Programme Area: Marine

Project: ReDAPT

Title: Method for Tidal Energy Conversion System CO2 Payback Calculation

Abstract:

This report defines a methodology to calculate the CO2 payback interval for a tidal stream generator, in terms of the embodied life-cycle Greenhouse Gas (GHG) emissions arising and displaced by the full life cycle of the generator. The report considers the CO2 payback calculations at both the turbine and array levels.

Context:

One of the key developments of the marine energy industry in the UK is the demonstration of near commercial scale devices in real sea conditions and the collection of performance and environmental data to inform permitting and licensing processes. The ETI's ReDAPT (Reliable Data Acquisition Platform for Tidal) project saw an innovative 1MW buoyant tidal generator installed at the European Marine Energy Centre (EMEC) in Orkney in January 2013. With an ETI investment of £12.6m, the project involved Alstom, E.ON, EDF, DNV GL, Plymouth Marine Laboratory (PML), EMEC and the University of Edinburgh. The project demonstrated the performance of the tidal generator in different operational conditions, aiming to increase public and industry confidence in tidal turbine technologies by providing a wide range of environmental impact and performance information, as well as demonstrating a new, reliable turbine design.

TECHNICAL REPORT

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Title#15

Method for Tidal Energy Conversion System CO_2 Payback Calculation

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Summary#60 This report defines a method for evaluating the carbon payback interval of a generic Tidal Energy Conversion System (TECS). It comprises the deliverable for MC-9.1 of the ReDAPT project, funded by the Energy Technologies Institute.

The purpose of the report is to define a methodology to calculate the CO_2 payback interval for a tidal stream generator, in terms of the embodied life-cycle Greenhouse Gas (GHG) emissions arising and displaced by the full life cycle of the generator. Within the context of this document, the term 'carbon payback' is used to refer to the assessment of all GHG recognised by the IPCC in the 2007 climate change report[1], and is not restricted to CO_2, as other GHG can be weighted by a factor to indicate the relative effect of the GHG compared to that of one unit of CO_2.

This report was prepared based upon the guidance of the Life Cycle Analysis (LCA) standards ISO14040:2006 [2] and ISO14044:2006 [3], and also in consideration of the specification for carbon footprinting as defined in PAS2050:2008 [4].

A standardised method for calculating the impact of a tidal stream array has been presented, along with specific guidance for modelling the different activities involved throughout the life cycle.

The methodology detailed in the report introduces a tiered approach to LCA, to allow for a model of the life cycle emissions to be created far earlier in the development phase, with well-defined and known assumptions being made. This approach will enable successive models of increasing accuracy to be developed, and also to create a realistic means of comparison between different tidal stream technologies.

To enable standardised carbon footprint models to be calculated at the earliest stage possible, an idealised tidal stream array site has been defined.

Interpretation and reporting techniques have been specified to allow suitable results and recommendations to be drawn from the LCA models, and the limitations of the methodology and model have been identified and discussed.

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ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
BTU	British Thermal Unit (1055.06 J)
CFC	Chlorofluorocarbon
CH_4	Methane
CO_2	Carbon dioxide
CPM	Centre for the environmental assessment of Product and Material systems
DC	Direct Current
DfT	Department for Transport
dwt	Deadweight tonnes
ETI	Energy Technologies Institute
EMEC	European Marine Energy Centre
GHG	Greenhouse Gas
GW	Giga-Watts ($1x10^9$ Watts)
GWP	Global Warming Potential
HFC	Hydrofluorocarbon
IPCC	International Panel on Climate Change
J	Joules
kg	Kilograms
$kgCO_2e$	Kilograms of Carbon Dioxide Equivalent (mass of GHG emissions referenced empirically to 1 kg of CO_2)
kg.km	Kilogram-kilometres
kW	Kilo-Watts ($1x10^3$ Watts)
kWh	Kilowatt-hours ($3.6x10^6$ Joules)
l	Litres
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCA	Life Cycle Assessment
MJ	Mega-Joule ($1x10^6$ Joules)
MW	Mega-Watts ($1x10^6$ Watts)
NO_X	Combination of Nitric Oxide (NO) and Nitrogen Dioxide (NO_2)
N_2O	Nitrous Oxide
POC	Point of Contact with the national electricity grid
PRL	Product Readiness Level
ReDAPT	Reliable Data Acquisition Platform for Tidal
SF_6	Sulphur Hexafluoride
t	Tonnes
TECS	Tidal Energy Conversion System
TGL	Tidal Generation Limited
TRL	Technology Readiness Level
t.km	Tonne-kilometres (1000 kg.km)

1 INTRODUCTION

1.1 Summary

This report defines a method for evaluating the carbon payback interval of a TECS. It comprises the deliverable for MC-9.1 of the ReDAPT project, funded by the Energy Technologies Institute.

The purpose of the report is to define a methodology to calculate the CO_2 payback interval for a tidal stream generator, in terms of the embodied life-cycle GHG emissions arising and displaced by the full life cycle of the generator. Within the context of this document, the term 'carbon payback' is used to refer to the assessment of all GHG recognised by the IPCC in the 2007 climate change report[1], and is not restricted to CO_2, as other GHG can be weighted by a factor to indicate the relative effect of the GHG compared to that of one unit of CO_2.

This report was prepared based upon the guidance of the LCA standards ISO14040:2006 [2] and ISO14044:2006 [3], and also in consideration of the specification for carbon footprinting as defined in PAS2050:2008 [4].

A standardised method for calculating the impact of a tidal stream array has been presented, along with specific guidance for modelling the different activities involved in material extraction, manufacturing, transportation, deployment, operation, in service support, and decommissioning activities. Boundaries with natural and technical systems have been identified. The requirements for qualitative and quantitative data have been detailed and the data collection and management requirements have been presented.

The methodology detailed in the report introduces a tiered approach to LCA, to allow for a model of the life cycle emissions to be created far earlier in the development phase, with well-defined and known assumptions being made. This approach will enable successive models of increasing accuracy to be developed, and also to create a realistic means of comparison between different tidal stream technologies.

