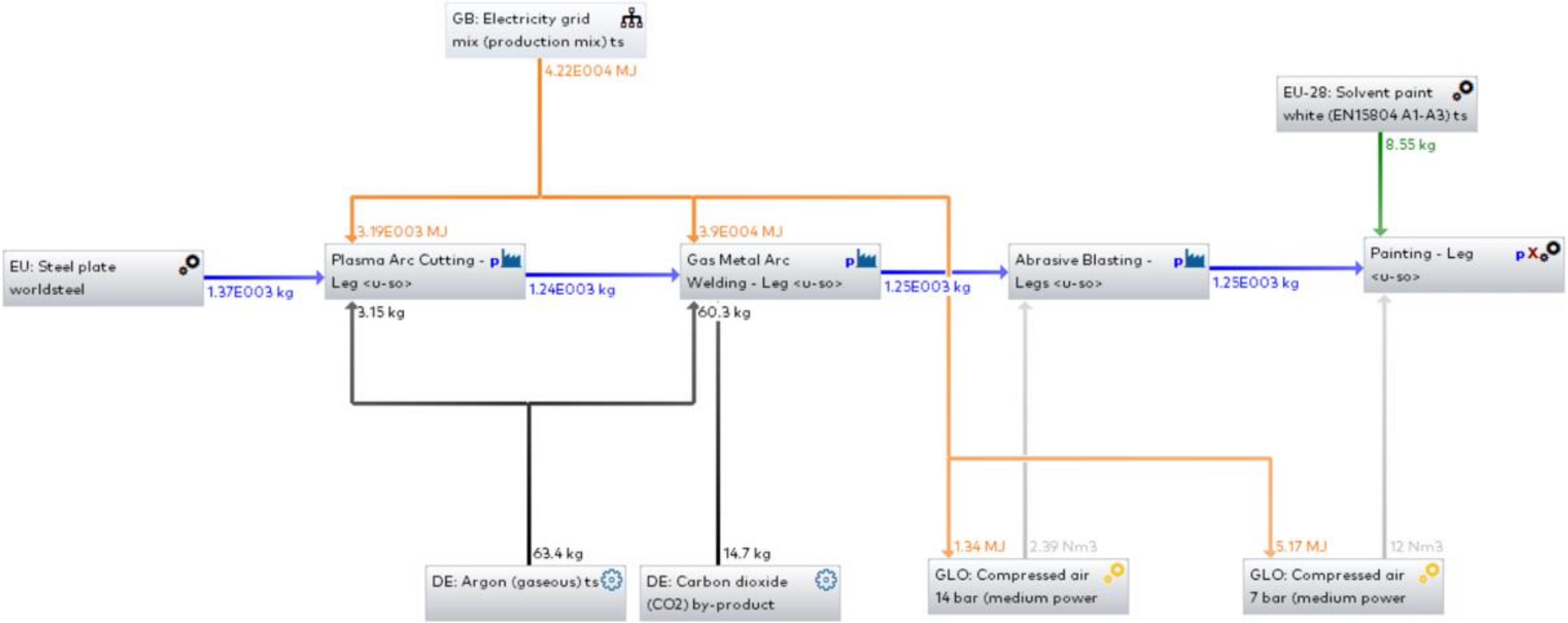


Figure 9-28: Leg manufacturing process sub-plan

Installation Phase

The second phase of the turbine's life cycle is the installation phase. This can be seen in Figure 9-29, which shows the deployment of the turbine and cable. In addition, it should be noted that the manufacturing of the cable is defined at this stage in a sub-plan. Both of these elements are linked to the distance data generated during the TFS. As a result, the mass flows for the fuel and cable are affected by the specification of a site.

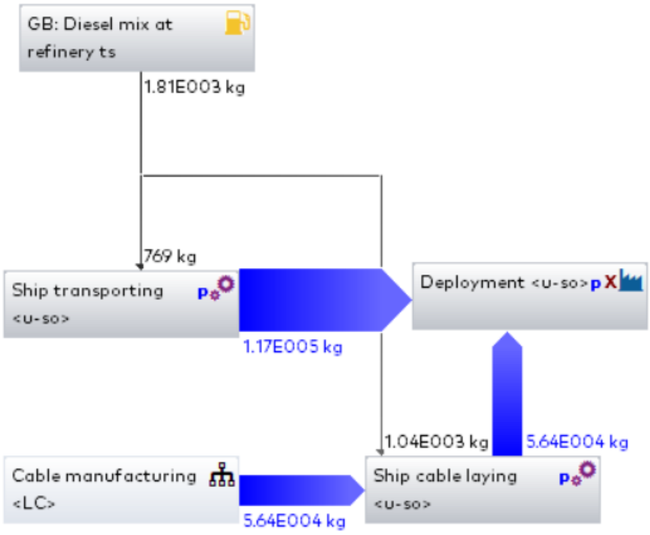


Figure 9-29: Turbine installation plan

The fuel consumed during this process is calculated using the following parameterised equations, with respect to the parameters previously defined in Table 9-10.

$$\left(\frac{\left(\mathrm{fuel}_{\mathrm{con}_{\mathrm{transport}}} + \mathrm{fuel}_{\mathrm{con}_{\mathrm{onsite}}}\right)}{\mathrm{Ship.\,F}_{\mathrm{density}}}\right) \qquad (9\text{-}6)$$

The following equations define the fuel consumption of transporting the device to the site (Fuel_con_Transp) and the time spent on site (Fuel_con_onsite).

$$\text{fuel\_con\_transp} = \left(\left(\frac{dis.\text{Harb}_{\text{to}_{\text{site}}}}{\text{Ship.Speed}}\right) \times \left(\left(\text{Ship.num}_{\text{engines}} \times \text{Ship.Fuel}_{\text{Rate}}\right) + \text{Ship.generator}_{\text{fuel}_{\text{con}}}\right) \times 2\right) \quad (9\text{-}7)$$

$$\text{fuel\_con\_onsite} = \left(\text{Ship.onsite}_{\text{fuel}_{\text{con}}} \times \text{Ship.time}_{\text{on}_{\text{site}}} \times \text{Ship.num}_{\text{engines}}\right) + \left(\text{Ship.generator}_{\text{num}} \times \text{Ship.generator}_{\text{fuel}} \times \text{Ship.time}_{\text{on}_{\text{site}}}\right) \quad (9\text{-}8)$$

Note that the parameter, Fuel_con_transp, is multiplied by two. This is to account for the ship having to make a return journey when travelling to and from the site.

Operation and Maintenance Phase

The operation and maintenance plan defines the operational phases of the turbine and can be seen in Figure 9-30. It should be noted that normally the Nova M100 turbine's modular design allows the nacelle and turbine blades to be lifted off and removed from the base of the structure. However, owing to the way that the component was defined in GaBi, it was assumed that the whole device was removed which is depicted by the mass flow value of 116.5T (displayed as 1.17E005kg). Despite this, it was assumed that maintenance would only be carried out on the nacelle section; this involved sanding and repainting the steel components. Due to the omission of the generator, no additional maintenance activities could be specified.

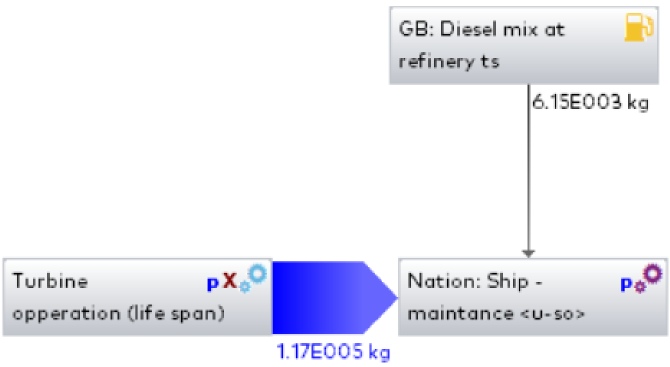


Figure 9-30: Operation and maintenance plan

The total fuel consumption during this stage is defined using the following equations

$$Total_{F_{Con}} = ((\mathrm{F_{To}} + \mathrm{F_{on}} + \mathrm{F_{back}}) \times \mathrm{num_{visit}})/\mathrm{Ship.F_{density}} \quad (9\text{-}9)$$

Where the following equations are used

$$num_{vist} = T_C.main_{Vist} \times 2 \quad (9\text{-}10)$$

$$F_{To} = \left(\frac{dis.Harb_{to_{site}}}{Ship.Speed}\right) \times \left(\left(Ship.num_{engins} \times Ship.Fuel_{Rate}\right) + Ship.generator_{fule_{con}}\right) \quad (9\text{-}11)$$

$$F_{back} = F_{To} \quad (9\text{-}12)$$

$$F_{on} = (\mathrm{Ship.onsite\_fuel_{con}} \times \mathrm{Ship.num_{engines}} \times \mathrm{T\_C.T\_on_{main}}) + \quad (9\text{-}13)$$

$$(\mathrm{T\_C.T\_on_{main}} \times \mathrm{Ship.generator_{num}} \times \mathrm{Ship.generator\_fuel_{con}})$$

Again, note that the fuel consumption accounts for the number of maintenance visits multiplied by 2 in the equation num_vist. This is to account for the ship having to sail to the site to originally pick up and return the turbine to port before taking it back at the end of the maintenance visit to reinstall it at the site.

End of Life Phase

The final stage is the end of life of the turbine. It is assumed that both the turbine and cable are recovered in keeping with typical UK procedures for removing devices at the end of seabed licensing agreements. Upon recovery, it was assumed that 80% of the mass of both the turbine and the cable were recyclable with the remaining 20% going to waste landfill. The end of life plan can be seen in Figure 9-31.

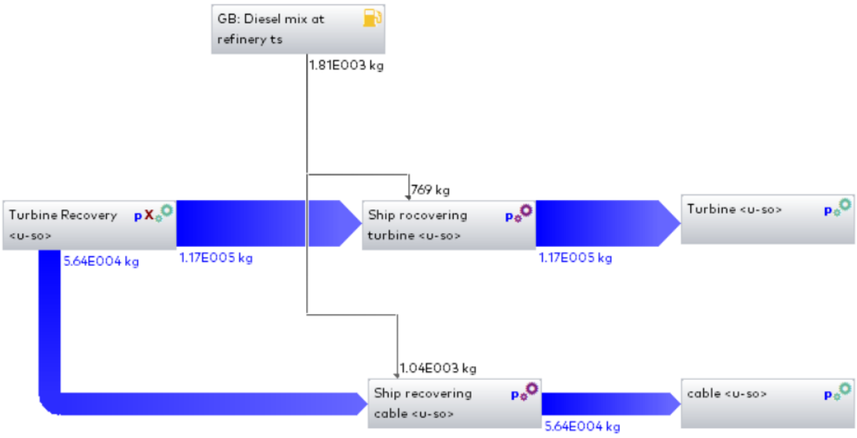


Figure 9-31: Turbine end of life phase

It should be noted that the fuel consumption at this stage is assumed to be the same as the installation phase. This is owing to the recovery of the turbine and the cable being carried out in a similar method to its deployment. As a result, the same equations for fuel consumption are used.

9.4.6. **Parameters**

In total, there are 103 parameters defined within the GaBi model, allowing the user to tailor the generic model specifically. A full list of parameters can be seen in Appendix G - GaBi Parameters.

Owing to the lack of primary data, the parameters for the generic manufacturing processes were defined from literature. This includes machinery specifications and research papers. The full list of the parameters defined and their values are provided in Appendix G – GaBi Parameters. However, the following summarises the key parameters defined alongside references to the literature:

Bending – It was assumed that steel that required bending during the manufacturing process was bent using a Haeusler plate bender. This machine is capable of cold rolling steel plates up to 60mm thick. This was well within the specified 19.05mm steel plates used in the manufacturing of the turbine (Mach4Metal, 2018). The information parameterised from this document included the speed of bending and machinery power consumption.

Blasting – The blasting process required both the blasting material usage and air pressure required to be defined. This information was provided by a technical document produced by the Society for Protective Coatings (SSPC, 2018).

Welding – The article "Environmental and Social Life Cycle Assessment of Welding Technologies" provided information on the Gas Metal Arc Welding process. This included the following information; weld speed, shield gas flow rates, shield gas composition, number of passes required, material added and electricity usage (Ya-JuChang, et al., 2015).

Cutting – No specific literature could be found referencing steel cutting processes; however, the paper "Environmental Impact of Ship Hull Repair" defined the process of plasma arc cutting. This is required during the removal of old sections of the ship hull before repairs can start. The paper provided the following information regarding the plasma arc cutting process including, energy consumption, cutting speed, Argon shield gas flow rates and thermal energy released.

A number of the manufacturing processes required the use of a shielding gas consisting of Argon or a mixture of Argon and Carbon dioxide (CO_2). The flow rate of the shield gas was typically listed as a flow rate of m^3. In order to calculate the mass flow rate of the gasses, the density of each of the gasses had to be defined as the following; argon as 1.784kg/m^3 and CO_2 as 1.977kg/m^3 (Engineering ToolBox, 2003). This allowed the mass of the gases to be calculated by multiplying the volume by the density.

9.4.7. **Impact Assessment**

During the impact assessment, the inventory analysis model is analysed and results attributed to their impact categories. This process is automated within the GaBi software. However, the results need to be weighed with respect to a characterisation factor. There are a number of different characterisation factors that can be applied; however, in this case, CML was chosen.

CML2001 - Jan. 2016, Global Warming Potential (GWP 100 years) excluding Bio C02, was applied to the analysis. CML was developed by the Institute of Environmental Science at the Leiden University in the Netherlands. It is world-renowned and was last updated in September 2016 (CML - Department of Industrial Ecology, 2016) (Thinkstep, 2016).

Figure 9-32 shows the raw data results generated in GaBi for site JG with respect to the four identified life cycle stages. These results are with respect to the positioning of site JG, and hence the following parameters have been defined; Cable_to_Site of 10.9km, Harb_to_Cable as18.8km and Harb_to_site as 28.3km.

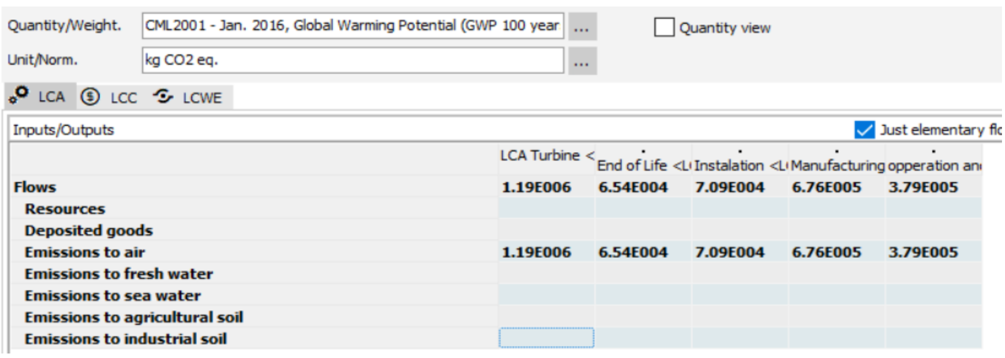


Figure 9-32: GaBi data results for site JG

Table 9-14: Emissions during each of the key life cycle stages of Site JG

Stage	Emissions (T CO2eq)
Manufacturing	676.17
Installation	70.86
Operation	378.55
End of life	65.37

In total, the emissions produced at site JG account for 1190.95T CO2eq over the lifetime of the turbine with emissions coming from each of the four key stages identified in Table 9-14. Using this information, the results can be depicted in a chart. This identifies the contribution of the key life cycle stages to the emissions of the device. The results of this can be seen in Figure 9-33, which identifies that a significant portion of the emissions occurs during the manufacturing and operational phases of the turbines life cycle. Further analysis of the results identifies a number of key resource flows and processes that attribute directly to these findings. These can be seen in Figure 9-34.

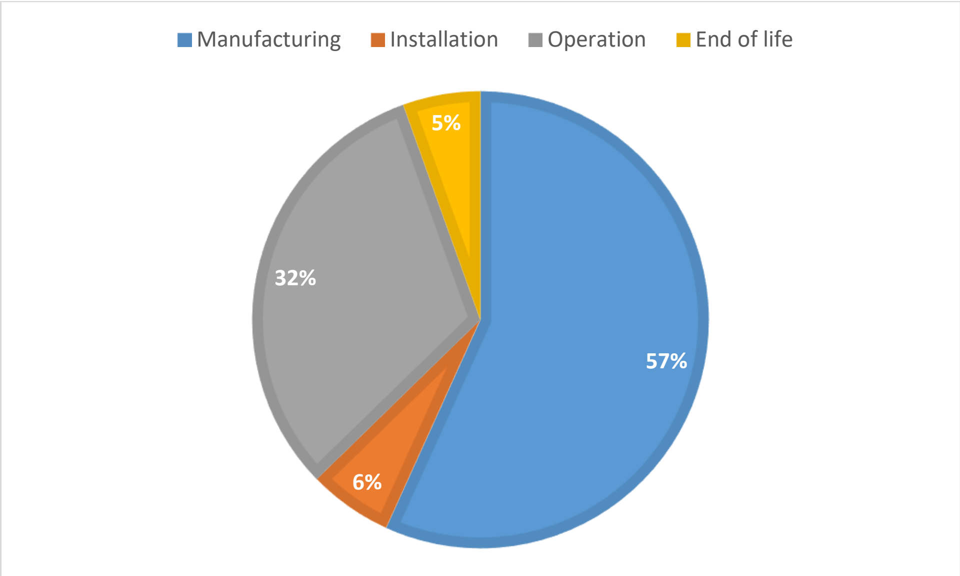


Figure 9-33: Percentage of the total emissions during key life cycle stages.