To enable standardised carbon footprint models to be calculated, an idealised tidal stream array site has been defined. The purpose of this is to allow meaningful calculations of the carbon footprint of a TECS to be carried out at the earliest possible stage of the project, and then compare as the project develops.

Interpretation and reporting techniques have been specified to allow suitable results and recommendations to be drawn from the LCA models, and the limitations of the methodology and model have been identified and discussed.

1.2 Motivation

The purpose of this report is to define a methodology to calculate the CO_2 produced over the full life cycle of a TECS and to establish the CO_2 payback interval. This is intended to promote and support the tidal stream industry by allowing the extent of CO_2 abatement to be calculated for different tidal stream systems, in a repeatable and comparable manner. This is in accordance with the objective of the ETI to "Inform development of policies, regulations and standards", as it delivers the capacity to quantify the relative environmental merits of different technologies.

1.3 Structure of this Report

This report is divided into eleven sections. Sections 1 to 3 detail the scope and content of the report, outlines the requirements for conducting a carbon payback study for a tidal stream array, and provides background information relating to the LCA process and tidal stream energy. It also provides an overview of the recommended approach for calculating the carbon payback interval of a tidal stream array. Sections 4 to 8 cover the LCI for a tidal stream array, and then go into detail covering the individual life cycle processes, the TRL, and specific site and modelling consideration. Sections 9 to 11 describe the method for calculating the carbon payback interval, and then detail the means of evaluating and reviewing the results. A diagram illustrating how the contents of this report may be applied to the lifecycle model of a tidal stream array is shown in Figure 1.

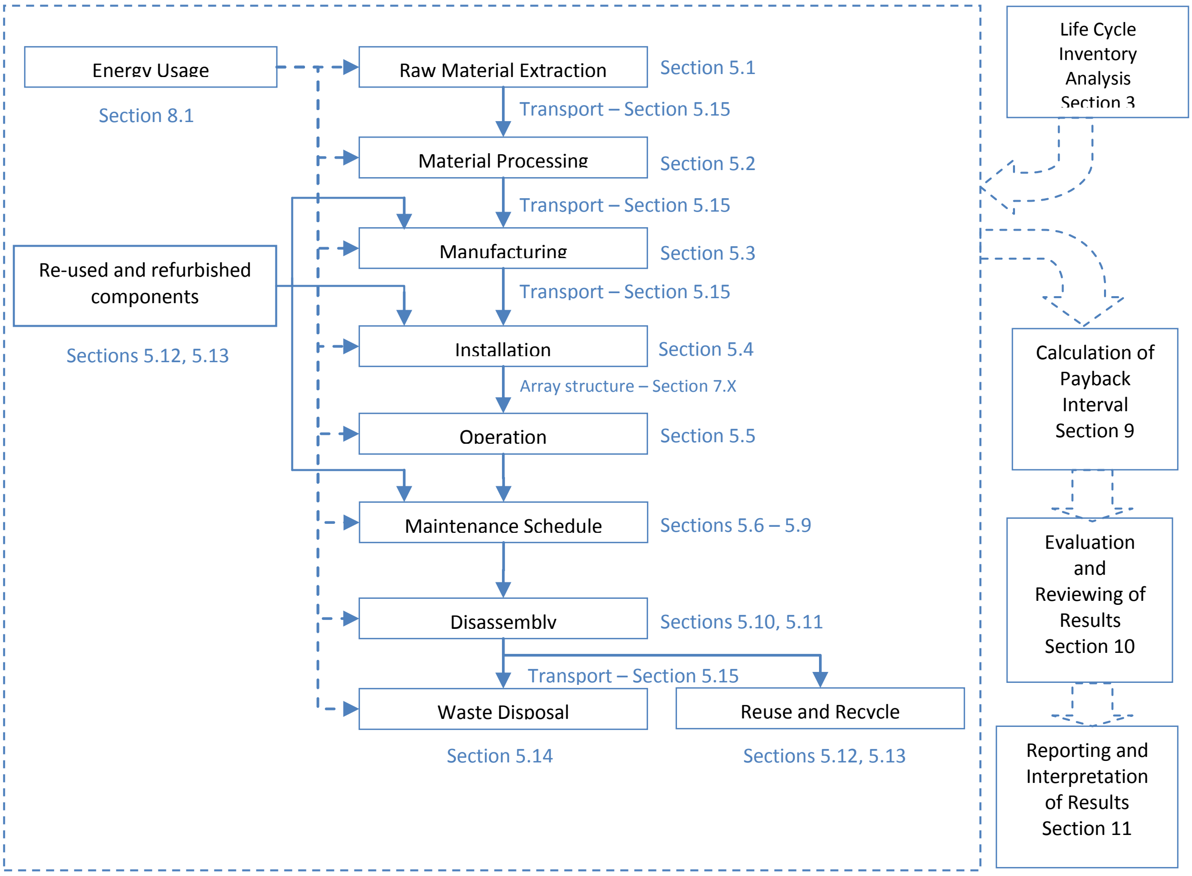

Figure 1 – Contents of this report as applied to a lifecycle model

1.4 Introduction to LCA and Carbon Footprinting

1.4.1 Introduction to LCA

The increased awareness of the importance of environmental protection, and the possible impacts associated with products, both manufactured and consumed has increased interest in the development of methods to better understand and address these impacts [2]. The technique used to evaluate the relative impacts of a product across all stages in its life cycle is the LCA, and a general methodology for conducting an LCA has been specified by ISO14040:2006, with detailed requirements provided by ISO14044:2006. The framework for an LCA can be split into four interrelated phases:

A. Goal and Scope definition

At the first stage, the purpose, requirements and assumptions for carrying out the study are defined. This is intended to allow the later stages of the assessment to be conducted effectively, by defining boundaries and planning data collection and modelling activities (See Section 3.4). ISO14040:2006 section 4.2.2 declares factors that must be stated during the definition of a goal for an LCA study:

- The intended application
- The reasons for carrying out the study
- The intended audience
- Whether the results are intended to be used in comparative assertions intended to be disclosed to the public.

The scope of the LCA is also defined in ISO14040:2006 (Section 5.2.1.2) and in ISO14044:2006 (Section 4.2.3.1). The factors to be considered and clearly described by the scope include:

- The product system to be studied
- The functions of the product system

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- The functional unit
- The system boundary
- Allocation procedures
- LCIA methodology and types of impacts
- Interpretation to be used
- Data requirements
- Assumptions
- Limitations
- Initial data quality requirements
- Type of critical review, if any
- Type and format of the report required for the study

B. Inventory Analysis

In the second stage, a linear model of the product or service is constructed and populated with data. (See Section 5)

C. Impact Assessment

In the third stage, defined assessment criteria are used to quantify the environmental impacts of the product or service at all stages of the product life cycle.

D. Interpretation

In the fourth stage, the environmental impacts calculated in the third section are evaluated and checked against defined quality criteria. These results may be published or used for decision-making, or for refining previous sections of the assessment to allow for a more accurate model to be produced.

Sections 9 and 10 of this report present a method for calculating and interpreting the carbon payback interval of a tidal stream array. These sections are based upon the four accepted stages of a LCA, as illustrated in Figure 2.

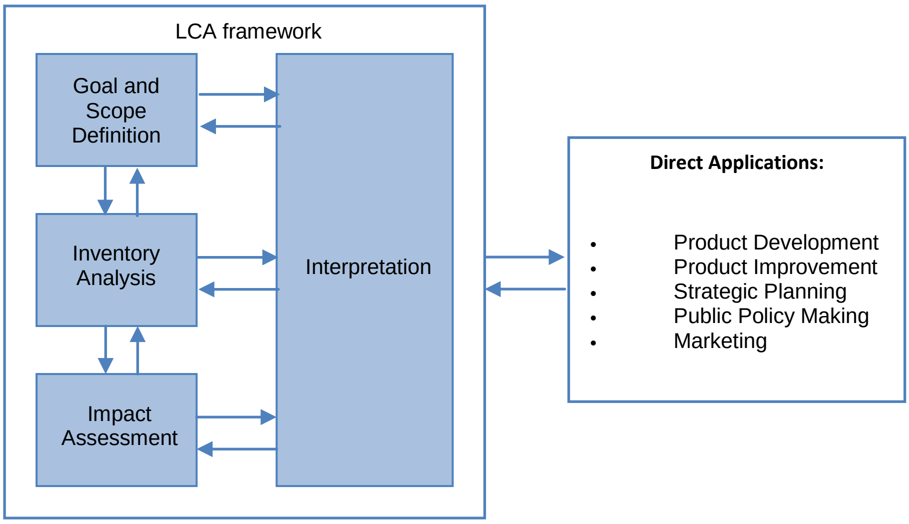

Figure 2 – Report Structure within a LCA context

LCA is a detailed and highly involved subject, for more details refer to ISO14040:2006[2] and ISO14044:2006[3].

1.4.2 Introduction to Carbon Footprinting

A carbon footprint analysis is a variant of a LCA that looks exclusively at the impact of the Green House Gas (GHG) emissions arising throughout the whole life cycle of a product or service. Currently there is no recognised standard to defining a methodology for calculating the impact of GHG that are created, either for general cases or for specific products or service, however guidelines are available on conducting an LCA on the carbon footprint of a product in order to assess its impact on global warming. (PAS2050:2008 [4])

In a carbon footprint analysis, several types of GHG are typically considered, including CO_2, CH_4, N_2O, NO_X, HFCs, CFCs and SF_6. The emission by mass of each gas is scaled by a Global Warming Potential (GWP)

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constant, which represents the predicted global warming impact of that gas in relation to an identical mass of carbon dioxide, over a prescribed timescale. The contributions from each gas are summed, to give a total impact in mass of carbon dioxide equivalent (CO_2e). GWP constants are not physical quantities, but are empirical quantities derived from current research data.

1.5 Introduction to Carbon Payback and Abatement Potential

1.5.1 Introduction to CO_2 and GHG

Atmospheric GHG emissions have been identified as one of the mechanisms for global climate change, which has been described as one of the greatest global challenges over future decades (IPCC 2007 [1]). Public concern regarding climate change is driving investment in novel low-carbon sources of energy, which are expected to play a significant part in reducing future GHG emissions in the drive towards a low-carbon economy. As a result of this, assessing and understanding of the climate change potential of emerging low-carbon technologies is an important process.

Determining the holistic global warming impact of a product requires an assessment of GHG emissions over the entire product life cycle, including manufacture, transportation, maintenance and disposal activities. Established best practice for calculating the life cycle GHG emissions of goods and services is defined in PAS2050:2008[4]. This report aims to define a similar best practise model for the specific case of tidal stream electricity generation systems, which may build upon established methods.

Calculating the energy yield in operation enables the avoided GHG emissions from tidal stream electricity generation methods to be estimated. In conjunction with calculating the life cycle emissions of a tidal stream generator array, this method will allow for an estimate for the carbon payback interval to be determined.

1.5.2 Definition of Carbon Payback

In this report, the term ‘carbon payback’ is used to refer to the length of time taken for the operation of the tidal stream array to repay the global warming impact caused by the emissions arising during the life cycle of that array. At this point, the GHG emissions avoided from displacement of other electricity generation technologies should equal the emissions created by the construction, upkeep and disposal of the array. It is considered appropriate to consider all known GHG, as this is more representative of the true global warming impact of the product. This is measured by mass of carbon dioxide equivalent, as specified in PAS2050 Annex A [4].

In comparing the relative economic merits of different technological options for future sources of low-carbon energy, it is sensible to draw comparisons based upon the cost of abatement, as it represents the GHG return upon a given financial investment.

It is considered outside the scope of this report to discuss life cycle financial costing of tidal stream arrays, and therefore the calculation of the cost of abatement will not be considered. Instead, this report will provide the basis for a method of calculating the abatement potential of a tidal stream array in addition to the payback interval; it should be decided for each individual study how the results of the carbon payback interval may be used for financial cost-benefit assessments.