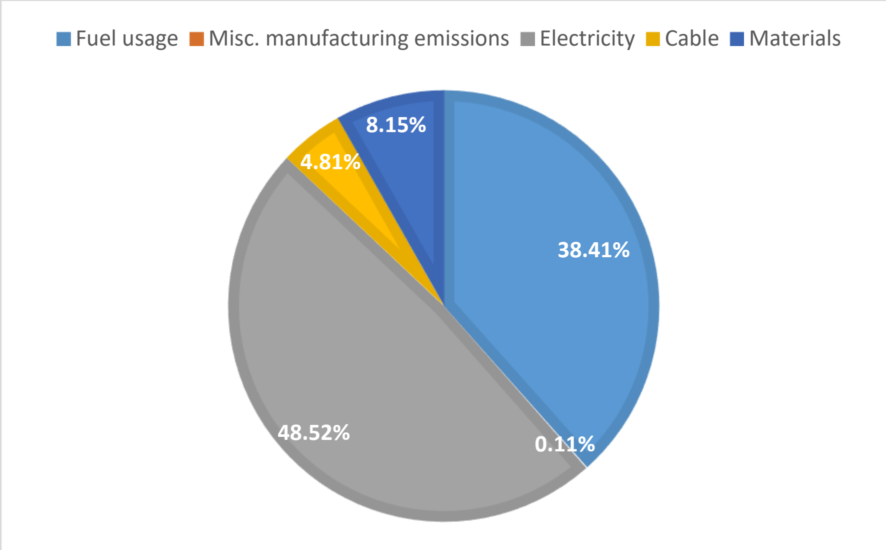


Figure 9-34: Percentage of emissions contribution from key processes

The information provided in the figures can be used to identify environmental hotspots, such as the manufacturing and operational phases for the device. These can be traced to individual elements such as in the operation phases, where 23t of fuel are used to power the support vessel servicing the site. Additionally, the large impact of the manufacturing process can be primarily attributed to the high energy manufacturing processes required to build the device, such as welding and plasma arc cutting. These processes draw power from the UK National Grid which is supplied by a variety of renewable and non-renewable energy sources, each of which has an impact on the environment.

Using this information, it is possible to address some of these hotspots to improve the impact of the device. This potential is discussed further in the LCA observations in subchapter 9.6.2.

For the proposed methodology, the overall impact of the device is of specific interest. As a result of this, the holistic impact results were exported from GaBi into an Excel spreadsheet. This process was repeated for each of the sites identified with respect to the three distance parameters defined. As previously mentioned, these values were calculated during the TFS.

9.4.8. **Interpretation**

The results from the GaBi software were calculated with respect to the scope of the project; this defined the functional unit as kg CO_2eq per deployment. Owing to the size of the units and space limitations, they are converted and displayed in metric tonnes of CO_2eq. The values across the site Varied between a maximum of 1254t CO_2eq per site and a minimum value of 1065t CO_2eq per site. A difference of 188t CO_2eq which equates to a site-specific change accounting to about 17%. This change in emissions is directly attributed to the site selection process and effects environmental impact of the installation, operation and end of life phases. This impact can be seen in Figure 9-35, which showcases the difference in environmental impact between site R and NM at each life cycle stage.

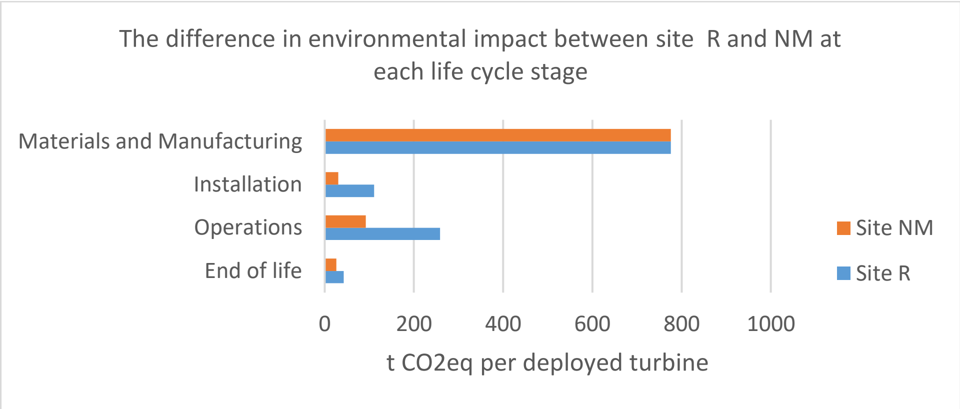


Figure 9-35: Impact of site selection on key life cycle stages between two different sites.

The LCA results are depicted in Figure 9-36. It should be noted that this image displays a varying colour scale to showcase the effects that site selection has on GWP, with sites that contribute more to GWP highlighted in red. It should be noted that the preferred sites from an environmental analysis seem to be located around the grid and maintenance port at Ilfracombe. This data is later used to rank the sites with respect to their GWP for uses in the combination tool.

1,247	1,243	1,240	1,237	1,236	1,235	1,236	1,237	1,240	1,243	1,246	1,244	1,243	1,243	1,243	1,245	1,247	1,254	1,248	1,242	1,236	1,231	1,225	1,220	1,214	1,210	1,205					
1,234	1,230	1,226	1,223	1,222	1,221	1,222	1,223	1,226	1,230	1,234	1,231	1,230	1,230	1,230	1,231	1,234	1,237	1,244	1,237	1,231	1,226	1,220	1,214	1,209	1,203	1,198					
1,221	1,216	1,212	1,210	1,207	1,207	1,207	1,210	1,212	1,216	1,221	1,219	1,217	1,216	1,217	1,219	1,221	1,225	1,230	1,234	1,228	1,222	1,217	1,211	1,206	1,200	1,194	1,189	1,184	1,183	1,192	
1,209	1,203	1,198	1,196	1,193	1,192	1,193	1,196	1,198	1,203	1,209	1,206	1,205	1,204	1,205	1,206	1,208	1,212	1,217	1,223	1,226	1,221	1,215	1,210	1,204	1,199	1,194	1,190	1,186	1,186	1,194	1,206
1,196	1,190	1,185	1,182	1,179	1,179	1,179	1,182	1,185	1,190	1,197	1,194	1,192	1,192	1,192	1,193	1,196	1,200	1,205	1,211	1,218	1,220	1,215	1,210	1,205	1,201	1,197	1,193	1,193	1,194	1,201	1,210
1,183	1,177	1,172	1,168	1,166	1,165	1,166	1,168	1,172	1,177	1,186	1,182	1,180	1,179	1,179	1,180	1,183	1,187	1,193	1,200	1,208	1,221	1,216	1,211	1,208	1,204	1,201	1,199	1,200	1,202	1,208	1,216
1,172	1,165	1,158	1,154	1,151	1,150	1,151	1,154	1,158	1,165	1,175	1,171	1,169	1,167	1,167	1,168	1,171	1,175	1,182	1,189	1,198	1,207	1,219	1,215	1,212	1,209	1,207	1,206	1,207	1,210	1,215	1,223
1,161	1,153	1,146	1,140	1,137	1,136	1,137	1,140	1,146	1,153	1,165	1,161	1,158	1,156	1,155	1,156	1,159	1,164	1,171	1,178	1,188	1,198	1,209	1,219	1,217	1,215	1,213	1,214	1,215	1,219	1,224	1,231
1,150	1,141	1,133	1,127	1,123	1,122	1,123	1,127	1,133	1,141	1,150	1,151	1,148	1,145	1,144	1,145	1,147	1,153	1,160	1,169	1,179	1,190	1,202	1,214	1,223	1,221	1,221	1,222	1,221	1,221	1,223	1,227
1,140	1,131	1,122	1,114	1,109	1,108	1,109	1,114	1,122	1,131	1,140	1,143	1,139	1,135	1,134	1,134	1,136	1,142	1,150	1,160	1,171	1,183	1,196	1,209	1,223	1,219	1,216	1,214	1,212	1,212	1,213	1,216
1,132	1,121	1,110	1,102	1,096	1,094	1,096	1,102	1,110	1,121	1,132	1,136	1,132	1,127	1,124	1,124	1,126	1,132	1,141	1,153	1,167	1,180	1,194	1,207	1,218	1,214	1,211	1,207	1,204	1,203	1,204	1,207
1,126	1,113	1,101	1,091	1,083	1,080	1,083	1,091	1,101	1,113	1,126	1,132	1,126	1,122	1,118	1,114	1,115			1,167	1,172	1,184	1,196	1,209	1,217	1,212	1,207	1,203	1,198	1,196	1,195	1,197
1,122	1,108	1,095	1,083	1,071	1,065	1,071	1,083	1,095	1,108	1,122	1,135														1,215						1,188
1,120	1,106	1,092																													
1,122																															

Figure 9-36: Emissions at each site in t CO_2eq

In addition to the original objective functional unit of kg CO_2eq per site, the typical value of g CO_2eq per kWh can also be calculated for each site by dividing the total emissions by the electrical power generated. This is determined during the TFS, and whilst not critical to the site selection methodology, it provides an additional metric for analysing the sites.

Sensitivity Analysis.

Due to dealing with a large number of parameters, a number of sensitivity analyses were carried out on the model. This was achieved using the inbuilt sensitivity analysis tool in GaBi. This allows variations to be specified for the parameters which were then used to calculate the knock-on impact to the overall outcome of the model. While it is impossible to verify all of the parameters in the model, the key ones were tested in this manner. The main parameters tested included the fuel consumption and distance values. These were specifically chosen due to their critical importance to the site selection methodology.

The results of the sensitivity analysis showed that the model responded within reasonable values when adjustments were made to the parameters. However, to ensure this was the case, a number of calculations were carried out to corroborate other parameters. This involved building an Excel calculator sheet in order to double-check the calculations in the GaBi software. The main focus of this was to visualise the material flows and ensure that values were specified in the correct units. Every calculation from the Excel sheet and GaBi was compared and corroborated to ensure that the model was calculating material flows as expected. Again, the fuel and distance parameters were highlighted as an area of particular importance to the methodology.

9.5. Combination Tool

With the decision-making data generated from both the TFS (net profits) and LCA (kg CO_2eq), the final stage of the case study is the combination of the results. In order to achieve this, the site scores have to be determined for both the financial and environmental elements before they are combined. This process is illustrated with example data determined for site JN across the following subsections.

9.5.1. Finance Score

The finance score was calculated from the net profits from the site. As previously defined, the sites with net profits below 0 were assigned negative scores. This was achieved by defining the minimum profits as 0 across the site. This meant the following calculation could be conducted for site JN, where the net profits produced at JN were equal to £1,253,869. This value was the maximum value across all of the sites, and hence, the financial score is calculated as 1.

$$\frac{(x - \min)}{(max - \min)} = Y \qquad (9\text{-}14)$$

$$\frac{1{,}253{,}869 - 0}{1{,}253{,}869} = 1$$

9.5.2. **Environmental Score**

Similarly, the site's environmental score can be calculated using the findings from the LCA, where for site JN the site contributes 2,118,200 kg CO_2eq. The maximum value for all of the sites identified is 2,140,849kg CO_2eq, and the minimum was 1,962,926 kg CO_2eq. The resulting calculation determines the environmental site score to be 0.169 at site JN.

$$y = 1 - \frac{(x - \min)}{(max - \min)} \qquad (9\text{-}15)$$

$$1 - \frac{(2{,}118{,}200 - 1{,}962{,}926)}{(2{,}140{,}849 - 1{,}962{,}926)} = 0.169$$

9.5.3. **Combined Score**

The combined site score can then be calculated using the weighting; in this example, a weighting of 50:50 is defined and applied to the scores for each site. In the case of site JN, a combined score is determined to be 0.5847. This ranks it as the 6th best site with respect to the other sites in terms of finance and environmental factors.

$$(0.169 \times 0.5) + \big(1 \times (1 - 0.5)\big) = 0.5847 \qquad (9\text{-}16)$$

This process was completed for each of the sites accounting for the defined exclusion criteria in Subsection 9.3.3. The results from this process can be observed in Figure 9-37, which shows the combined score across the sites for the 50:50 weighting.

Figure 9-38 and Figure 9-39 show the site weightings for the financial and environmental elements that inform the results in Figure 9-37. Note that the purple sites indicated in Figure 9-38 are sites that have negative finance scores due to them being unprofitable.

NA	NA	NA	-0.12	-0.11	-0.11	-0.13	-0.11	-0.1	-0.12	NA	NA	NA	NA	-0.1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA					
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-0.05	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA					
-0.07	-0.05	-0.04	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
-0.01	0.007	0.029	0.041	0.052	0.042	0.044	0.062	0.065	0.046	0.037	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
0.038	0.077	0.086	0.099	NA	NA	NA	NA	NA	NA	NA	NA	0.153	0.161	NA	NA	0.205	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	0.15	NA	0.148	0.156	0.163	NA	NA	NA	0.23	NA	NA	NA	0.333	0.393	0.38	0.314	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
0.133	0.185	0.225	0.243	0.249	0.24	0.231	0.216	0.208	0.212	0.214	0.246	0.275	NA	0.329	0.325	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
0.184	0.237	0.283	0.311	NA	0.319	NA	0.287	0.249	0.251	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.4	0.467	0.476	0.463	0.572	NA	NA	NA	0.406
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.424	NA	NA	NA	0.564	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	0.524	0.527	0.507	0.453	0.428	0.407	0.355	0.335	0.356	0.389	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
0.385	NA	0.573	0.605	0.615	NA	NA	NA	NA	0.338	NA	NA	NA	NA	NA	NA	NA			NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
0.448	0.467	NA	NA	0.588	0.542	NA	NA	NA	NA	NA	NA														NA						NA
NA	NA	NA																													
NA																															

Figure 9-37: Combined sites scores for 50:50 weighting

NA	NA	NA	-0.28	-0.26	-0.28	-0.3	-0.26	-0.23	-0.24	NA	NA	NA	NA	-0.2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA					
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-0.18	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA					
-0.26	-0.24	-0.26	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
-0.22	-0.21	-0.2	-0.19	-0.18	-0.2	-0.19	-0.14	-0.12	-0.13	-0.12	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
-0.19	-0.15	-0.15	-0.15	NA	NA	NA	NA	NA	NA	NA	NA	0.017	0.031	NA	NA	0.144	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	-0.14	NA	-0.11	-0.06	0.002	NA	NA	NA	0.1	NA	NA	NA	0.384	0.54	0.561	0.501	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
-0.14	-0.07	-0.03	-0.01	-0.02	-0.04	-0.06	-0.07	-0.06	-0.02	0.043	0.086	0.131	NA	0.229	0.226	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
-0.1	-0.04	0.018	0.044	NA	0.037	NA	-0.01	-0.05	-0.01	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.664	0.783	0.792	0.758	0.977	NA	NA	NA	0.74
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.73	NA	NA	NA	1	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	0.254	0.228	0.174	0.08	0.061	0.065	0.022	0.046	0.107	0.149	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
0.109	NA	0.347	0.352	0.33	NA	NA	NA	NA	-0.05	NA	NA	NA	NA	NA	NA	NA			NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
0.211	0.172	NA	NA	0.207	0.084	NA	NA	NA	NA	NA	NA														NA						NA
NA	NA	NA																													
NA																															

Figure 9-38: Financial scores used to calculate the site score shown in Figure 9-37

NA	NA	NA	0.035	0.044	0.049	0.044	0.035	0.021	0.003	NA	NA	NA	NA	0.000	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA					
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.075	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA					
0.127	0.154	0.177	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
0.195	0.227	0.255	0.268	0.282	0.287	0.282	0.268	0.255	0.227	0.192	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
0.268	0.300	0.328	0.346	NA	NA	NA	NA	NA	NA	NA	NA	0.289	0.291	NA	NA	0.266	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	0.437	NA	0.401	0.373	0.325	NA	NA	NA	0.361	NA	NA	NA	0.282	0.245	0.199	0.127	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
0.401	0.442	0.479	0.502	0.520	0.524	0.520	0.502	0.479	0.442	0.386	0.405	0.420	NA	0.430	0.423	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
0.465	0.511	0.547	0.579	NA	0.602	NA	0.579	0.547	0.511	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.137	0.150	0.161	0.169	0.167	NA	NA	NA	0.071
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.117	NA	NA	NA	0.127	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	0.794	0.826	0.840	0.826	0.794	0.748	0.689	0.625	0.605	0.628	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
0.662	NA	0.799	0.858	0.899	NA	NA	NA	NA	0.730	NA	NA	NA	NA	NA	NA	NA			NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
0.684	0.762	NA	NA	0.968	1.000	NA	NA	NA	NA	NA	NA														NA						NA
NA	NA	NA																													
NA																															

Figure 9-39: Environmental scores used to calculate the site score shown in Figure 9-37

The overall results are presented in an overview identifying the top 10 sites alongside the exclusion parameters. This can be seen in Figure 9-40. Alongside this, detailed results can be provided for the top 10 sites identified from the data generated in the model. The complete overview page for the tool displaying the full results can be seen in Appendix I - Combination Tool Overview. This overview provides all of the information regarding the assumptions made as well as the weightings allocated and a range of additional technical information. This acts as the overall decision-making tool.