The method for calculating the abatement potential of the tidal stream array is presented in Section 9.7. As the focus of this report is upon the calculation of a carbon payback interval, and identical data is needed for the calculation of both results, GHG abatement potential will not be discussed further until Section 9.7. However, it should be borne in mind that calculation of the carbon payback interval alone is not sufficient for assessing the global warming impacts of different technologies.

1.5.3 Limitations

This report focuses primarily upon calculation of the carbon payback interval of a tidal stream array, and additionally allows the abatement potential to be evaluated. It does not consider other environmental impacts such as toxicity or acidification. Evaluation of global warming impact represents only one of many environmental analysis techniques that may be used to compare different products. The comparison of technologies on basis of the GWP effect of GHG alone does not offer an appreciation of the wider environmental impact associated with that technology, and can therefore be misleading if considered in isolation. It should be noted that many of the GHG have the potential to cause more damage to the environment than is suggested by the GWP, for example hydrocarbons can cause a degradation to the ozone layer. For the purpose of this study, these potential further effects have been neglected.

1.6 Scope and Application of this Report

1.6.1 Scope of this Report

This report details a specific case of carbon footprint analysis, applicable to a general tidal stream generator or array. This carbon footprint analysis will fall under the branch of generalised carbon footprinting, as laid out in specification PAS2050:2008. Carbon footprinting is itself a form of LCA which is a means of determining the effects and impacts of a product or service throughout its life.

This report aims to define a general methodology for calculating the carbon payback interval of a TECS and array that is based on current best practise as derived from standards ISO14040:2006 and ISO14044:2006, and specification PAS2050:2008. The purpose of this report is to provide a standardised set of methods and assumptions for this calculation, to allow a quantitative value of the lifecycle carbon footprint to be calculated, and to be able to model the effects of changing the design and size of a single TECS or array. It is important to state that the assumptions and models presented in this document are intended to provide the whole life cycle carbon footprint of a TECS, and as a result, a number of activities fall outside the scope of the study, such as the financial and carbon cost of reinforcing the electricity grid, and the financial costs of the TECS.

1.6.2 Application of this report

An LCA comprises the core of this study. This report describes how a LCA suitable for enabling the calculation of the payback interval of a tidal stream array should be conducted, and also how the results of this study may be used to calculate the payback interval. A process map of a carbon payback calculation for a tidal stream array is shown in Figure 3, illustrating the underlying method that is the focus of this report.

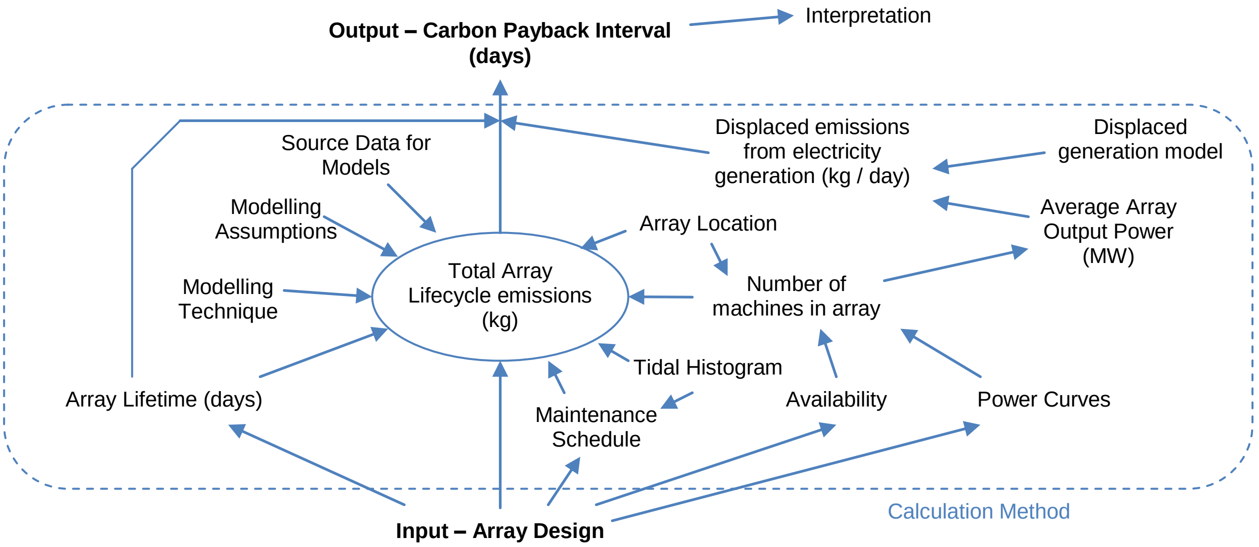

Figure 3 – Process Map for calculating Carbon Payback Interval

The purpose of this report is to identify and normalise the modelling choices that influence the final value for the carbon payback interval, which are shown in Figure 3.

2 REQUIREMENTS

In creating an LCA of the carbon footprint of a TECS array, it is important to adhere to requirements that have previously been established in the more general LCA field. A number of standards and specifications have been created, which form the basis of most modern LCA studies, and the processes described by these should be included where possible, unless better methods are developed that are product-specific.

2.1 Normative References

Current best practice for LCA has already defined in international Standards ISO14040:2006[2] and ISO14044:2006[3]. IS14040:2006 provides a general description of the LCA process with an overview of the principles, methodology and requirements, while ISO14044:2006 provides a more detailed view of the requirements of an LCA along with details of how to interpret the findings from the LCA and the means of reporting the results.

A specific method for assessing the GHG emissions of goods and services has been set out in PAS2050[4], which was published by British Standards along with the Carbon Trust and DEFRA. This builds upon the LCA method defined in ISO14040:2006[2] and ISO14044:2006[3]. As discussed in Section 1.4, PAS2050 is directly relevant to the calculation of carbon payback intervals, and is considered an essential reference.
Normative references for application of the method defined in this document are:

- BS EN ISO14040:2006 - Environmental management – LCA – principles and framework [2]
- BS EN ISO14044:2006 - LCA requirements and guidelines [3]
- PAS2050 - Specification for the assessment of the life cycle of GHG emissions of goods and services [4]

Where the guidance of ISO14040 or ISO14044 contradicts that of PAS2050, the guidance of PAS2050 shall take precedence. Where the guidance of ISO14040, ISO14044 or PAS2050 contradicts the guidance of this report, the guidance of this report should take precedence.

2.2 Other Useful References

2.2.1 Guide to PAS2050

To complement the PAS2050 standard [4], the Carbon Trust published a guide [5] describing how the standard should be implemented. The guide to PAS2050 [5] offers a introduction to carbon footprinting for a general manufacturing process. Of particular relevance is Section II, which provides an understandable reference for the correct approach for assessing the carbon footprint of a product.

2.2.2 Previous Studies

LCA is an established technique for investigating the environmental merits of new technologies. There already exist a number of studies into the global warming impact of renewable marine electricity generation systems, including a study into the SeaGen TECS[6].

2.3 Data Requirements

Any LCA requires the collection and use of significant amounts of data. This is often the most time-consuming element of the assessment, and establishing a list of data sources at an early stage of the assessment can be very beneficial. Existing standards such as ISO14044 [4] offer limited guidance on data collection, and thus constructing data considerations are often overlooked at the planning stage.

Data required for the carbon payback study may be categorised into either qualitative (descriptive) data or quantitative (numerical) data. The former is used to define the architecture of the model, and the latter is used to populate that model. Qualitative data is usually product-specific, whilst quantitative data may be more general. A list of possible sources of qualitative and quantitative data is illustrated in Figure 4.

The level of data required by an LCA will depend on the required level of accuracy of the study. Conventionally, the LCA should be conducted with the greatest degree of actual design data, to minimise the inaccuracies. The methodology laid out in this report provides a tiered mechanism of calculating the carbon footprint and payback interval of a TECS with increasing accuracy as the TRL of the design increases and is described in detail in Section 6.

A number of software packages exist to perform LCA calculations. The different packages typically offer a different "front-end" to the data, as the LCA depends on the quality of data used in the model. As a result, the different LCA packages make use of a number of different general databases for most of the process and material data when no actual data has been supplied. These databases hold totally generic processes and so are suitable for most applications, but should be replaced with actual process data if at all possible, and also it should be noted that very specialised processes may not be covered by the databases.

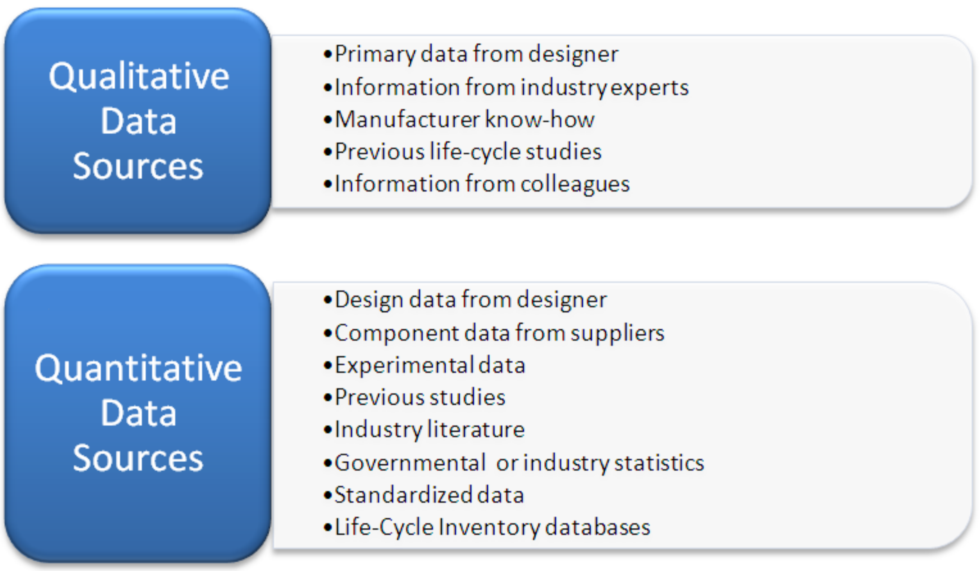

Figure 4 – List of possible sources of Qualitative and Quantitative Data

Further information on data collection and management is presented in Appendix Section E.3. Access to these resources should be considered as a requirement of the carbon payback study.

2.4 Technology Readiness

The validity of the method for calculating the carbon payback interval presented in this report is dependant upon the maturity of the technology under consideration. The existing models for creating an LCA require sufficiently detailed activities, such as the supply chain, deployment, maintenance, and disposal that are associated with a tidal stream array. To allow for an accurate result, the LCA requires that these are all well defined in advance of the study. However, as the tidal stream energy sector is still in a growth stage, the level of technical detail is currently limited. This is compounded by the lack of commonality between the deployment sites for tidal stream arrays, as the conditions faced by each individual site can vary considerably, with a wide number of variables affecting the site.

A different approach to the issue of technology readiness has been outlined in this report to remove the limitations previously imposed by low technology readiness (see Section 6). In this new approach, a tiered model of technology readiness has been created, to enable the carbon footprint of a tidal stream array to be calculated from a very early stage of the design process. As the development of the tidal array continues, and the technology readiness of the device improves, the tiered modelling approach will pass through pre-defined gates to allow for a more accurate model of the carbon payback of the resultant array to be calculated.

This methodology will allow for a rapid means of determining the impact of a tidal array, and will allow for designs at a similar level of development to be compared against the others, provided they are both being modelled at the same tier.

To enable this tiered system to be used, it will also be required that an idealised site is created. As the conditions for each site for the array will be different, and a site may not be selected until relatively late in the development process, an idealised site will allow for an estimate of the impact of the array to be measured. It will also prove useful in allowing comparison between the competing designs, as if both are compared at the same tier of technology readiness and on the same idealised site, then the optimal design can be identified.