	4.24	4.21	4.19	4.16	4.14	4.11	4.09	4.06	4.04	4.01	3.99	3.96	3.94	3.91	3.89	3.86	3.84	3.81	3.79	3.76	3.74	3.71	3.69	3.66	3.64	3.61	3.59	3.56	3.54	3.51	3.49	3.46
51.43	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA					
51.41	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	BB					
51.39	BC	BD	BE	BF	BG	BH	BI	BJ	BK	BL	BM	BN	BO	BP	BQ	BR	BS	BT	BU	BV	BW	BX	BY	BZ	CA	CB	CC	CD	CE	CF	CG	
51.38	CH	CI	CJ	CK	CL	CM	CN	CO	CP	CQ	CR	CS	CT	CU	CV	CW	CX	CY	CZ	DA	DB	DC	DD	DE	DF	DG	DH	DI	DJ	DK	DL	DM
51.36	DN	DO	DP	DQ	DR	DS	DT	DU	DV	DW	DX	DY	DZ	EA	EB	EC	ED	EE	EF	EG	EH	EI	EJ	EK	EL	EM	EN	EO	EP	EQ	ER	ES
51.34	ET	EU	EV	EW	EX	EY	EZ	FA	FB	FC	FD	FE	FF	FG	FH	FI	FJ	FK	FL	FM	FN	FO	FP	FQ	FR	FS	FT	FU	FV	FW	FX	FY
51.33	FZ	GA	GB	GC	GD	GE	GF	GG	GH	GI	GJ	GK	GL	GM	GN	GO	GP	GQ	GR	GS	GT	GU	GV	GW	GX	GY	GZ	HA	HB	HC	HD	HE
51.31	HF	HG	HH	HI	HJ	HK	HL	HM	HN	HO	HP	HQ	HR	HS	HT	HU	HV	HW	HX	HY	HZ	IA	IB	IC	ID	IE	IF	IG	IH	II	IJ	IK
51.29	IL	IM	IN	IO	IP	IQ	IR	IS	IT	IU	IV	IW	IX	IY	IZ	JA	JB	JC	JD	JE	JF	JG	JH	JI	JJ	JK	JL	JM	JN	JO	JP	JQ
51.28	JR	JS	JT	JU	JV	JW	JX	JY	JZ	KA	KB	KC	KD	KE	KF	KG	KH	KI	KJ	KK	KL	KM	KN	KO	KP	KQ	KR	KS	KT	KU	KV	KW
51.26	KX	KY	KZ	LA	LB	LC	LD	LE	LF	LG	LH	LI	LJ	LK	LL	LM	LN	LO	LP	LQ	LR	LS	LT	LU	LV	LW	LX	LY	LZ	MA	MB	MC
51.24	MD	ME	MF	MG	MH	MI	MJ	MK	ML	MM	MN	MO	MP	MQ	MR	MS	MT			MU	MV	MW	MX	MY	MZ	NA	NB	NC	ND	NE	NF	NG
51.23	NH	NI	NJ	NK	NL	NM	NN	NO	NP	NQ	NR	NS														NT						NU
51.21	NV	NW	NX																													
51.19	NY																															

Figure 9-40: Results of a 50:50 Environmental and Finance weighting factor

The results from this methodology when applying the inclusions criteria previously specified, identified site MH as the optimal site for deploying a turbine. This site received a score of 61.46/100. The remaining top 10 sites are identified in Table 9-15. Note that these results are with respect to the 50:50 weighting specified for the environmental and financial factors.

Table 9-15: Top 10 sites identified when results are weighted 50:50

	Site	Latitude (DD)	Longitude (DD)	Combined site score	Environmental site score	Financial site score
1	MH	51.242	4.1375	61.46	89.94	32.98
2	MG	51.242	4.1625	60.52	85.82	35.21
3	NL	51.225	4.1375	58.77	96.80	20.75
4	MF	51.242	4.1875	57.27	79.88	34.66
5	IG	51.308	3.5625	57.18	16.68	97.68
6	JN	51.292	3.5375	56.36	12.73	100.00
7	NM	51.225	4.1125	54.22	100.00	8.44
8	LB	51.258	4.1375	52.71	82.62	22.80
9	LA	51.258	4.1625	52.42	79.42	25.42
10	LC	51.258	4.1125	50.67	83.99	17.36

As previously explained, adjustments to the weightings will result in different outcomes of the decision-making tool. This can be seen when adjusting the weightings in the case of 75:25 in favour of the financial element. This would identify site JN with a score 78.18/100 as the optimal site for deploying the turbine. Similarly, when weighting purely with respect to the environment, site NM is identified as the optimal site with a score of 100/100.

These results from the methodology can then be used to make a location decision with respect to the environmental and financial factors analysed in the methodology and, accounting for the user's specified weighting towards either the financial or environmental elements.

9.6. Discussion

The following subsections discuss the assumptions and additional observations made during the undertaking of the case study.

9.6.1. Assumptions

Throughout the case study, a number of assumptions had to be made due to data limitations. These assumptions were stated throughout the case study, where appropriate. However, they will have had an impact on the findings. The main example of this is the previously mentioned exclusion of the generator from the LCA. This will have had a large effect on the results of the LCA owing to the generator having accounted for approximately six metric tons of material mass attributed to the turbine, approximately 7.5% of the turbine's total mass.

Despite this exclusion, it does not affect the decision-making aspects of the model. This is because the manufacturing stage of each turbine was uniform across each of the sites. Hence variations due to the addition of a generator to the device will not have affected the difference in emissions associated between sites. However, the additional emissions would have impacted the typically functional unit of g CO_2eq per kWh, which is applied in other methodologies and calculated as an additional metric in this one.

9.6.2. Observations

In addition to the assumptions made, several observations were recorded regarding the results from both the LCA and TFS. These are detailed in the following subsections.

LCA Observations

One advantage of the LCA methodology is the ability to identify potentially harmful environmental hotspots across the lifespan of the device. One example of this is the large volume of concrete used to weight the device to the seafloor. At 81.36t this accounts for just under 70% of the total weight of the device. Concrete is renowned for its environmental impact, contributing around 8% of global greenhouses emissions globally. This is due to its expansive uses in the construction industry (Lingwood, 2019). As a result of this, it could be suggested that alternative materials are used to replace the material and reduce the environmental impact of the turbine. For example, sand could be used to weigh down the device. In order to achieve the same weight required 42.3m3 of sand would be required, an increase of 8.4m^3 assuming the sand's density is 1922kg/m^3. This potentially could have cost savings associated with it, too. As a result of this, further investigations could be undertaken to investigate the GWP that this change would have. This highlights the ability to make design decisions using the LCA component of the model.

Additionally, it was noted that the electricity used throughout the manufacturing stages of the device had one of the largest environmental impacts. This is due to a large number of high energy manufacturing processes such as welding, bending and plasma arc cutting. While it could be possible to reduce the requirements for the undertaking of these processes during the manufacturing stage, another alternative method of addressing the environmental impact is to assess the mix of the energy used to power these processes.

For the LCA conducted, the British generic energy mix "GB - Electricity grid mix (production mix)" was specified within the GaBi software. This provided data for a generic mix of energy found supplying the UK National Grid. The percentage break down of this energy mix can be seen in Table 9-16 alongside the contribution to emissions from the process.

Table 9-16: Percentage GB electrical mix and subsequent contribution to emissions

Source	Mix makeup	Contribution to emissions
Coal gases	0.34%	1.34%
Heavy fuel oil	0.49%	1.75%
Photovoltaic	1.19%	0.48%
Waste to energy	1.19%	3.12%
Biogas	2.39%	1.18%
Hydro power	2.59%	0.05%
Solid biomass	4.09%	0.58%
Wind power	9.45%	0.18%
Nuclear energy	18.81%	0.26%
Natural gas	29.71%	35.07%
Hard coal	29.75%	55.99%

From the table, it is clear that coal plays a significant part in the energy make up, accounting for 29.75% of the energy produced. The negative environmental impact of coal is well documented and clear to see. In this example, it accounts for 55.99% of the emission produced during electrical generation. As a result of this, the UK has set to phase out coal from the National Grid by 2024 (GOV.UK, 2020). With the exclusion of coal from this power makeup and the assumption that the remaining methods will increase equally to provide the required power, the environmental impact of power generation for electrical generation could be reduced by 44%.

Alternatively, it may be possible for the company to adopt a completely green approach and buy energy from a specialist's energy supplier that deals in renewables. Whilst the company would have to pay a premium for the energy supplied, it has the potential to drastically reduce the environmental impact of the device when considering its holistic impact.

Another incredibly important observation is made by comparing the inputted distance parameters and the LCA results. These could be used to determine the emissions per metre for each of the respective defined parameters. These are calculated as follows:

Harbour to site	2.615 kg CO_2eq per m
Harbour to cable	0.234 kg CO_2eq per m
Cable to site	5.526 kg CO_2eq per m

This is of particular interest as it identifies the precise impact that the deployment of the turbine has per meter of the defined parameters. However, it should be noted that these values are not exclusively defined by the distance parameters, but are additionally defined with respect to other parameters within the model. These include parameters such as the vessel specification, number of maintenance trips and the cable manufacturing process. As a result of this, if any of these parameters were altered, the observed impacts would be altered as well.

However, it was observed that the emissions of sailing from the harbour to site are 11 times larger than that of sailing between the harbour and cable site. This is as a result of the boat travelling to and from the site for maintenance activities and accounts for the additional journeys' and fuel burnt on site. In contrast, the journey from the harbour to cable site is a one-way trip. As a result of this, it was expected that this value would be approximately ten times larger and is validated by this finding.

TFS Observations

The Nova M100 is a first-generation device developed by Nova Innovation. Currently, Nova is testing the second iteration of their device, the Nova M100-D turbine (Nova Innovation, 2019). This turbine operates using direct drive, removing the need for a gearbox to drive the generator. As a result of this, the mechanical efficiency of the device has been improved from 38.34% to 42.98%, and in addition, the cut-in speed for the device has been reduced from 0.6m/s to 0.5m/s. The full specifications of the new device can be seen in Table 9-17.

Table 9-17: Comparison of the Nova M100 and M100-D specifications

	M100-D	M100
Rated capacity (kW)	100	100
Life (years)	20	20
Diameter (m)	8.5	9
Cut in speed (m/s)	0.5	0.6
Rated speed (m/s)	2	2
Cp	42.98%	38.34%
Cut in power (W)	1562.5	2700
Cut in power (kW)	1.56	2.70

In the case of site JN, by adopting the newer second-generation M100-D turbine, the average power output of the device increases from 33.276kW to 33.541kW, a change of 0.265 kW. Whilst this is a relatively low figure, but over the 20-year lifespan of the device, it results in a potential increase in profits of £14,027- up from £1.764m to £1.779m. While this is still relatively small, this value does not account for changes in the cost of the turbine and maintenance activities, both of which are likely to be reduced due to its improved mechanical design.

Alternatively, if a yawing version of the Nova M100 turbine could be positioned at the same location, it would be capable of producing an average power of 34.879kW. This would increase profit by £85,000. However, this is likely to come with the additional installation and maintenance costs and would probably not be worth the additional investment.

Combination Tool Observations

The combined results presented in the combination tool allow the user to identify a preferred site with respect to the user-defined weightings of the environment and financial factors. However, as suggested, these weightings are subjective owing to the fact that they are altered by the user. The specification of these weightings has a large impact on the results of the methodology. As there is currently no requirement to consider the global environmental impact of tidal devices, there is the concern that most companies will focus purely on the financial aspect of the methodology and ignore the environmental impact.

However, the additional benefit of the methodology is the large quantity of data produced during its undertaking. This can be presented alongside the results to provide an in-depth technical understanding of the findings of both the LCA and TFS. This information can be used in to additionally inform site selection decisions and provide a holistic understanding of the impact of deployment of the device, including informing the user about the direct environmental impact that they will have. It is hoped that this will prompt developers to think about the impact of their devices, both financially and environmentally.

It should be noted that data generated in the TFS and LCA could also be used to define additional inclusion/exclusion criteria during the combination of the results. This can be showcased in the example of the installation cost of the device, which is calculated in the TFS. This value defines the upfront capital cost required to deploy a turbine at the site. This can be used to determine if the company has enough capital to deploy the turbine at the site and hence help inform a decision regarding the financial viability for the deployment of the device.

9.7. **Conclusion**

The chapter has detailed how the combination tool can be applied in a case study setting by selecting a site for the Nova M100 turbine off of the North Devon coast. This showcases how a user-defined weighting system can be used to determine the optimal deployment site for the turbine with respect to the environmental and financial factors.

In addition to this, the case study showcased the large volume of data that is produced during the undertaking of the methodology. This additional information is detailed in Appendix I - Combination Tool Overview, which highlights the holistic environmental and financial consequences of site selecting. This technical information can provide additional assistance to the user during the site selection process.

CHAPTER 10: DISCUSSION

10.1. Summary

The following chapter details the key findings of the research, and the methodology developed, defining and explaining them in the following subsections: Research design methodology, contribution to the field, encountered difficulties and recommendations for further work.

10.2. Research Design Methodology

The methodology developed has been created in line with the research design adopted as outlined in CHAPTER 2: RESEARCH DESIGN METHODOLOGY. This acted as a guide for the undertaking of the research and outlined the goals of each stage of the methodology development. This provides a clear path for the undertaking of the research and the structure outlined in the thesis.

The research design adopted for this thesis outlined four key stages for the development of the new methodology, a literature review, methodology development, testing and evaluation. This is a logical and systematic process for the development of the final methodology as each stage is developed using information and decisions made in the subsequent stage. As a result, its application to the thesis provides additional confidence in the newly developed site selection methodology.

10.3. **Contribution to Research Field**

A generic combined methodology has been developed for site selecting TSGs with respect to the environmental findings from an LCA study and the financial elements of a TFS. Its application has been showcased in a case study, thus achieving the overall aim of the research project. The following key elements from this process represent the contribution to the field of knowledge.

A comprehensive literature review was conducted. This examined the historical and current states of research into both tidal power and LCA, identifying a number of key findings:

- Tidal power is a renewable, reliable and predictable form of power generation.
- The development of tidal technology is coming to an end. Companies are now beginning to deploy their technology commercially.
- Current site selection technology emphasises the financial impact that the device will have; this results in the focus of increasing power generation from a site when site selecting.
- Current site selection process pays some consideration to the environmental impact of the devices, solely at a local level, but with particular attention paid to the interaction between wildlife and the device. Typically this takes place once a site has been identified due to the costs associated with conducting a wildlife study. It is noted that there are no requirements to account for the global impact of emissions over the life cycle of the device.
- LCA can be used to holistically analyse a product or system across the entire life cycle, encompassing important phases such as raw material extraction,

transportation and end of life. These are not always accounted for in other environmental impact methodologies.

This identified a knowledge gap, leading to the development and proposal for a generic site selection tool, for TSGs with emphasis placed on both environmental and financial factors. The methodology developed is defined by three key stages, which allow information and decisions made within them to inform the subsequent stages of the investigation.

- Stage 1: Site and device specification.
- Stage 2: TFS and LCA studies. During this stage, both a generic TFS and LCA framework are applied to the site and device specified.
- Stage 3: Combination tool. Results from the two studies are combined and sites identified using a user-defined weighting system combining environmental and financial factors.

The application of this methodology provides a holistic understanding of the impact of the device, both financially and environmentally. With the inclusion of a weighting system within the methodology, the user can precisely tailor the outcome of the tool with respect to their particular criteria regarding these key elements.

The developed methodology was tested throughout the undertaking of a case study to site select the deployment of the Nova M100 turbine at a location off the North Devon coast. This identified one of the most critical elements of the tool, the ability to incorporate and present large quantities of additional data. This additional data was generated throughout the undertaking of the TFS and LCA and can be used to provide an in-depth understanding of the effect of site selection. As a result, it can be used in conjunction with the results from the tool as part of the decision-making process, providing an additional holistic understanding of the impact of site selection.

It is expected that the methodology developed will be used as a tool for promoting sustainable and holistic decision-making in an emerging renewable energy market. This is achieved by focusing on not just the local environmental impact that is typically addressed in TFS, but the broader impact of device deployment at a global level. The adoption of this methodology will allow users to holistically understand the impact of device deployment on the environment, whilst still identifying the need for the company to make a profit. This is achieved by balancing the environmental site selection process with the profitability of each scheme. The combined output of the methodology promotes a greater understanding of both these factors which are impacted by site selection and will encourage users to tailor their decision criteria for the identification of a preferred site concerning each element.

This style of decision-making tool could be further promoted through the introduction of legislation and regulation which promotes companies to holistically understand and mitigate the environmental impact of device deployment before permits for deployment are granted.

10.4. Encountered Difficulties

A number of issues and limitations were encountered throughout the undertaking of the research. Some of these limitations have been previously discussed in earlier chapters. However, the following are worthy of note:

Data - A large amount of data is typically required for the undertaking of the LCA methodology. One of the significant limitations of this project was the lack of available primary data for conducting the case study. This issue was addressed in part with the development of the generic model using parameters. This allowed the user to enter their own specific parameters. However, the results generated are based on values specified in literature and a number of assumptions. As a direct result of this, there is the potential for any uncertainties in the data to affect the outcome of the methodology directly. The use of secondary data and assumptions was a far cry from the original intention, which specified the use of primary data in order to create a more specific and realistic case study. However, this was mandated due to the lack of available data. It should be noted that attempts were made to validate this data, and a sensitivity analysis was carried out to ensure that there were no adverse effects on the overall finding when alterations were made to this data.

Data Costs - One reason for the lack of data is the cost associated with obtaining it. Typically, data will be generated from onsite measurements of material and energy usage. This process is often very costly, both financially and in time. It should be noted that this requirement for the undertaking of the LCA is one of the major limiting factors of the methodology, which can be affected by uncertainties in the assumed or generic data used in place of primary data. As a result, any uncertainties within the data have a direct result on the findings of the methodology.

Flow Simulation - The use of flow simulation software was crucial for the generation of data within the TFS. Whilst attempts were made to validate this data, specifically against known values in the local area, it is highly recommended that once a site is identified, further investigation is undertaken before deployment of a device. This is required in order to assess the precise flow conditions at the site, which can be obtained using onsite measurements. This data could later then be used to corroborate and even update the findings of the TFS before a TSG is deployed at the site.

Specialist Software - Finally, the undertaking of this thesis required the mastery of two specialist software packages, POLPRED and GaBi. Which, in order to operate them appropriately, required a robust and technical understanding of how the programs worked. Of particular note is the GaBi software, which requires a holistic understanding of the procedure required to connect and define; processes, plans and flows detailed within the model. This was additionally complicated by the requirement to develop a generic model, which additionally mandated an in-depth understanding of the parametrization process. This was critical for the development of the generic LCA component of the developed methodology.

Site selection - Owing to the sensitive nature of the decision-making process that companies will use for site selecting commercial turbines, no references could be found for the process of optimizing deployment angles for them. However, it can be assumed that it is highly likely that companies carry out a similar assessment to the one presented. This assumption is based on the idea that by optimizing the power output for a turbine at a site, larger profits can be generated from the sale of electricity at the same deployment cost per deployed fixed turbine. Therefore, companies can increase their return on their investment over the lifespan of the device by optimizing device placement.

10.5. Recommendations for Further Work

The focus of this research was on the environmental impact of site selecting TSG's. As a result of this, the scope of the LCA was limited to the GWP of the tidal device. This decision was made due to the inherent link between GWP and the adoption of renewable energy devices to tackle the global problem of climate change. However, it should be noted that when applied, the LCA methodology is typically used to investigate a number of different impact categories such as Acidification and Eutrophication potential. As a result of this, further work could be undertaken to incorporate these values into the site selection process via a complex user-defined weighting system. Alternatively, the results could just be reported as additional data provided for the device. This would offer an increased understanding regarding the impact the deployment of a device at each site will have.

Another major limiting factor of the case study was the decision to deploy just a single dedicated turbine at each site. In reality, with the commercialisation of TSGs, it is predicted that turbines will be deployed in farms/arrays. This deployment strategy will allow for specific infrastructure to be shared between devices, potentially minimising the environmental impact that each turbine has on its own. One example of this is the environmental impact of the grid connection cable. This component could be shared between a number of turbines in the array, which, when compared to laying dedicated cables, could lead to a reduction in emissions.

It is highly recommended that this methodology is developed further to account for multiple turbines and the impact that shared components could have. However, this will bring with it its own complex problems of minimum TSG spacing, required to avoid wake turbulence, and the incorporation of additional infrastructure into the model, such as seabed power hubs. However, these issues should be explored further due to the commercial focus on developing tidal arrays as a source of power generation.

Finally, the methodology and tool could be expanded to create a comparative tool that would allow sites to be analysed with respect to multiple turbines. This would then provide a decision-making element that identifies to the user the best turbine for each site with respect to the financial and environmental factors. This methodology could be particularly useful in the future if companies develop multiple devices, allowing a decision to be made. However, it should be noted that while LCA can be used to perform internal device comparisons, comparisons between devices manufactured by different companies would require additional scrutiny in line with ISO standards.

10.6. Conclusion

The aims and objectives of the project were achieved via the completion of a comprehensive literature review into LCA and tidal power. This directed the development of the defined methodology. This methodology was then tested in a case study showing its applicability for site selecting TSG's with respect to financial and environmental factors. Throughout this undertaking, a number of difficulties have been identified and discussed, paving the way for recommendations for future work to address the shortcomings of the developed methodology.

CHAPTER 11: CONCLUSION

The work presented within this Thesis has explored in detail the current state of research into the fields of tidal power and LCA throughout the undertaking of a literature review. This identified that TSG's are current site selected with respect to the findings of a TFS, and as a result, site selection is determined by the financial factors of each site. Whilst accounting for the viability of device deployment at the site. As a result of this, typically, the TFS decision-making process is purely financially motivated.

However, with the issues of global warming promoting the uptake of renewable energy sources, it is important to have a holistic understanding of the environmental impact of implementing these schemes. This understanding is especially important when the impact of increased transportation of a device is a potential concern, due to the environmental emissions associated with it. This impact can be assessed holistically using the LCA methodology to determine the direct GWP that the device has over its entire life cycle.

This thesis sets about detailing a new methodology for site selecting TSGs with respect to both financial and environmental factors. This is achieved by combining the already established TFS, and LCA methodology's into one concise tool, to aid in the decision making processes of site selection. This methodology provides a holistic overview of the impact of the site selection process for the specified site and device with respect to both financial and environmental aspects.

The proposed methodology is intended for application in an emerging renewable energy market to aid in the site selection decision-making process. As a result of this, the methodology was validated and tested using a case study. This was achieved by using the tool to identify a deployment site for a Nova M100 horizontal axis turbine off of the North coast of Devon.

The findings of this application showed how different user groups could apply the methodology by varying the weighting of the combined methodology results between financial (TFS) and environmental (LCA) methodologies'. Additionally, the case study highlighted how the extra data generated by each methodology provides a complete understanding of the impact that device placement will have. This additional data can also be used to inform decisions with respect to individual aspects of the findings. The undertaking of the case study acted as a means to validate the methodology as a whole. However, a number of potential issues were identified during the process. This lead to a discussion of how to improve and develop the methodology further in future iterations.

In conclusion, it is found that the methodology developed within this thesis can aid in the decision-making process in an emerging renewable energy market. However, with the development of technology, additional considerations should be made, such as for the deployment of multiple devices. With these changes, it is expected that the methodology developed will provide a specialist tool in order to support decision making in an energy industry that has the potential to supply renewable and reliable power for generations to come.

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Appendices

Appendix A - Site Selection Appraisal for Tidal Turbine Development in the River Mersey – Abstract

Kelly, C. L., Blanco-Davis, E., Michailides, C., Davies, P. A., & Wang, J, "Site Selection Appraisal for Tidal Turbine Development in the River Mersey", *Journal of Marine Science and Application*. 112-121, online March 2018

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RESEARCH ARTICLE

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Site Selection Appraisal for Tidal Turbine Development in the River Mersey

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Abstract
This paper used a specialist software package to produce a detailed model of the River Mersey estuary, which can be subjected to a range of simulated tidal conditions. The aim of this research was to use the validated model to identify the optimal location for the positioning of a tidal turbine. Progress was made identifying a new optimal site for power generation using velocity data produced from simulations conducted using the MIKE 3 software. This process resulted in the identification of site 8, which sits mid-river between the Morpeth Dock and the Albert Dock, being identified as the favoured location for tidal power generation in the River Mersey. Further analysis of the site found that a 17.2-m diameter single rota multidirectional turbine with a 428-kW-rated capacity could produce 1.12 GWh annually.

Keywords Tidal power generation · Tidal energy · Tidal site analysis · River Mersey · MIKE 3

Appendix B- Investigation into the uses of Life Cycle Analysis (LCA) as an alternative method of selecting tidal power schemes - Conference paper

Investigation into the uses of Life Cycle Analysis (LCA) as an alternative method of selecting tidal power schemes

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Abstract. Tidal power generation is a renewable source of energy, however this does not automatically guarantee that it is an environmentally-friendly method of producing power. In an attempt to ascertain the true environmental effects of tidal power generation, this investigation outlines the key stages of a project which has set out discover the direct impact that a Tidal Stream Generator (TSG) has on the environment. To achieve this, a comprehensive Life Cycle Analysis (LCA) will be conducted in order to determine the impact of a TSG from "cradle to grave". This will produce a holistic assessment of the costs associated with this renewable energy source.

While a project may seem environmentally friendly does not mean that it will be economically viable. Similarly, economic impact will be a major factor in company's decision to invest in a project or not. In order to account for this in the proposed study, a Cost Benefit Analysis (CBA) will also be undertaken using data generated from a Technical Feasibility Study (TFS), which is conducted to identify the position of the TSG in a hypothetical location.

By combining the results of TFS and CBA, the author intends to create an innovative methodology which can help support decision-making within an emerging renewable energy industry that will be at the forefront of producing reliable, renewable and sustainable power for generations to come.

Keywords. Tidal power, Life Cycle Analysis, Technical Feasibility Study, Cost Benefit Analysis Feasibility study,

Introduction

Tidal power is the generation of power from the global shift in sea levels caused by the interaction between the gravitational forces of the Earth, Moon and Sun. Typically two tidal periods occur every 24 hours and 50 minutes, which is the time it takes for the Moon to realign overhead at the same point on the Earth. This is due to the rotation of the moon around the Earth being in the same direction as the rotation of the Earth.

Currently it is accepted that there are four major methods for extracting tidal energy: Tidal barrages, Tidal lagoons, Dynamic tidal power and Tidal stream generators (1). The focus of this report is on Tidal Stream Generators (TSG) which are also known as Tidal Stream Convertors. They consist of devices that are positioned directly in flowing tidal stream and come in a variety of different styles. These vary from the traditional 'bladed' tidal turbine to the more unfamiliar orientations, such as: tidal kites and oscillating hydrofoil concepts.

TSG technology is currently still in its infancy as a source of renewable energy. New devices are being developing and tested, as companies compete with each other to develop their own technology as it is scaled to commercial levels. In a world looking to reduce its environmental impact and tackle climate change the appeal of a renewable, predictable source of power is clear to see. But while that should be the limit, this report outlines the key analysis packages for site selection for tidal power schemes in an environmentally-friendly way. This is done through the combination of LCA and a CBA, and then combining them within an overall feasibility study to understand the effects of site selection of a turbine.

Technical Feasibility Study

A Technical Feasibility Study sets out to assess a sites ability to produce power. In order to achieve this, initially the site has to be compared to the specification of the proposed turbine to determine if it conforms to the local/national requirements (planning/nautical/Health & Safety). Typically at this stage the water depth, site access and ability to connect to the local power grid are assessed. Any problems encountered at this stage of the feasibility study will, most likely, put a hold on development.

Once it is clear that a turbine can be positioned at the site, the next stage is to determine the power available using Equation 1. In order to account for varying tidal conditions the power produced can be calculated over a lunar month providing a realistic assessment of the potential available output power. To do this, water velocity data for the lunar month has to be obtained via a computer simulation or from onsite data measurements. Equation 1 demonstrates the power, P, calculation of tidal turbine (2), where, ρ is the density of seawater (kg/m3), A is the swept area of the turbine blades (m2), V is the velocity of water flowing through the turbines (m/s), and CP is the turbine power coefficient. The power, P, is generated in Watts.

$$\boldsymbol{P = \frac{\rho A V^3}{2} C_P}$$

CBA

As mentioned at the outset, one of the major factors a company must take in to account when choosing to invest in a project is the financial viability or Return On Investment (ROI), of the scheme of which the agreed 'strike price' for energy produced is a major factor. The current strike price for tidal power is fixed at £305 per MWh until 2019. Using the power data generated by the feasibility study it is possible to calculate how much the device will earn over its lifetime, by extrapolating the power generated during the lunar period. The lifetime earnings can then be offset against the costs associated with the project, including installation, maintenance (including 'down time') and, also, decommissioning in order to calculate the lifetime profits and the ROI.

ROI is, almost without exception, the most important indicator for investors in determining the value of the scheme and whether or not it should receive investment.

LCA

Life Cycle Analysis, also known as Life Cycle Assessment, is a method of holistically examining a product or system with respect to a functional unit. It was first used by the Coca-Cola Company in 1969 when they commissioned the Midwest Research Institute to quantify the emissions and resource requirements for different beverage container materials for their soft drinks. Unfortunately, this report was unpublished (3), however it established the concept of LCA which, in turn, lead to the modern regulations developed by the International Organization for Standardization (ISO) in ISO 14040 and ISO 14044.

Methodology

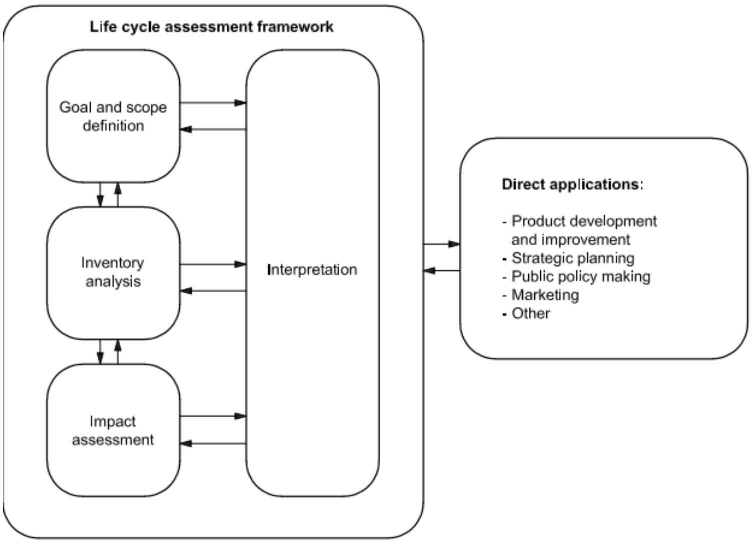

Figure 1: Key stages of conducting a LCA (4)

The framework set out by ISO 14040 outlines the four key phases for conducting a LCA which can be seen in Figure 1. The four key areas are further defined in ISO 14044 as;

- Goal and Scope: details the extent of the investigation conducted by outlining the product/system being investigated and defining the boundary conditions of the assessment and the functional units that will be used.
- Inventory Analysis: outlines all of the parts and processes in the system being investigated, providing data on inputs to the process such as material and energy and the outputs such as emissions and waste.
- Impact Assessment: this collates all the information from the inventory analysis in to the relevant impact categories specified in the Goal and Scope.
- Interpretation: defines how the results are reported, ensuring that the process is fair and the method conforms to the regulations set out in ISO 14040 and the results meet the criteria set out in the Scope.

Impact categories

There are a number of varying impact categories that make up the functional unit for an LCA investigation. The goal of the functional unit is to create a base unit for comparison against other studies. The key functional unit for this particular report will be Global Warming Potential (GWP). There are a number of different gases that contribute to GWP. In order to collate all the different emissions carbon dioxide equivalents are calculated for each of the gases that contribute to the GWP using conversion values. This allows for the gases to be collated in to the functional unit of kg CO_2eq which is used in the Kyoto Protocol (5).

Combination

To bring together the above three work packages (TFS, LCA & CBA) into a developed methodology it is important to understand the effects that each has on the other because the data generated in each methodology will feed between them and inform results. The following Table 1 shows some of the impact that site selection can have on each of the main work packages.

Table 1: The effects of site selection on the key methodologies

Methodology	Impact of site selection
Technical Feasibility Study	• Outlines characteristics of selected sites – factors that affect the amount of power available at each of the locations • Confirms if the site meets the specifications of the turbine • Determines the distances from the location from the Grid connection and the distance travelled by the maintenance craft
LCA	• Location of the site effects the travel distance which will result in changes in the environmental impact of the turbine with regards to laying of the connection cable and the amount of fuel used to reach the site.
CBA	• Changes in the power available effect the profitability of the scheme • Changes in distance from maintenance ports and gird connection result in changes in the quantities of material used resulting in a change in the cost of the project

The functional unit of the final analysis will be, £/kg CO_2eq. This quantitative outcome will be generated by combining the data from the CBA and LCA. This value can be used to compare a number of locations within a specified site allowing a user to identify a preferred site with respect to the environment and the financial aspect. In order to be industry friendly, the methodology will incorporate user defined cut-off options that allow users to identify and eliminate sites that don’t meet specified characteristics. One such example for this requirement is a minimum ROI; because companies will only invest if a minimum ROI is achieved. In this case only results from sites that could meet this value will be displayed. Once a site is selected, it will be possible to interrogate the methodology to determine more information about the individual components that comprise the product, thereby allowing a greater in-depth look into any sites chosen.

Conclusion

By combining these three methodologies into one combined assessment the intention is to create, a decision making tool to assess the environmental and financial impact of site selecting tidal turbines. These considerations mean that the very core of the process is built on the understanding of the environmental impact and strives to reduce the environmental footprint of what is a highly attractive renewable energy resource.

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Appendix C - Case Study - Site Information

The following information provided the precise longitude and latitude value of each identified site, alongside the site-specific information calculated for the distances between key infrastructure points and the site.