2.5 Software Requirements

There is no requirement for an LCA to be conducted electronically, although this can simplify the project by providing referenced databases of values for parts, materials and processes, and the automation of the calculations can reduce the project workload and time. It may prove beneficial for the project to use a specifically designed LCA software package, such as GaBi [50], TEAM™ [51], SimaPro [52] or CCaLC [53]. The different software packages all rely on accessing databases of values for the parts, materials and processes used in the life cycle of a given product, and the accuracy of the resulting model will be dependent on the choice of database in the study. The database used in the study may be particular to tidal generation, or may be a more general database. The ecoinvent™ [54] database is one of the leading databases for LCA studies, and is the default choice of a number of LCA software packages, although other databases are available. Other means of conducting an LCA may be achieved through adapting existing modelling tools, for example it may be possible to adapt the Vanguard cost-modelling tool to allow a suitably accurate carbon payback model to be created. Before selection of a single tool, it will be necessary to perform a comparative assessment of the tools under consideration.

3 LCA SYSTEM DEFINITIONS

An LCA for a product is conducted by defining the product system as a model that describes the key elements of the physical system in relation to the functional unit of the LCA study. In an ideal situation, it would be possible to model the system in such a way that all inputs and outputs to the product can be included for the greatest level of accuracy. However to save expending unnecessary resources, system boundaries are established to define which unit processes need to be included in the system (adapted from ISO14040:2006 section 5.2.2). The following sections identify and explain the criteria that are used in defining the system boundaries, processes and systems, and the application of these to creating a carbon payback study of a TECS array.

3.1 Functional Unit

In defining the scope of an LCA study, the performance characteristics and functions of the system should be clearly specified, and be consistent with the goal and scope of the study. One of the primary purposes of the functional unit is to provide a reference to which the input and output data are normalised (in a mathematical sense). To enable this, the functional unit shall be clearly defined and measurable (taken from ISO14044:2006 – 4.2.3.2 and ISO14040:2006 – 5.2.2).

In the case of creating an LCA to model the rate of CO_2 payback from a TECS, then the functional unit that is required is CO_2. By selecting this as the functional unit, it will be possible to compare the different unit processes during the life of the product in a quantifiable way.

The sizing of the array and the calculation of the lifetime energy yield is discussed later in this document, in Section 7.3.

3.2 System Definitions

An LCA for a product is conducted by defining the product system as a model that describes the key elements of the physical system. In an ideal situation, it would be possible to model the system in such a way that all inputs and outputs to the product can be included for the greatest level of accuracy. However to save expending unnecessary resources, system boundaries are established to define which unit processes need to be included in the system (adapted from ISO14040:2006 section 5.2.2). The following sections identify and explain the criteria that are used in defining the system boundaries, processes and systems, and the application of these to creating a carbon payback study of a TECS. ISO14040:2006 declares that during this process "decisions shall be made regarding which unit processes to include in the study and the level of detail to which these unit processes shall be studied. Decisions shall also be made regarding which inputs and outputs shall be included and the level of details of the LCA shall be clearly stated."

3.2.1 Processes and Systems

LCA represents activity as a collection of interacting processes. A collection of interacting processes is termed a 'system'. The particular collection of processes that describe the life cycle of the tidal stream array and are considered within the scope of the carbon payback study is termed the 'product system'.

3.2.2 Unit Processes

It is useful to describe the product system using a process flow diagram, showing the unit processes and their interrelations. Each unit process should be initially described to define:

- Where the unit process begins, in terms of raw materials or intermediate products
- The nature of the transformations and operations that occur as part of the unit process
- Where the unit process ends, in terms of the destination of the intermediate or final products

A generic process flow diagram for the TECS has been included, and is presented in Figures 6 and 7. These flow diagrams describe the most simplistic view of the life cycles of a tidal stream array, and can be further broken down by levels from whole device through to the individual component level.

3.2.2.1 Types of Process

The product system comprises of a series of unit processes, however unit processes are not limited to those contained within the product system. Any unit processes that are excluded from the study must be termed as 'essential' or 'non-essential' processes. An 'essential' process is defined as being a technical process, which although it does not fall within the scope of the LCA, must still occur to allow the tidal stream array to be

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deployed and the functional unit to be measured. An example of an essential process for a tidal stream array would be any activities relating to the reinforcing of the electricity grid to allow the array to be connected. It would be invalid to group these activities to the tidal array process, but they are essential to the operation of the array. Conversely, any other excluded technical process that is not required as part of the life cycle of the tidal array is defined as ‘non-essential’. An example of a non-essential process would be the incineration of manufacturing waste to produce heat, as this process does not contribute towards the life cycle of a tidal stream array.

3.2.3 System Boundaries

As previously mentioned, not all of the unit processes fall within the scope of the product; these include but are not limited to the production of energy sources for use in unit processes, production of capital goods, financial investments and natural processes. Technical processes that have been excluded from the product system are termed to lie in the ‘technosphere’. These technical processes may be connected to the required processes of the tidal array life cycle, such as electricity distribution. The product system will also interact with natural processes. Natural processes are defined as processes that occur within the natural environment, such as the formation of oil and gas reserves, and these processes are termed to fall within the ‘biosphere’. A system boundary is used to define the point at which processes interacting with the product system are excluded from the scope of the study, and instead form part of the technosphere or biosphere. A further system has been defined for use in LCA as the ‘value sphere’, however due to the focus of this model on the carbon footprint of a tidal stream array, the financial impact of the product system is neglected. Further details regarding system boundaries have been included in Appendix Section A.

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4 LIFE CYCLE IMPACT (LCI) ASSESSMENT

The Life Cycle Impact (LCI) Assessment is conducted to establish the levels of volume of the functional unit created over the life cycle of a product, and involves data collection and calculation procedures to quantify the relevant inputs and outputs of the system. The goal and scope of the study will go some way towards defining the initial plan for carrying out this study.

The operational steps involved in the life cycle should be defined in terms of unit processes, to allow the inputs and outputs of the individual processes to be identified, and can be controlled by the specifying of parameters to define the quantity of flows entering or exiting a process.