Sites	Longitude	Latitude	Cable to site (m)	Harb to cable (m)	Harb to site (m)
A	4.2375	51.4250	24,000	0	24,000
B	4.2125	51.4250	23,500	0	23,500
C	4.1875	51.4250	23,100	0	23,100
D	4.1625	51.4250	22,800	0	22,800
E	4.1375	51.4250	22,600	0	22,600
F	4.1125	51.4250	22,500	0	22,500
G	4.0875	51.4250	22,600	0	22,600
H	4.0625	51.4250	22,800	0	22,800
I	4.0375	51.4250	23,100	0	23,100
J	4.0125	51.4250	23,500	0	23,500
K	3.9875	51.4250	23,100	18,800	24,000
L	3.9625	51.4250	22,400	18,800	24,700
M	3.9375	51.4250	21,900	18,800	25,400
N	3.9125	51.4250	21,400	18,800	26,200
O	3.8875	51.4250	21,100	18,800	27,100
P	3.8625	51.4250	20,900	18,800	28,100
Q	3.8375	51.4250	20,800	18,800	29,100
R	3.8125	51.4250	20,500	44,500	30,200
S	3.7875	51.4250	18,800	44,500	31,400
T	3.7625	51.4250	17,200	44,500	32,600
U	3.7375	51.4250	15,500	44,500	33,800
V	3.7125	51.4250	13,900	44,500	35,100
W	3.6875	51.4250	12,300	44,500	36,400
X	3.6625	51.4250	10,700	44,500	37,700
Y	3.6375	51.4250	9,100	44,500	39,100
Z	3.6125	51.4250	7,600	44,500	40,500
AA	3.5875	51.4250	6,100	44,500	41,900
AB	4.2375	51.4083	22,400	0	22,400
AC	4.2125	51.4083	21,900	0	21,900
AD	4.1875	51.4083	21,400	0	21,400
AE	4.1625	51.4083	21,100	0	21,100

AF	4.1375	51.4083	20,900	0	20,900
AG	4.1125	51.4083	20,800	0	20,800
AH	4.0875	51.4083	20,900	0	20,900
AI	4.0625	51.4083	21,100	0	21,100
AJ	4.0375	51.4083	21,400	0	21,400
AK	4.0125	51.4083	21,900	0	21,900
AL	3.9875	51.4083	21,600	18,800	22,400
AM	3.9625	51.4083	20,800	18,800	23,100
AN	3.9375	51.4083	20,200	18,800	23,900
AO	3.9125	51.4083	19,700	18,800	24,800
AP	3.8875	51.4083	19,400	18,800	25,700
AQ	3.8625	51.4083	19,100	18,800	26,700
AR	3.8375	51.4083	19,100	18,800	27,800
AS	3.8125	51.4083	19,100	18,800	29,000
AT	3.7875	51.4083	18,600	44,500	30,200
AU	3.7625	51.4083	16,900	44,500	31,400
AV	3.7375	51.4083	15,200	44,500	32,700
AW	3.7125	51.4083	13,600	44,500	34,000
AX	3.6875	51.4083	11,900	44,500	35,300
AY	3.6625	51.4083	10,200	44,500	36,700
AZ	3.6375	51.4083	8,600	44,500	38,100
BA	3.6125	51.4083	6,900	44,500	39,500
BB	3.5875	51.4083	5,300	44,500	41,000
BC	4.2375	51.3917	20,800	0	20,800
BD	4.2125	51.3917	20,200	0	20,200
BE	4.1875	51.3917	19,700	0	19,700
BF	4.1625	51.3917	19,400	0	19,400
BG	4.1375	51.3917	19,100	0	19,100
BH	4.1125	51.3917	19,100	0	19,100
BI	4.0875	51.3917	19,100	0	19,100
BJ	4.0625	51.3917	19,400	0	19,400
BK	4.0375	51.3917	19,700	0	19,700
BL	4.0125	51.3917	20,200	0	20,200
BM	3.9875	51.3917	20,100	18,800	20,800
BN	3.9625	51.3917	19,300	18,800	21,600
BO	3.9375	51.3917	18,600	18,800	22,400
BP	3.9125	51.3917	18,000	18,800	23,300
BQ	3.8875	51.3917	17,700	18,800	24,300
BR	3.8625	51.3917	17,400	18,800	25,400
BS	3.8375	51.3917	17,300	18,800	26,600
BT	3.8125	51.3917	17,400	18,800	27,800

BU	3.7875	51.3917	17,700	18,800	29,000
BV	3.7625	51.3917	16,800	44,500	30,300
BW	3.7375	51.3917	15,100	44,500	31,600
BX	3.7125	51.3917	13,400	44,500	33,000
BY	3.6875	51.3917	11,800	44,500	34,400
BZ	3.6625	51.3917	10,100	44,500	35,800
CA	3.6375	51.3917	8,400	44,500	37,200
CB	3.6125	51.3917	6,700	44,500	38,600
CC	3.5875	51.3917	5,000	44,500	40,100
CD	3.5625	51.3917	3,400	44,500	41,600
CE	3.5375	51.3917	1,700	44,500	43,100
CF	3.5125	51.3917	800	44,500	44,600
CG	3.4875	51.3917	1,700	44,500	46,100
CH	4.2375	51.3750	19,300	0	19,300
CI	4.2125	51.3750	18,600	0	18,600
CJ	4.1875	51.3750	18,000	0	18,000
CK	4.1625	51.3750	17,700	0	17,700
CL	4.1375	51.3750	17,400	0	17,400
CM	4.1125	51.3750	17,300	0	17,300
CN	4.0875	51.3750	17,400	0	17,400
CO	4.0625	51.3750	17,700	0	17,700
CP	4.0375	51.3750	18,000	0	18,000
CQ	4.0125	51.3750	18,600	0	18,600
CR	3.9875	51.3750	18,600	18,800	19,300
CS	3.9625	51.3750	17,700	18,800	20,100
CT	3.9375	51.3750	17,000	18,800	20,900
CU	3.9125	51.3750	16,400	18,800	21,900
CV	3.8875	51.3750	16,000	18,800	23,000
CW	3.8625	51.3750	15,700	18,800	24,100
CX	3.8375	51.3750	15,600	18,800	25,300
CY	3.8125	51.3750	15,700	18,800	26,600
CZ	3.7875	51.3750	16,000	18,800	27,900
DA	3.7625	51.3750	16,400	18,800	29,200
DB	3.7375	51.3750	15,200	44,500	30,600
DC	3.7125	51.3750	13,600	44,500	32,000
DD	3.6875	51.3750	11,900	44,500	33,400
DE	3.6625	51.3750	10,200	44,500	34,900
DF	3.6375	51.3750	8,600	44,500	36,300
DG	3.6125	51.3750	6,900	44,500	37,800
DH	3.5875	51.3750	5,300	44,500	39,300
DI	3.5625	51.3750	3,800	44,500	40,800

DJ	3.5375	51.3750	2,400	44,500	42,400
DK	3.5125	51.3750	1,700	44,500	43,900
DL	3.4875	51.3750	2,400	44,500	45,500
DM	3.4625	51.3750	3,800	44,500	47,000
DN	4.2375	51.3583	17,700	0	17,700
DO	4.2125	51.3583	17,000	0	17,000
DP	4.1875	51.3583	16,400	0	16,400
DQ	4.1625	51.3583	16,000	0	16,000
DR	4.1375	51.3583	15,700	0	15,700
DS	4.1125	51.3583	15,600	0	15,600
DT	4.0875	51.3583	15,700	0	15,700
DU	4.0625	51.3583	16,000	0	16,000
DV	4.0375	51.3583	16,400	0	16,400
DW	4.0125	51.3583	17,000	0	17,000
DX	3.9875	51.3583	17,100	18,800	17,700
DY	3.9625	51.3583	16,200	18,800	18,600
DZ	3.9375	51.3583	15,400	18,800	19,500
EA	3.9125	51.3583	14,800	18,800	20,600
EB	3.8875	51.3583	14,300	18,800	21,700
EC	3.8625	51.3583	14,000	18,800	22,900
ED	3.8375	51.3583	13,900	18,800	24,200
EE	3.8125	51.3583	14,000	18,800	25,500
EF	3.7875	51.3583	14,300	18,800	26,800
EG	3.7625	51.3583	14,800	18,800	28,200
EH	3.7375	51.3583	15,400	18,800	29,600
EI	3.7125	51.3583	13,900	44,500	31,100
EJ	3.6875	51.3583	12,300	44,500	32,600
EK	3.6625	51.3583	10,700	44,500	34,000
EL	3.6375	51.3583	9,100	44,500	35,500
EM	3.6125	51.3583	7,600	44,500	37,100
EN	3.5875	51.3583	6,100	44,500	38,600
EO	3.5625	51.3583	4,800	44,500	40,100
EP	3.5375	51.3583	3,900	44,500	41,700
EQ	3.5125	51.3583	3,500	44,500	43,300
ER	3.4875	51.3583	3,900	44,500	44,800
ES	3.4625	51.3583	4,800	44,500	46,400
ET	4.2375	51.3417	16,200	0	16,200
EU	4.2125	51.3417	15,400	0	15,400
EV	4.1875	51.3417	14,800	0	14,800
EW	4.1625	51.3417	14,300	0	14,300
EX	4.1375	51.3417	14,000	0	14,000

EY	4.1125	51.3417	13,900	0	13,900
EZ	4.0875	51.3417	14,000	0	14,000
FA	4.0625	51.3417	14,300	0	14,300
FB	4.0375	51.3417	14,800	0	14,800
FC	4.0125	51.3417	15,400	0	15,400
FD	3.9875	51.3417	15,800	18,800	16,200
FE	3.9625	51.3417	14,800	18,800	17,100
FF	3.9375	51.3417	13,900	18,800	18,200
FG	3.9125	51.3417	13,100	18,800	19,300
FH	3.8875	51.3417	12,600	18,800	20,500
FI	3.8625	51.3417	12,200	18,800	21,800
FJ	3.8375	51.3417	12,100	18,800	23,100
FK	3.8125	51.3417	12,200	18,800	24,500
FL	3.7875	51.3417	12,600	18,800	25,900
FM	3.7625	51.3417	13,100	18,800	27,300
FN	3.7375	51.3417	13,900	18,800	28,800
FO	3.7125	51.3417	14,400	44,500	30,300
FP	3.6875	51.3417	12,900	44,500	31,800
FQ	3.6625	51.3417	11,300	44,500	33,300
FR	3.6375	51.3417	9,900	44,500	34,800
FS	3.6125	51.3417	8,500	44,500	36,400
FT	3.5875	51.3417	7,200	44,500	37,900
FU	3.5625	51.3417	6,200	44,500	39,500
FV	3.5375	51.3417	5,500	44,500	41,100
FW	3.5125	51.3417	5,200	44,500	42,700
FX	3.4875	51.3417	5,500	44,500	44,300
FY	3.4625	51.3417	6,200	44,500	45,900
FZ	4.2375	51.3250	14,800	0	14,800
GA	4.2125	51.3250	13,900	0	13,900
GB	4.1875	51.3250	13,100	0	13,100
GC	4.1625	51.3250	12,600	0	12,600
GD	4.1375	51.3250	12,200	0	12,200
GE	4.1125	51.3250	12,100	0	12,100
GF	4.0875	51.3250	12,200	0	12,200
GG	4.0625	51.3250	12,600	0	12,600
GH	4.0375	51.3250	13,100	0	13,100
GI	4.0125	51.3250	13,900	0	13,900
GJ	3.9875	51.3250	14,500	18,800	14,800
GK	3.9625	51.3250	13,400	18,800	15,800
GL	3.9375	51.3250	12,400	18,800	16,900
GM	3.9125	51.3250	11,600	18,800	18,100

GN	3.8875	51.3250	10,900	18,800	19,400
GO	3.8625	51.3250	10,500	18,800	20,700
GP	3.8375	51.3250	10,400	18,800	22,100
GQ	3.8125	51.3250	10,500	18,800	23,500
GR	3.7875	51.3250	10,900	18,800	25,000
GS	3.7625	51.3250	11,600	18,800	26,500
GT	3.7375	51.3250	12,400	18,800	28,000
GU	3.7125	51.3250	13,400	18,800	29,500
GV	3.6875	51.3250	13,700	44,500	31,000
GW	3.6625	51.3250	12,200	44,500	32,600
GX	3.6375	51.3250	10,900	44,500	34,200
GY	3.6125	51.3250	9,700	44,500	35,700
GZ	3.5875	51.3250	8,600	44,500	37,300
HA	3.5625	51.3250	7,700	44,500	38,900
HB	3.5375	51.3250	7,100	44,500	40,500
HC	3.5125	51.3250	6,900	44,500	42,100
HD	3.4875	51.3250	7,100	44,500	43,700
HE	3.4625	51.3250	7,700	44,500	45,400
HF	4.2375	51.3083	13,400	0	13,400
HG	4.2125	51.3083	12,400	0	12,400
HH	4.1875	51.3083	11,600	0	11,600
HI	4.1625	51.3083	10,900	0	10,900
HJ	4.1375	51.3083	10,500	0	10,500
HK	4.1125	51.3083	10,400	0	10,400
HL	4.0875	51.3083	10,500	0	10,500
HM	4.0625	51.3083	10,900	0	10,900
HN	4.0375	51.3083	11,600	0	11,600
HO	4.0125	51.3083	12,400	0	12,400
HP	3.9875	51.3083	13,300	18,800	13,400
HQ	3.9625	51.3083	12,100	18,800	14,500
HR	3.9375	51.3083	11,000	18,800	15,700
HS	3.9125	51.3083	10,000	18,800	17,000
HT	3.8875	51.3083	9,300	18,800	18,400
HU	3.8625	51.3083	8,800	18,800	19,800
HV	3.8375	51.3083	8,700	18,800	21,200
HW	3.8125	51.3083	8,800	18,800	22,700
HX	3.7875	51.3083	9,300	18,800	24,200
HY	3.7625	51.3083	10,000	18,800	25,700
HZ	3.7375	51.3083	11,000	18,800	27,300
IA	3.7125	51.3083	12,100	18,800	28,800
IB	3.6875	51.3083	13,300	18,800	30,400

IC	3.6625	51.3083	13,300	44,500	32,000
ID	3.6375	51.3083	12,100	44,500	33,600
IE	3.6125	51.3083	11,000	44,500	35,200
IF	3.5875	51.3083	10,000	44,500	36,800
IG	3.5625	51.3083	9,300	44,500	38,400
IH	3.5375	51.3083	8,800	44,500	40,000
II	3.5125	51.3083	8,700	44,500	41,700
IJ	3.4875	51.3083	8,800	44,500	43,300
IK	3.4625	51.3083	9,300	44,500	44,900
IL	4.2375	51.2917	12,100	0	12,100
IM	4.2125	51.2917	11,000	0	11,000
IN	4.1875	51.2917	10,000	0	10,000
IO	4.1625	51.2917	9,300	0	9,300
IP	4.1375	51.2917	8,800	0	8,800
IQ	4.1125	51.2917	8,700	0	8,700
IR	4.0875	51.2917	8,800	0	8,800
IS	4.0625	51.2917	9,300	0	9,300
IT	4.0375	51.2917	10,000	0	10,000
IU	4.0125	51.2917	11,000	0	11,000
IV	3.9875	51.2917	12,100	0	12,100
IW	3.9625	51.2917	10,900	18,800	13,300
IX	3.9375	51.2917	9,700	18,800	14,600
IY	3.9125	51.2917	8,600	18,800	16,000
IZ	3.8875	51.2917	7,700	18,800	17,400
JA	3.8625	51.2917	7,100	18,800	18,900
JB	3.8375	51.2917	6,900	18,800	20,400
JC	3.8125	51.2917	7,100	18,800	22,000
JD	3.7875	51.2917	7,700	18,800	23,500
JE	3.7625	51.2917	8,600	18,800	25,100
JF	3.7375	51.2917	9,700	18,800	26,700
JG	3.7125	51.2917	10,900	18,800	28,300
JH	3.6875	51.2917	12,200	18,800	29,900
JI	3.6625	51.2917	13,700	18,800	31,500
JJ	3.6375	51.2917	13,400	44,500	33,100
JK	3.6125	51.2917	12,400	44,500	34,700
JL	3.5875	51.2917	11,600	44,500	36,300
JM	3.5625	51.2917	10,900	44,500	38,000
JN	3.5375	51.2917	10,000	44,600	39,600
JO	3.5125	51.2917	9,300	44,600	41,300
JP	3.4875	51.2917	8,800	44,600	42,900
JQ	3.4625	51.2917	8,700	44,600	44,600