4.1 Functional Unit

The functional unit of a LCA is related to the purpose of the assessment being carried out. In the case of a CO_2 payback calculation for a TECS, the functional unit will be the CO_2 arising over the processes involved in the whole life cycle of the generator. As a result of selecting CO_2 as the functional unit, the measurable output from each unit process will be the emissions arising from the process.

4.2 Representation of Unit Processes

Each unit process is represented by an inventory of inputs and outputs, corresponding to flows entering and leaving the process respectively. This data is usually stored in inventory form. An example of a unit process and a corresponding inventory is shown in Figure 5 and Table 1.

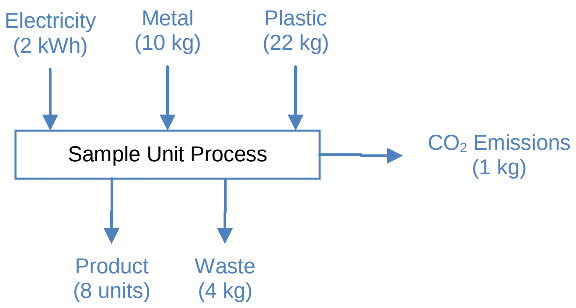

Figure 5 – Sample Unit Process

Flow Number	Flow Type	Substance	Quantity	Unit	Functional Unit?
1	Input	Electricity	2	kWh	N
2	Input	Metal	10	Kg	N
3	Input	Plastic	22	Kg	N
4	Output	Product	8	Unit	N
5	Output	Waste	4	Kg	N
6	Output	CO_2 Emissions	50	Kg	Y

Table 1 - Sample Unit Process Inventory

Each unit process should be normalised to the functional unit. In Table 1, the 'Product' output is the functional unit, and thus all other inputs and outputs have been linearly scaled to the functional unit.

4.3 Use of Parameters

Local and global parameters may be used to specify the quantity of flows entering or exiting processes. This can be useful for constructing parametric models, which allows modification of process models to be investigated retrospectively. This is particularly useful for scaling of unknown component sizes or performing sensitivity analysis (see Section 10.4).

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4.4 Modelling a Life Cycle as Flows and Unit Processes

The product life cycle should be modelled as a flow diagram, constructed from unit processes. These unit processes should be linked by flows. A diagram illustrating a simple model of this topology is shown in Figure 6. The boxes represent unit processes or systems of unit processes, and the arrows represent flows within the system.