JR	4.2375	51.2750	10,900	0	10,900
JS	4.2125	51.2750	9,700	0	9,700
JT	4.1875	51.2750	8,600	0	8,600
JU	4.1625	51.2750	7,700	0	7,700
JV	4.1375	51.2750	7,100	0	7,100
JW	4.1125	51.2750	6,900	0	6,900
JX	4.0875	51.2750	7,100	0	7,100
JY	4.0625	51.2750	7,700	0	7,700
JZ	4.0375	51.2750	8,600	0	8,600
KA	4.0125	51.2750	9,700	0	9,700
KB	3.9875	51.2750	10,900	0	10,900
KC	3.9625	51.2750	9,900	18,800	12,200
KD	3.9375	51.2750	8,500	18,800	13,700
KE	3.9125	51.2750	7,200	18,800	15,100
KF	3.8875	51.2750	6,200	18,800	16,600
KG	3.8625	51.2750	5,500	18,800	18,200
KH	3.8375	51.2750	5,200	18,800	19,700
KI	3.8125	51.2750	5,500	18,800	21,300
KJ	3.7875	51.2750	6,200	18,800	22,900
KK	3.7625	51.2750	7,200	18,800	24,500
KL	3.7375	51.2750	8,500	18,800	26,200
KM	3.7125	51.2750	9,900	18,800	27,800
KN	3.6875	51.2750	11,500	18,800	29,400
KO	3.6625	51.2750	13,100	18,800	31,000
KP	3.6375	51.2750	13,700	44,600	32,700
KQ	3.6125	51.2750	12,200	44,600	34,300
KR	3.5875	51.2750	10,900	44,600	36,000
KS	3.5625	51.2750	9,700	44,600	37,700
KT	3.5375	51.2750	8,600	44,600	39,300
KU	3.5125	51.2750	7,700	44,600	41,000
KV	3.4875	51.2750	7,100	44,600	42,700
KW	3.4625	51.2750	6,900	44,600	44,300
KX	4.2375	51.2583	9,900	0	9,900
KY	4.2125	51.2583	8,500	0	8,500
KZ	4.1875	51.2583	7,200	0	7,200
LA	4.1625	51.2583	6,200	0	6,200
LB	4.1375	51.2583	5,500	0	5,500
LC	4.1125	51.2583	5,200	0	5,200
LD	4.0875	51.2583	5,500	0	5,500
LE	4.0625	51.2583	6,200	0	6,200
LF	4.0375	51.2583	7,200	0	7,200

LG	4.0125	51.2583	8,500	0	8,500
LH	3.9875	51.2583	9,900	0	9,900
LI	3.9625	51.2583	9,100	18,800	11,300
LJ	3.9375	51.2583	7,600	18,800	12,900
LK	3.9125	51.2583	6,100	18,800	14,400
LL	3.8875	51.2583	4,800	18,800	16,000
LM	3.8625	51.2583	3,900	18,800	17,600
LN	3.8375	51.2583	3,500	18,800	19,200
LO	3.8125	51.2583	3,900	18,800	20,800
LP	3.7875	51.2583	4,800	18,800	22,500
LQ	3.7625	51.2583	6,100	18,800	24,100
LR	3.7375	51.2583	7,800	18,800	25,800
LS	3.7125	51.2583	9,500	18,800	27,500
LT	3.6875	51.2583	11,200	18,800	29,100
LU	3.6625	51.2583	12,800	18,800	30,800
LV	3.6375	51.2583	12,900	44,600	32,500
LW	3.6125	51.2583	11,300	44,600	34,200
LX	3.5875	51.2583	9,900	44,600	35,900
LY	3.5625	51.2583	8,500	44,600	37,500
LZ	3.5375	51.2583	7,200	44,600	39,200
MA	3.5125	51.2583	6,200	44,600	40,900
MB	3.4875	51.2583	5,500	44,600	42,600
MC	3.4625	51.2583	5,200	44,600	44,300
MD	4.2375	51.2417	9,100	0	9,100
ME	4.2125	51.2417	7,600	0	7,600
MF	4.1875	51.2417	6,100	0	6,100
MG	4.1625	51.2417	4,800	0	4,800
MH	4.1375	51.2417	3,900	0	3,900
MI	4.1125	51.2417	3,500	0	3,500
MJ	4.0875	51.2417	3,900	0	3,900
MK	4.0625	51.2417	4,800	0	4,800
ML	4.0375	51.2417	6,100	0	6,100
MM	4.0125	51.2417	7,600	0	7,600
MN	3.9875	51.2417	9,100	0	9,100
MO	3.9625	51.2417	8,600	18,800	10,700
MP	3.9375	51.2417	6,900	18,800	12,300
MQ	3.9125	51.2417	5,300	18,800	13,900
MR	3.8875	51.2417	3,800	18,800	15,500
MS	3.8625	51.2417	2,400	18,800	17,200
MT	3.8375	51.2417	1,700	18,800	18,800
MU	3.7625	51.2417	7,900	18,800	25,800

MV	3.7375	51.2417	8,500	18,800	26,500
MW	3.7125	51.2417	9,900	18,800	27,900
MX	3.6875	51.2417	11,500	18,800	29,400
MY	3.6625	51.2417	13,100	18,800	31,000
MZ	3.6375	51.2417	12,600	44,600	32,700
NA	3.6125	51.2417	10,900	44,600	34,300
NB	3.5875	51.2417	9,200	44,600	36,000
NC	3.5625	51.2417	7,600	44,600	37,700
ND	3.5375	51.2417	6,100	44,600	39,300
NE	3.5125	51.2417	4,800	44,600	41,000
NF	3.4875	51.2417	3,900	44,600	42,700
NG	3.4625	51.2417	3,500	44,600	44,300
NH	4.2375	51.2250	8,600	0	8,600
NI	4.2125	51.2250	6,900	0	6,900
NJ	4.1875	51.2250	5,300	0	5,300
NK	4.1625	51.2250	3,800	0	3,800
NL	4.1375	51.2250	2,400	0	2,400
NM	4.1125	51.2250	1,700	0	1,700
NN	4.0875	51.2250	2,400	0	2,400
NO	4.0625	51.2250	3,800	0	3,800
NP	4.0375	51.2250	5,300	0	5,300
NQ	4.0125	51.2250	6,900	0	6,900
NR	3.9875	51.2250	8,600	0	8,600
NS	3.9625	51.2250	10,200	0	10,200
NT	3.6125	51.2250	11,300	44,600	34,800
NU	3.4625	51.2250	1,700	44,600	44,600
NV	4.2375	51.2083	8,400	0	8,400
NW	4.2125	51.2083	6,700	0	6,700
NX	4.1875	51.2083	5,000	0	5,000
NY	4.2375	51.1917	8,600	0	8,600

Appendix D - Distance from Port to Sites (km)

24	23.5	23.1	22.8	22.6	22.5	22.6	22.8	23.1	23.5	24	24.7	25.4	26.2	27.1	28.1	29.1	30.2	31.4	32.6	33.8	35.1	36.4	37.7	39.1	40.5	41.9					
22.4	21.9	21.4	21.1	20.9	20.8	20.9	21.1	21.4	21.9	22.4	23.1	23.9	24.8	25.7	26.7	27.8	29	30.2	31.4	32.7	34	35.3	36.7	38.1	39.5	41					
20.8	20.2	19.7	19.4	19.1	19.1	19.1	19.4	19.7	20.2	20.8	21.6	22.4	23.3	24.3	25.4	26.6	27.8	29	30.3	31.6	33	34.4	35.8	37.2	38.6	40.1	41.6	43.1	44.6	46.1	
19.3	18.6	18	17.7	17.4	17.3	17.4	17.7	18	18.6	19.3	20.1	20.9	21.9	23	24.1	25.3	26.6	27.9	29.2	30.6	32	33.4	34.9	36.3	37.8	39.3	40.8	42.4	43.9	45.5	47
17.7	17	16.4	16	15.7	15.6	15.7	16	16.4	17	17.7	18.6	19.5	20.6	21.7	22.9	24.2	25.5	26.8	28.2	29.6	31.1	32.6	34	35.5	37.1	38.6	40.1	41.7	43.3	44.8	46.4
16.2	15.4	14.8	14.3	14	13.9	14	14.3	14.8	15.4	16.2	17.1	18.2	19.3	20.5	21.8	23.1	24.5	25.9	27.3	28.8	30.3	31.8	33.3	34.8	36.4	37.9	39.5	41.1	42.7	44.3	45.9
14.8	13.9	13.1	12.6	12.2	12.1	12.2	12.6	13.1	13.9	14.8	15.8	16.9	18.1	19.4	20.7	22.1	23.5	25	26.5	28	29.5	31	32.6	34.2	35.7	37.3	38.9	40.5	42.1	43.7	45.4
13.4	12.4	11.6	10.9	10.5	10.4	10.5	10.9	11.6	12.4	13.4	14.5	15.7	17	18.4	19.8	21.2	22.7	24.2	25.7	27.3	28.8	30.4	32	33.6	35.2	36.8	38.4	40	41.7	43.3	44.9
12.1	11	10	9.3	8.8	8.7	8.8	9.3	10	11	12.1	13.3	14.6	16	17.4	18.9	20.4	22	23.5	25.1	26.7	28.3	29.9	31.5	33.1	34.7	36.3	38	39.6	41.3	42.9	44.6
10.9	9.7	8.6	7.7	7.1	6.9	7.1	7.7	8.6	9.7	10.9	12.2	13.7	15.1	16.6	18.2	19.7	21.3	22.9	24.5	26.2	27.8	29.4	31	32.7	34.3	36	37.7	39.3	41	42.7	44.3
9.9	8.5	7.2	6.2	5.5	5.2	5.5	6.2	7.2	8.5	9.9	11.3	12.9	14.4	16	17.6	19.2	20.8	22.5	24.1	25.8	27.5	29.1	30.8	32.5	34.2	35.9	37.5	39.2	40.9	42.6	44.3
9.1	7.6	6.1	4.8	3.9	3.5	3.9	4.8	6.1	7.6	9.1	10.7	12.3	13.9	15.5	17.2	18.8			25.8	26.5	27.9	29.4	31	32.7	34.3	36	37.7	39.3	41	42.7	44.3
8.6	6.9	5.3	3.8	2.4	1.7	2.4	3.8	5.3	6.9	8.6	10.2														34.8						44.6
8.4	6.7	5			Ilfracombe																										
8.6																															

Appendix E - Distance Between Grid Connection Points and Sites (km)

			3.8	4.8	6.2	7.7	9.3	8.7	6.9	5.2	3.5	1.7	Minhead	
		1.7	2.4	3.9	5.5	7.1	8.8	8.8	7.1	5.5	3.9			
	Llantwit Major	0.8	1.7	3.5	5.2	6.9	8.7	9.3	7.7	6.2	4.8			
		1.7	2.4	3.9	5.5	7.1	8.8	10	8.6	7.2	6.1			
		3.4	3.8	4.8	6.2	7.7	9.3	10.9	9.7	8.5	7.6			
6.1	5.3	5	5.3	6.1	7.2	8.6	10	11.6	10.9	9.9	9.2			
7.6	6.9	6.7	6.9	7.6	8.5	9.7	11	12.4	12.2	11.3	10.9	11.3		
9.1	8.6	8.4	8.6	9.1	9.9	10.9	12.1	13.4	13.7	12.9	12.6			
10.7	10.2	10.1	10.2	10.7	11.3	12.2	13.3	13.7	13.1	12.8	13.1			
12.3	11.9	11.8	11.9	12.3	12.9	13.7	13.3	12.2	11.5	11.2	11.5			
13.9	13.6	13.4	13.6	13.9	14.4	13.4	12.1	10.9	9.9	9.5	9.9			
15.5	15.2	15.1	15.2	15.4	13.9	12.4	11	9.7	8.5	7.8	8.5			
17.2	16.9	16.8	16.4	14.8	13.1	11.6	10	8.6	7.2	6.1	7.9			
18.8	18.6	17.7	16	14.3	12.6	10.9	9.3	7.7	6.2	4.8				
20.5	19.1	17.4	15.7	14	12.2	10.5	8.8	7.1	5.5	3.9				
20.8	19.1	17.3	15.6	13.9	12.1	10.4	8.7	6.9	5.2	3.5	1.7	Lynton		
20.9	19.1	17.4	15.7	14	12.2	10.5	8.8	7.1	5.5	3.9	2.4			
21.1	19.4	17.7	16	14.3	12.6	10.9	9.3	7.7	6.2	4.8	3.8			
21.4	19.7	18	16.4	14.8	13.1	11.6	10	8.6	7.2	6.1	5.3			
21.9	20.2	18.6	17	15.4	13.9	12.4	11	9.7	8.5	7.6	6.9			
22.4	20.8	19.3	17.7	16.2	14.8	13.4	12.1	10.9	9.9	9.1	8.6	10.2		
23.1	21.6	20.1	18.6	17.1	15.8	14.5	13.3	12.1	10.9	9.9	9.1	8.6		
23.5	21.9	20.2	18.6	17	15.4	13.9	12.4	11	9.7	8.5	7.6	6.9		
23.1	21.4	19.7	18	16.4	14.8	13.1	11.6	10	8.6	7.2	6.1	5.3		
22.8	21.1	19.4	17.7	16	14.3	12.6	10.9	9.3	7.7	6.2	4.8	3.8		
22.6	20.9	19.1	17.4	15.7	14	12.2	10.5	8.8	7.1	5.5	3.9	2.4		
22.5	20.8	19.1	17.3	15.6	13.9	12.1	10.4	8.7	6.9	5.2	3.5	1.7	Ilfracombe	
22.6	20.9	19.1	17.4	15.7	14	12.2	10.5	8.8	7.1	5.5	3.9	2.4		
22.8	21.1	19.4	17.7	16	14.3	12.6	10.9	9.3	7.7	6.2	4.8	3.8		
23.1	21.4	19.7	18	16.4	14.8	13.1	11.6	10	8.6	7.2	6.1	5.3	5	
23.5	21.9	20.2	18.6	17	15.4	13.9	12.4	11	9.7	8.5	7.6	6.9	6.7	
24	22.4	20.8	19.3	17.7	16.2	14.8	13.4	12.1	10.9	9.9	9.1	8.6	8.4	8.6

Appendix F - Turbine Operational Information

F.1: Percentage of Time Spent at Rated Power (%)

			0.00%	0.23%	4.37%	4.83%	3.37%	3.01%	3.42%	3.33%	1.12%	0.24%		
		0.00%	0.00%	0.12%	1.95%	4.89%	4.61%	3.00%	3.50%	3.45%	10.73%			
		0.00%	0.00%	0.00%	0.53%	0.31%	3.35%	5.26%	6.13%	5.48%	1.49%			
		0.00%	0.00%	0.95%	1.06%	1.03%	6.77%	9.88%	3.61%	0.82%	0.00%			
		0.00%	1.94%	2.50%	5.16%	8.63%	9.17%	7.35%	3.08%	0.49%	0.00%			
0.00%	0.00%	0.15%	2.25%	3.07%	4.20%	6.27%	4.10%	4.64%	4.60%	1.32%	0.20%			
0.00%	0.00%	0.00%	0.33%	1.79%	3.24%	3.68%	5.21%	6.56%	3.49%	1.19%	0.00%	0.00%		
0.00%	0.00%	0.00%	0.00%	0.00%	0.38%	1.44%	5.21%	4.27%	2.27%	0.61%	0.00%			
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.37%	3.66%	2.73%	1.64%	0.96%	0.00%			
0.00%	0.00%	0.00%	0.00%	0.00%	1.16%	2.08%	4.88%	4.23%	2.73%	0.19%	0.00%			
0.00%	0.00%	0.00%	0.00%	0.12%	1.19%	2.40%	3.83%	9.04%	3.42%	0.00%	0.00%			
0.00%	0.00%	0.00%	0.68%	1.01%	1.84%	2.16%	4.66%	3.87%	0.62%	0.00%	0.00%			
0.00%	0.00%	0.00%	0.00%	0.29%	1.57%	2.84%	2.93%	0.29%	0.43%	0.00%	0.00%			
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.74%	0.34%	0.00%	0.32%	2.56%				
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.20%	0.74%	0.30%	0.89%	3.24%				
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.26%	0.79%	2.01%	0.00%	0.00%			
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.44%	0.14%	0.00%	0.00%			
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%			
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%			
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%			
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%		
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%		
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%		
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%		
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%		
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%		
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%		
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.60%		
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.59%	0.00%	
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

F.2: Percentage of Time Turbine is Non-Operational (%)

48.61%	48.87%	48.09%	46.30%	44.04%	45.79%	47.35%	44.51%	41.80%	42.45%	42.78%	41.23%	41.70%	42.22%	40.50%	39.45%	37.84%	38.05%	39.40%	35.90%	31.48%	34.23%	37.92%	43.23%	41.43%	46.94%	73.63%					
46.96%	47.67%	47.97%	45.67%	42.82%	44.51%	44.87%	43.85%	42.74%	40.26%	40.22%	39.93%	40.34%	39.64%	38.92%	38.05%	37.04%	35.50%	34.75%	33.25%	31.00%	29.62%	32.12%	33.60%	34.82%	42.37%	41.97%					
45.76%	44.92%	46.19%	44.53%	42.93%	43.65%	42.92%	41.90%	41.09%	40.03%	38.86%	38.12%	37.94%	37.63%	36.72%	36.89%	36.42%	33.88%	33.85%	31.13%	28.14%	28.18%	29.99%	30.77%	31.00%	29.95%	26.98%	30.39%	34.36%	54.91%	89.41%	
43.92%	43.52%	42.67%	42.21%	41.71%	43.37%	42.70%	39.76%	38.66%	38.95%	38.19%	37.39%	36.01%	34.85%	34.98%	35.16%	33.32%	32.69%	31.69%	29.00%	26.89%	28.72%	29.65%	28.83%	28.43%	26.84%	25.09%	25.28%	29.43%	34.87%	34.92%	44.02%
42.62%	40.31%	41.00%	40.75%	39.74%	42.68%	43.30%	39.30%	38.75%	37.20%	36.80%	37.11%	34.44%	34.14%	34.09%	32.81%	31.72%	30.59%	29.98%	27.34%	26.52%	27.99%	28.09%	28.66%	27.72%	25.49%	24.86%	25.19%	26.48%	28.03%	27.97%	27.66%
42.36%	38.56%	39.02%	38.36%	38.42%	40.63%	40.92%	39.45%	39.01%	37.04%	34.90%	34.85%	33.85%	33.25%	32.95%	31.32%	30.11%	30.59%	28.16%	26.35%	26.04%	26.59%	26.50%	28.25%	27.23%	24.60%	24.17%	23.81%	26.39%	27.36%	25.65%	23.93%
40.76%	38.06%	36.72%	36.28%	36.57%	37.49%	38.03%	38.46%	38.02%	36.23%	34.25%	33.36%	32.56%	30.88%	30.83%	30.89%	29.47%	30.59%	27.23%	25.51%	25.89%	25.69%	25.96%	26.46%	26.26%	24.82%	23.55%	22.73%	26.74%	27.81%	23.84%	23.90%
39.41%	37.21%	35.56%	34.97%	34.74%	35.27%	35.08%	36.49%	37.90%	36.22%	34.82%	32.84%	30.62%	30.09%	29.64%	29.61%	28.22%	30.59%	28.05%	25.49%	24.34%	25.04%	24.14%	25.06%	24.19%	24.19%	24.51%	22.70%	23.43%	25.14%	24.13%	24.50%
37.50%	36.00%	35.38%	34.76%	33.89%	34.46%	33.98%	34.42%	36.96%	36.62%	34.47%	32.25%	30.69%	30.79%	30.24%	27.84%	27.04%	30.59%	28.21%	27.82%	24.91%	22.70%	24.40%	25.40%	24.43%	23.62%	24.39%	23.43%	22.50%	24.00%	24.91%	25.31%
36.32%	34.14%	33.38%	33.47%	33.04%	33.75%	34.46%	34.16%	34.59%	35.74%	34.19%	32.41%	31.19%	31.24%	31.10%	28.64%	25.57%	30.59%	26.80%	26.97%	27.10%	24.91%	25.23%	25.94%	25.42%	24.80%	24.06%	25.34%	24.63%	23.69%	25.13%	25.18%
35.24%	33.00%	31.01%	30.94%	31.58%	32.68%	35.02%	35.31%	34.82%	35.89%	34.69%	33.06%	32.31%	31.40%	33.47%	34.61%	28.53%	30.59%	24.59%	27.61%	32.07%	31.66%	27.60%	26.15%	26.50%	25.88%	25.78%	26.83%	26.48%	23.64%	24.47%	24.92%
33.99%	31.43%	29.48%	29.40%	29.71%	33.16%	34.91%	35.35%	37.38%	38.58%	39.67%	34.31%	30.08%	37.12%	42.54%	54.51%	80.12%			32.45%	46.63%	38.45%	32.82%	29.32%	27.62%	28.13%	26.93%	30.65%	29.60%	25.59%	21.80%	25.99%
31.46%	32.51%	27.78%	25.68%	32.00%	35.15%	35.96%	36.65%	40.71%	48.62%	58.27%	72.41%														41.06%						26.96%
30.84%	36.58%	78.66%																													
38.14%																															

F.3: Percentage of Time Spent Cutting in (%)

51.39%	51.13%	51.91%	53.70%	55.96%	54.21%	52.65%	55.49%	58.20%	57.55%	57.22%	58.77%	58.30%	57.78%	59.50%	60.55%	62.16%	61.95%	60.60%	64.10%	68.52%	65.77%	62.08%	56.77%	58.57%	53.06%	26.37%					
53.04%	52.33%	52.03%	54.33%	57.18%	55.49%	55.13%	56.15%	57.26%	59.74%	59.78%	60.07%	59.66%	60.36%	61.08%	61.95%	62.96%	64.50%	65.25%	66.75%	69.00%	70.38%	67.88%	66.40%	65.18%	57.63%	58.03%					
54.24%	55.08%	53.81%	55.47%	57.07%	56.35%	57.08%	58.10%	58.91%	59.97%	61.14%	61.88%	62.06%	62.37%	63.28%	63.11%	63.58%	66.12%	66.15%	68.87%	71.86%	71.82%	70.01%	69.23%	69.00%	70.05%	72.87%	69.61%	65.64%	45.09%	10.59%	
56.08%	56.48%	57.33%	57.79%	58.29%	56.63%	57.30%	60.24%	61.34%	61.05%	61.81%	62.61%	63.99%	65.15%	65.02%	64.84%	66.68%	67.31%	68.31%	71.00%	72.43%	71.28%	70.35%	71.17%	71.57%	72.83%	72.66%	72.78%	70.57%	65.13%	65.08%	55.98%
57.38%	59.69%	59.00%	59.25%	60.26%	57.32%	56.70%	60.70%	61.25%	62.80%	63.20%	62.89%	65.56%	65.86%	65.91%	67.19%	68.28%	69.41%	70.02%	72.36%	72.47%	71.89%	71.91%	71.34%	72.28%	72.71%	72.07%	72.32%	72.58%	71.97%	71.91%	72.11%
57.64%	61.44%	60.98%	61.64%	61.58%	59.37%	59.08%	60.55%	60.99%	62.96%	65.10%	65.15%	66.15%	66.75%	67.05%	68.68%	69.89%	69.41%	71.84%	72.08%	72.13%	72.22%	72.35%	71.75%	72.40%	72.16%	71.63%	71.03%	72.55%	72.10%	72.39%	71.70%
59.24%	61.94%	63.28%	63.72%	63.43%	62.51%	61.97%	61.54%	61.98%	63.77%	65.75%	66.64%	67.44%	69.12%	69.17%	69.11%	70.53%	69.21%	72.03%	71.65%	71.95%	71.92%	71.96%	72.18%	72.30%	71.49%	70.17%	68.64%	72.23%	71.88%	71.27%	71.27%
60.59%	62.79%	64.44%	65.03%	65.26%	64.73%	64.92%	63.51%	62.10%	63.78%	65.18%	67.16%	69.38%	69.91%	70.36%	70.39%	71.51%	68.67%	71.61%	71.58%	71.01%	71.12%	70.98%	71.28%	70.60%	70.60%	71.39%	68.14%	69.80%	71.50%	71.27%	72.14%
62.50%	64.00%	64.62%	65.24%	66.11%	65.54%	66.02%	65.58%	63.04%	63.38%	65.53%	67.75%	69.31%	69.21%	69.76%	71.72%	72.17%	69.11%	71.79%	71.89%	71.21%	68.26%	71.37%	71.87%	71.30%	69.82%	70.97%	69.22%	67.62%	70.74%	72.08%	71.68%
63.68%	65.86%	66.62%	66.53%	66.96%	66.25%	65.54%	65.84%	65.41%	64.26%	65.81%	67.59%	68.81%	68.76%	68.90%	71.22%	72.43%	68.53%	72.88%	72.59%	72.27%	71.67%	72.03%	72.43%	72.31%	71.71%	71.33%	71.58%	71.76%	70.18%	71.37%	71.41%
64.76%	67.00%	68.99%	69.06%	68.42%	67.32%	64.98%	64.69%	65.18%	64.11%	65.31%	66.94%	67.69%	68.60%	66.53%	65.39%	71.47%	66.17%	72.85%	72.39%	67.93%	68.34%	72.21%	72.89%	72.88%	72.93%	72.90%	72.68%	72.70%	70.88%	72.08%	71.75%
66.01%	68.57%	70.52%	70.60%	70.29%	66.84%	65.09%	64.65%	62.62%	61.42%	60.33%	65.69%	69.92%	62.88%	57.46%	45.49%	19.88%			67.55%	53.37%	61.55%	67.18%	70.68%	72.38%	71.87%	72.87%	69.35%	70.40%	72.92%	67.48%	72.88%
68.54%	67.49%	71.63%	72.72%	68.00%	64.85%	64.04%	63.35%	59.29%	51.38%	41.73%	27.59%														58.94%						72.80%
69.16%	63.42%	21.34%																													
61.86%																															

Appendix G - GaBi Parameters

The following is a list of the parameters defined and used in the GaBi LCA model for the case study presented. Note that parameters highlighted are variable between sites.

Parameter folder	Parameter	Value	Comments
Back pillars Info	BP_area	24.8	Surface area of Back pillars (m^2)
Back pillars Info	BP_cut	8.2	Cut length of Back pillars (m)
Back pillars Info	BP_mass_F	869.6	Final mass value of Back pillars (kg)
Back pillars Info	BP_number	2	Number of components
Back pillars Info	BP_weld	3.7	Length of weld required (m)
Concrete blocks	back_mass	17460	Mass of concrete back block (kg)
Concrete blocks	back_num	2	Number of back blocks
Concrete blocks	front_mass	46440	Mass of concrete front block (kg)
Concrete blocks	Front_num	1	Number of front blocks
Concrete Holders Info	CH_area	2.84	Surface area of concrete holder (m^2)
Concrete Holders Info	CH_Cut	8.8	Cut length of Concrete Holders (m)
Concrete Holders Info	CH_mass_F	203	Final mass value of Concrete Holders (kg)
Concrete Holders Info	CH_number	4	Number of components
Concrete Holders Info	CH_Weld	4	Length of weld required (m)
Core Cable Par	CP	5.5	Outer radius of the copper cores (mm)
Core Cable Par	PP_Cover1	7.5	Outer diameter of the pp cover layer 1(mm)
Core Cable Par	PP_Cover2	9	Outer diameter of the pp cover layer 2(mm)
Core Cable Par	PP_fill1	7	Outer radius of the pp filler layer 1(mm)
Core Cable Par	ST_pro1	8.5	Outer diameter of the steel protection layer 1(mm)
Distance	cable_mass	5.641	Mass of cable per m (kg/m)
Distance	cable_to_site	20000	Distance from cable land connection to site (m)
Distance	Elec	20	Avg power output from turbine (kW)
Distance	Harb_to_cable	15000	Distance from harbour to cable shore connection (m)
Distance	Harb_to_site	10000	Distance from harbour to site (m)
Distance	turbine_mass	116591.05	Total turbine mass (kg)
End of Life	St_RR	0.8	Steel recovery rate (%)
Front pillar Info	FP_Area	29.6	Surface area of Front pillar (m^2)
Front pillar Info	FP_cut	8.2	Cut length of Front pillar (m)
Front pillar Info	FP_mass_F	2255.7	Final mass value of Front pillar (kg)
Front pillar Info	FP_number	1	Number of components
Front pillar Info	FP_weld	3.7	Length of weld required (m)
Leg Info	L_Area	5.7	Surface area of leg (m^2)
Leg Info	L_Cut	15.8	Cut length of leg (m)

Leg Info	L_Mass_F	421.1	Final mass value of leg (kg)
Leg Info	L_Number	3	Number of components
Leg Info	L_Weld	9.5	Length of weld required (m)
Manufacturing processes	Abrasive	60	Abrasive required per meter squared (kg/m^2)
Manufacturing processes	Air_blasting	0.14	Volume of 14 bar compressed air required to blast 1m of surface area (m^3)
Manufacturing processes	Air_Paint	0.7	Volume of 6 bar compressed air required to paint 1m of surface area (m^3)
Manufacturing processes	Argon_den	1.7839	Density of Argon Kg/m^3
Manufacturing processes	Bending_Pass	2	Number of bending passes required to bend 3/4inch steel sheet
Manufacturing processes	bending_power	55	Bending power consumption (kW)
Manufacturing processes	bending_speed	3	Bending speed in meters per min (m/min)
Manufacturing processes	blasting_removal	0.1	kg steel removed per meter squared blasting (kg/m^2)
Manufacturing processes	CO2_den	1.977	Density of carbon dioxide (kg/m^3)
Manufacturing processes	Cut_speed	40	Speed of PAC cutting meters per hour
Manufacturing processes	elec_cutting	16	Electricity used per meter cutting (kwh per m)
Manufacturing processes	elec_weld	8	Electricity used per meter welding (kw)
Manufacturing processes	PAC_Heat	169.53	Waste heat from plasma arc cutting (KJ)
Manufacturing processes	PAC_S_gas_AR	0.0378	PAC shield gas flow rate (m^3 per m cut)
Manufacturing processes	Paint	0.5	kg paint applied per meter squared (kg/m^2)
Manufacturing processes	S_Gas_Argon	0.82	(%) shield gas Argon
Manufacturing processes	S_Gas_CO2	0.18	(%) shield gas CO2
Manufacturing processes	S_Gas_weld	241	Shield gas consumption welding (L/m)
Manufacturing processes	Steel_scrap_rate	10	Steel scrap rate (%)
Manufacturing processes	W_pass	6	Number of welding passes (#)
Manufacturing processes	W_Speed	21.6	Speed of welding in meters per hour
Manufacturing processes	Weld	0.1	Mass of weld per meter (kg/m)
Manufacturing processes	Weld_heat	1	Heat out of welding process (KJ)
Outer Cable Parameters	Core_num	3	(#) number of core cables
Outer Cable Parameters	CP_den	8960	(kg/m^3) density of copper
Outer Cable Parameters	HDPE_den	930	(kg/m^3) density of HDPE outer casing
Outer Cable Parameters	HDPE_out	24	(mm) outer diameter of the HDPE outer casing
Outer Cable Parameters	PP_C_den	860	(kg/m^3) density of PP covers
Outer Cable Parameters	pp_cover3	21	(mm) outer diameter of the pp cover layer 3
Outer Cable Parameters	pp_F_den	860	(kg/m^3) density of PP filler
Outer Cable Parameters	pp_filler2	20.5	(mm) outer diameter of the pp filer layer 2

Outer Cable Parameters	st_den	7000	(kg/m^3) density of the steel protection wires
Outer Cable Parameters	St_pro2	22	(mm) outer diameter of the steel protection layer 2
Ship	cable_fule_con	200	L/h fuel consumption of engines when laying cable
Ship	cable_laying_speed	10000	ship cable laying speed (m/h)
Ship	F_density	1.194	1.194 L of fuel = 1kg fuel
Ship	Fuel_Rate	376.5	engine fuel consumption (L/hr) when ship is transporting goods
Ship	generator_fule_con	24.6	(L/h)
Ship	generator_num	2	
Ship	num_engins	2	number of engines on ship
Ship	onsite_fule_con	100	(L/h) fuel consumed by main engine when stationary at site
Ship	S_Content_fule	10	Sulphur content in diesel fuel (ppm)
Ship	Share_CO2_bio	0.05	Share of biogenic C in fuel (%)
Ship	Speed	19600	ship transport speed (m/h)
Ship	time_on_site	0.5	(h) time spend onsite deploying turbines
T-Base info	TB_area	209.7	surface area of T-Base (m^2)
T-Base info	TB_cut	304.7	cut length of T-Base (m)
T-Base info	TB_mass_F	15579.3	final mass value of T-Base (kg)
T-Base info	TB_number	1	number of components
T-Base info	TB_weld	300.4	length of weld required (m)
Turbine Holder info	TH_area	24.5	surface area of Turbine Holder (m^2)
Turbine Holder info	TH_bend	3.14	(m) length of bend in the turbine holder
Turbine Holder info	TH_cut	15.9	cut length of Turbine Holder (m)
Turbine Holder info	TH_mass_F	1788.5	final mass value of Turbine Holder (kg)
Turbine Holder info	TH_number	1	Number of components
Turbine Holder info	TH_weld	0	Length of weld required (m)
Turbine Nacelle	TN_area	62.2	Surface area of Turbine Nacelle (m^2)
Turbine Nacelle	TN_bend	6.28	(m) length of bend
Turbine Nacelle	TN_cut	16.3	Cut length of Turbine Nacelle (m)
Turbine Nacelle	TN_mass_F	5823.8	final mass value of Turbine Nacelle (kg)
Turbine Nacelle	TN_number	1	Number of components
Turbine Nacelle	TN_weld	12.3	Length of weld required (m)
Turbine_Char	DT_main	30	(days) number of days taken to maintain the turbine
Turbine_ Char	Life	20	(years) expected life of turbine
Turbine_ Char	Main_vist	4	(years) number of maintenance visits
Turbine_ Char	T_on_main	0.5	(hours) time on site for maintenance visit
Turbine_ Char	Turb_num	1	(#) number of turbines being deployed

Appendix H - Voe Earl - Fuel Consumption Specifications

H.1: Voe Earl Specification Sheet

General

Type of vessel	: Damen Multicat®2613
Builder	: Damen Shipyards Hardinxveld
	: Yard No. 571655
Basic Functions	: Anchor handling, dredger service, supply, Towing, hose handling, survey, ship assist, Cable lay, dive support, ROV support. Salvage & salvage support
Classification	: Bureau Veritas, I✠Hull•MACH Tug • AUT UMS
	: Unrestricted Navigation
	: Nat. Authorities
	: MCA workboat Category 1
	: 150 miles from shore

Dimensions

Length o.a.	: 24.07m
Beam	: 12.97m
Depth at sides	: 4.00m
Draught aft	: 3.5m

Tank Capacities

Fuel oil	: 120.00m^3
Fresh water	: 51.10m^3
Ballast water	: 30.00m^3
Black/grey water	: 7.30m^3
Dirty oil	: 3.60m^3
Free deck space	: 180m^2
Deck loading	: 10 t/m^2

Performances

Bollard Pull	: 53.4 tons (certified)
Bollard Pull astern	: 35.0 tons
Speed	:10.6 knots

Propulsion System

Main engines	: 2 x Caterpillar 3512 B TA
Total power	: 2850 bkW at 1600 rpm
Gearboxes	: 2 x Reintjes WAF 773 7.087:1
Propulsion	: 2 x fixed pitch props in nozzles, 2400mm
Bowthruster	: 2 x Kalkman 257kW in pushbows
Rudders	: 2 x Independent fishtail 45º

Auxiliary Systems

Generator sets	: 2 x Caterpillar C 04.4, 107kVA each
Harbour set	: Caterpillar – C 04.4, 60kVA
Hydraulic power	: Caterpillar C-32 TTA, 970kW at 1800 rpm
Transfer pumps	: Fuel & fresh water - 50m^3/hr

Deck Lay-out

Deck cranes	: 2 x Effer 200.000 4S | 10.5 T @ 16m
Towing winch	: 50T pull, 125T brake | 700m x 48mm
Anchor handling	: 100T pull, 150T brake | 150m x 48mm
Tugger/Mooring winches	: 4 x 13T pull | 200m x 22mm + 19mm ground chain
Mooring spread	: 4 x 1000kg Delta Flippers + cowcatchers
Pop-ups fore deck	: Shark Jaw – Triplex H-200
	: Guide Pins – Triplex S-65
	: Side pins – WK 400
Pop-ups aft deck	: WK Triple pin type
Towing hook	: Mampaey 45 T
Bow roller	: 100 T SWL 6m, Ø 1200mm
Stern roller	: 60 T SWL 2m, Ø 760mm
Capstan	: WK 5 tons

Accommodation

Comfortable heated and air-conditioned accommodation
For 8 persons, in 4 cabins, galley, sanitary facilities, etc.

Navigation & Communication

Radar system	: 2 x JMA 5208-6'+4' (ARPA)
Compass	: Caessens & Plath
Gyrocompass	: Alphaminicourse
Echosounder	: 2 x JRC JFE-380 in pushbows
DGPS	: 2 x JRC JLR7800
Speedlog	: JRC JLN 205
Chart Plotter	: Navisailor 4000ECS + Backup
Autopilot	: Alphatron Multicourse
Navtex	: JRC NCR 333
Intercom	: Alphacall MF (9 Stations)
VHF	: 2 x Sailor RT 6222 / DSC
VHF Handheld	: 3 x Icom IC-M71
VHF GMDSS	: 2 x Sailor SP3520
Inmarsat-C	: 2 x Sailor TT6110
AIS	: JRC JHS 182 Class A
SSB	: Sailor System TT6000
UPS system	: APC 1600W – 220V
CCTV	: 4 x Alphatron Eclips
Sat TV	: Intellian I6p

GSM cellphone, email & internet (coastal)

Additional

DP System	: Navis JP3000
Seabed levelling/dredging	: Aft Portal A-frame (1 x 60t SWL or 2 x 30t SWL)

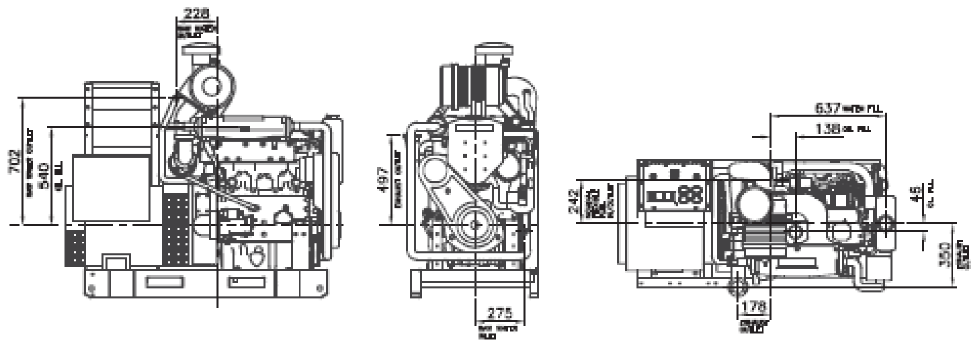
H.2: Caterpillar C4.4 Generator Set Specification

CATERPILLAR®

C4.4 MARINE GENERATOR SET

50 Hz, 1500 rpm **86 ekW (107 kVA)**

Right Side Front Footprint (Bottom View)



DIMENSIONS

Engine Dimensions		
	Open mm (in)	Enclosed mm (in)
Overall Length	1589 (62.56)	1750 (68.9)
Overall Height*	1132 (44.60)	1215 (47.8)
Overall Width	724 (28.54)	1000 (39.4)

*Height dimension does not include remote-mounted air filter or electronic control panel.

CATERPILLAR GENERATOR

Power Factor 1.0
Frame C4.4
Insulation .... Class H
Temperature Rise
@ 40°C Ambient .... Class H (150°K)
Winding Pitch Code 2/3
Terminals .... 12 lead reconnectable
Drip Proof .... IP 23
Air Flow 50 Hz .... 0.37 m³/s (784 cfm)
Excitation System .... AREP
Voltage Regulation (steady state) .... ±0.5%
Total Harmonic Content LL/LN............. <4%
Wave Form: NEMA=TIF.................... <50
Wave Form: I.E.C.=THF .... <2%

PERFORMANCE DATA

50 Hz DITA

Fuel Consumption
@ Full Power 24.6 L/hour 6.50 gph

ENCLOSED SOUND DATA

50 Hz DINA

Sound levels are average sound pressure level @ 1 meter and 100% load 71.9 db(A)

RATING CONDITIONS

***Ratings** are based on SAE J1228/ISO8665 standard conditions of 100 kPa (29.61 in. Hg), 25°C (77°F), and 30% relative humidity. These ratings also apply at ISO3046/1, DIN6271/3, and BS5514 conditions of 100 kPa (29.61 in. Hg), 27°C (81°F), and 60% relative humidity.

Fuel rates are based on fuel oil of 35° API [16°C (60°F)] gravity having an LHV of 42 780 kJ/kg (18,390 Btu/lb) when used at 29°C (85°F) and weighing 838.9 g/L (7.001 lb/U.S. gal).

Additional ratings may be available for specific customer requirements. Consult your Caterpillar representative for additional information.

*Ratings at 50°C (122°F) ambient are 85.5 ekW (107 kVA).

Performance data is calculated in accordance with tolerances and conditions stated in this specification sheet and is only intended for purposes of comparison with other manufacturers' engines. Actual engine performance may vary according to the particular application of the engine and operating conditions beyond Caterpillar's control.

UK Sourced
LEHM5096-03 (8-07)

Materials and specifications are subject to change without notice.
The International System of Units (SI) is used in this publication.

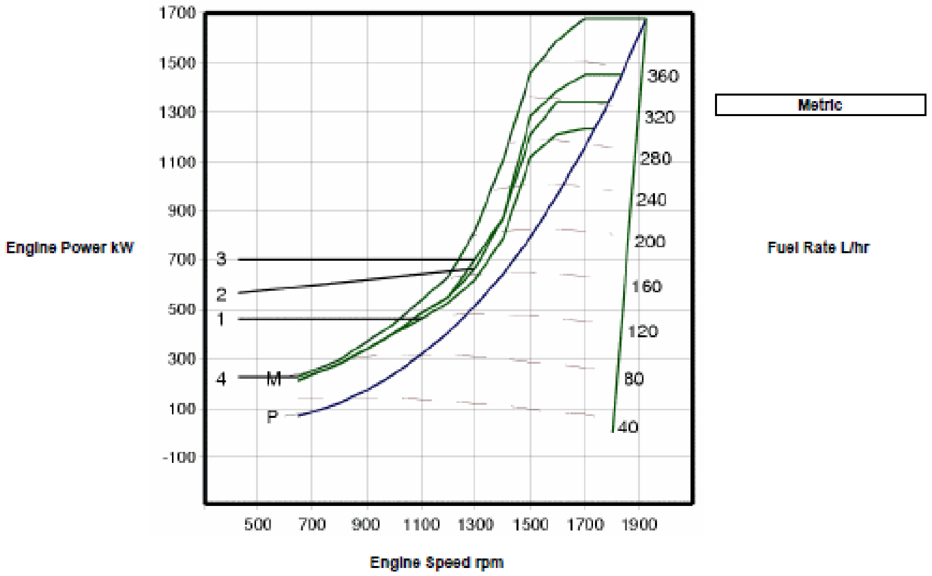
H.3: Caterpillar 3512B Marine Propulsion Unit Specification

CATERPILLAR **3512B** **MARINE PROPULSION**

2282 mhp (2250 bhp) 1678 bkW

PERFORMANCE CURVES

E-HP/HIP - DM6904-01 Aftercooler Temperature 30° C (86° F)



Engine Speed rpm	Engine Power kW	Engine Torque N·m	BSFC g/kW-hr	Fuel Rate L/hr	Engine Speed rpm	Engine Power kW	Engine Torque N·m	BSFC g/kW-hr	Fuel Rate L/hr
Zone 1 Curve 1					**Max Limit Curve 4**				
1735	1230.5	6773	201	294.8	1925	1678	8324	207.4	414.9
1500	1122	7143	200.2	267.7	1600	1586	9466	199.1	376.5
1300	623	4576	208.3	154.7	1400	1108	7558	202.1	266.9
1100	464	4028	213.9	118.3	1100	533	4627	218.4	138.8
900	340	3608	221.6	89.8	900	370	3926	225	99.2
650	211	3100	230	57.9	650	224	3291	233.2	62.3
Zone 2 Curve 2					**Prop Demand Curve P**				
1785	1342	7179	202.4	323.8	1925	1678	8324	207.4	414.9
1500	1210	7703	199.3	287.5	1600	963.5	5751	200.9	230.7
1300	665	4885	208.3	165.1	1400	645.5	4403	206.3	158.8
1100	481	4176	214.8	123.2	1100	313.1	2718	213.1	79.5
900	340	3608	221.7	89.9	900	171.5	1820	226.1	46.2
650	211	3100	230	57.9	650	64.6	949	285.1	22.0
Zone 3 Curve 3									
1835	1454	7567	203.9	353.4	1925	1678	8324	207.4	414.9
1500	1289	8206	199.2	306.1	1600	1586	9466	199.1	376.5
1300	705	5179	208.3	175.1	1400	1108	7558	202.1	266.9
1100	481	4176	214.8	123.2	1100	533	4627	218.4	138.8
900	340	3608	221.7	89.9	900	370	3926	225	99.2
650	211	3100	230	57.9	650	224	3291	233.2	62.3

NOTE: Curve P is a cubic prop demand curve with 3.0 exponent for displacement hulls only.

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Appendix I - Combination Tool Overview

Turbine spec

63.62	m2	Turbine area
1025	kg/m3	Density
0.333	%	Back Cp
0.383	%	Front Cp
2.7	kW	Cut in power
100	kW	Rated power
9	m	Rota diameter
0.6	m/s	Cut in speed
2	m/s	Rated power speed

Exclusion crieteria

25	m	Min water depth
100	m	Max water depth
YES		Include shipping lanes
YES		Include sub-sea infrastrcure
YES		Include Wrecks
389		Total number of sites
300		Sites excluded
89		Sites included

Project costing

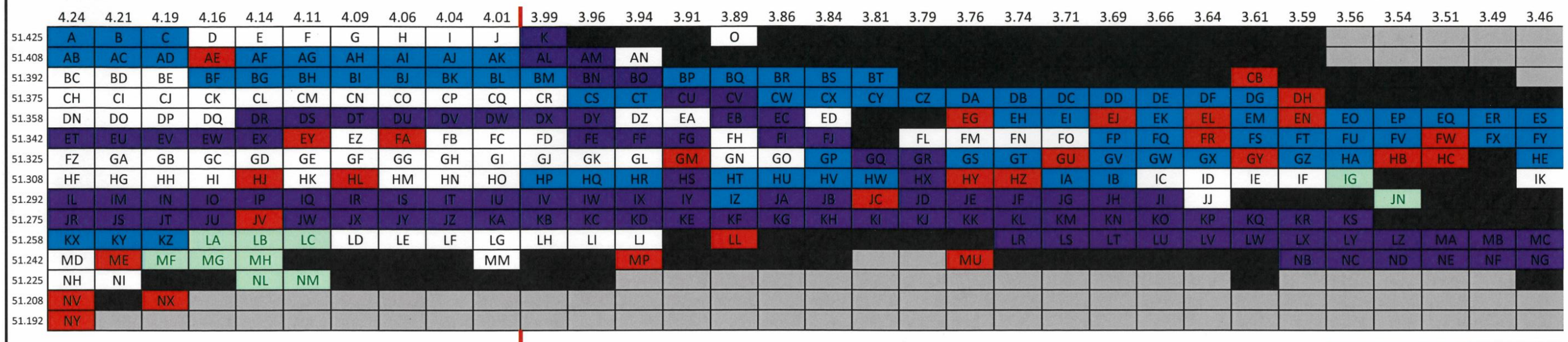
£250,000	£	Intial turbine cost
£25,000	£	Maintenance cost
20	years	Project life
£50,000	£	Decommisioning cost
£10,000	£	Cost per km cable
4	#	Maintenance visits
£0.316	£	Cost per kg fuel
£0.305	£	Strike price (£/kWh)
14	days	maintaince down time

LCA

CML	LCA Analysis
Excl	Biogenic carbon

Addtiaonl costing

400	$ per T	0.79	Exchange rate ($ - £)
£305	per MWh		



LCA	50
Finance	50

Top 10 Sites

	Site	Latitude (DD)	Longitude (DD)	Combined site score	Enviromental score	Finacial score	Average power poduced (kW)	Optimal turbine direction (deg)	Time spent at rated power (%)	Time spent non-opperational (%)	Time spend cuting in (%)	Grid connection point	Length of grid connection cable (km)	Distance from mantiance port (km)	Distance of port to grid connection (km)	Fule consumption (kg)	Total cost expected cost (£)	Cable cost	Fule Cost	Turbine Earnings	Net Profit (2012 £)	Cost of energ	Simple pay back period (years)	LCA emmsions (kgCO2eq)	g CO2eq /kWh
1	MH	51.2417	4.1375	61.46	89.94	32.98	16.1018	81	0	29.7119	70.2881	Ilfracomb	3.9	3.9	0	4187.91	£440,323	£39,000	£1,323	£853,817	£413,494	0.14179	10.2351	1,083,381.6	384.0
2	MG	51.2417	4.1625	60.52	85.82	35.21	16.8043	76	0	29.3974	70.6026	Ilfracomb	4.8	4.8	0	4913.53	£449,553	£48,000	£1,553	£891,065	£441,512	0.13586	10.0128	1,090,704.8	370.5
3	NL	51.225	4.1375	58.77	96.80	20.75	12.9202	89	0	31.9983	68.0017	Ilfracomb	2.4	2.4	0	2978.54	£424,941	£24,000	£941	£685,110	£260,169	0.17671	12.3099	1,071,176.2	473.2
4	MF	51.2417	4.1875	57.27	79.88	34.66	16.9254	72	0	29.4754	70.5246	Ilfracomb	6.1	6.1	0	5961.64	£462,884	£61,000	£1,884	£897,486	£434,603	0.13489	10.236	1,101,282.9	371.4
5	IG	51.3083	3.5625	57.18	16.68	97.68	32.5899	93	9.16537	22.6989	68.1357	Lantwit Majour	9.3	38.4	44.5	32771	£503,356	£93,000	£10,356	£1,728,114	£1,224,759	0.07006	5.7808	1,213,729.2	212.6
6	JN	51.2917	3.5375	56.36	12.73	100.00	33.2765	98	9.87715	22.499	67.6238	Minehead	10	39.6	44.6	33707.5	£510,652	£100,000	£10,652	£1,764,521	£1,253,869	0.06861	5.74359	1,220,754.4	209.4
7	NM	51.225	4.1125	54.22	100.00	8.44	9.87326	88	0	35.1453	64.8547	Ilfracomb	1.7	1.7	0	2414.17	£417,763	£17,000	£763	£523,540	£105,778	0.23124	15.8367	1,065,480.3	616.0
8	LB	51.2583	4.1375	52.71	82.62	22.80	14.0053	78	0	31.5766	68.4234	Ilfracomb	5.5	5.5	0	5477.9	£456,731	£55,000	£1,731	£742,648	£285,917	0.16302	12.2057	1,096,400.7	446.8
9	LA	51.2583	4.1625	52.42	79.42	25.42	14.7597	76	0	30.9404	69.0596	Ilfracomb	6.2	6.2	0	6042.27	£463,909	£62,000	£1,909	£782,651	£318,742	0.15468	11.7639	1,102,096.6	426.2
10	LC	51.2583	4.1125	50.67	83.99	17.36	12.6593	82	0	32.6833	67.3167	Ilfracomb	5.2	5.2	0	5236.02	£453,655	£52,000	£1,655	£671,274	£217,619	0.18035	13.4125	1,093,959.6	493.2

Key

- Locked paramters
- Results
- Variable Parameters
- Shore
- WD critera not met
- Shipping lanes
- Sub sea infrastrucutre
- ship wrekcs

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