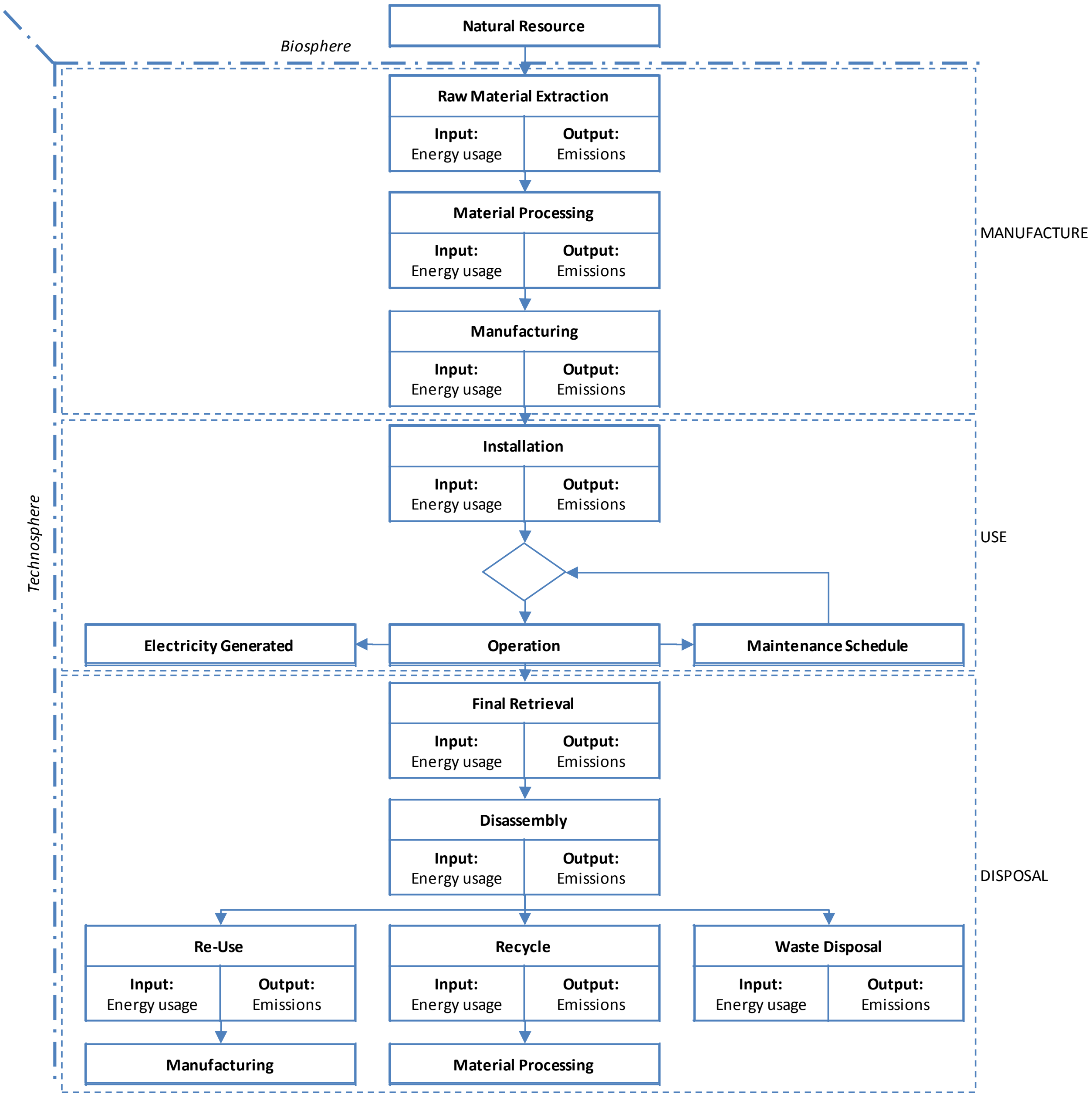

Figure 6 – Model of array life cycle constructed from processes and flows

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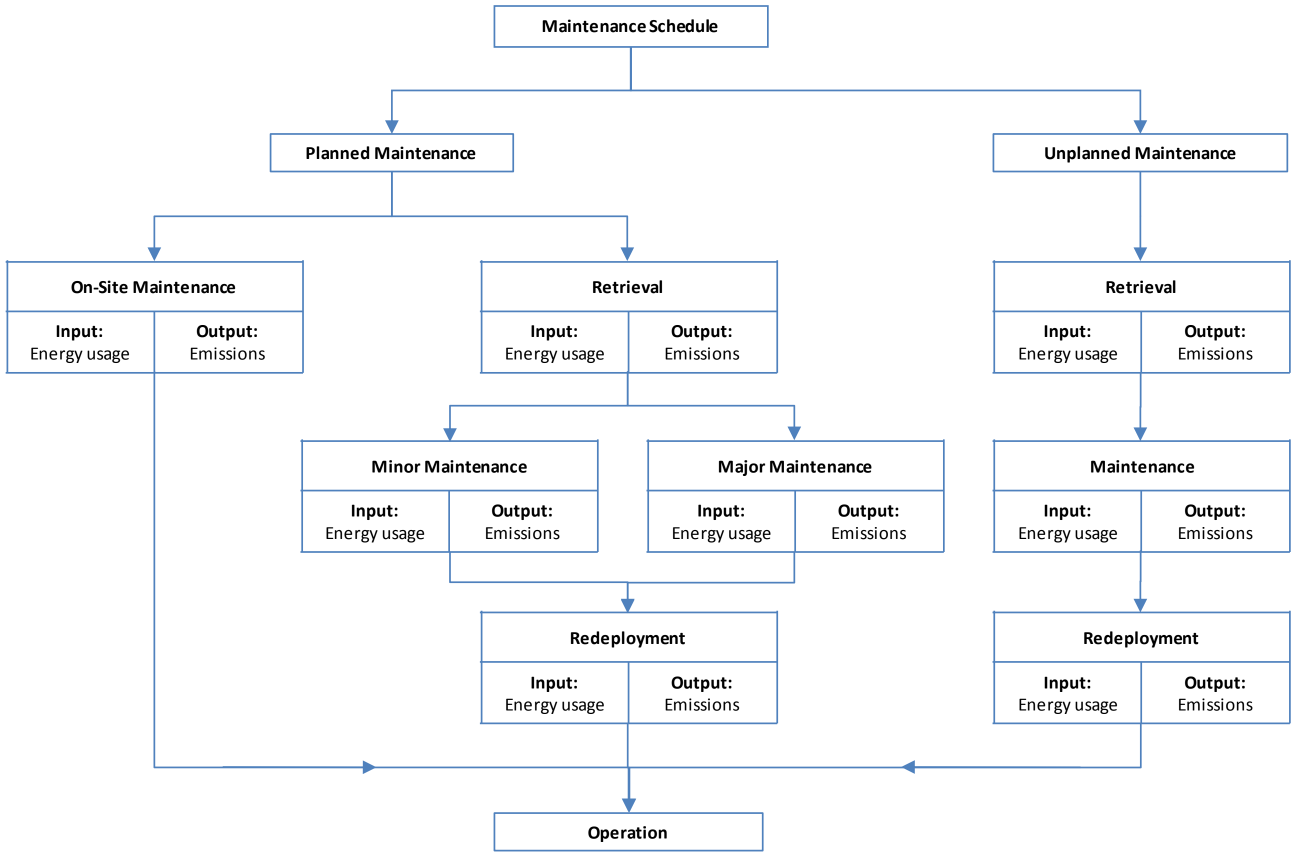

Figure 7 – Model of array life cycle – maintenance element

Each unit process or system represents an operation within the life cycle that accepts and emits flows. A flow may consist of a material, a component, a product, an emission, a resource, energy, a service or waste. The magnitude of a flow is represented in a suitable unit, representative of the useful quantity transferred. Examples of this include representing a material in units of kg, energy in terms of J, and a transport service may be represented in units of kg.km. As a guide, the emissions associated with the use of a flow should scale linearly with the quantity used, at least to a first approximation. Linear scaling is inherently assumed within this type of model. Both of these models are high-level models, and so only show a single unit process for each stage, however many of these processes may comprise of a tree of sub-systems.

In economic terms, flow may be considered a flow of resource and a process may be considered to be an activity that adds value to a resource. Processes may be grouped into systems or sub-systems for clarity.

The model shown in Figure 6 represents the typical top-level of a model that could be used for evaluating the carbon payback interval of a product. The goal of this assessment is to obtain the total GHG emissions for the manufacture, use and disposal phases of the array life cycle. These values may be used with the expected array lifetime, in order to calculate the payback interval. This calculation was discussed in Section 9.1.

For each process, an inventory of input and output flows is required (see section 5). The process inventory should show mass being conserved, and for that the total mass of input materials, components, and resources should equal the total mass of output materials, components, waste and emissions. Conservation of mass provides a check to ensure that the process has been modelled completely and accurately, and if mass is not conserved then this is an indicator that at least one input or output has been omitted or modelled incorrectly. As a minimum standard, the process inventories should at least be complete to the level specified in the cut-off criteria (see Appendix Section A.4). Specific guidance on the structure of the life cycle model is presented in Section 8.

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5 LIFE CYCLE PROCESSES

The life cycle model shown in Figure 6 and Figure 7 of Section 4.4 shows a number of different unit processes. These processes are now been individually modelled in the following sections and any specific requirements of the processes involved are detailed.

5.1 Raw Material Extraction

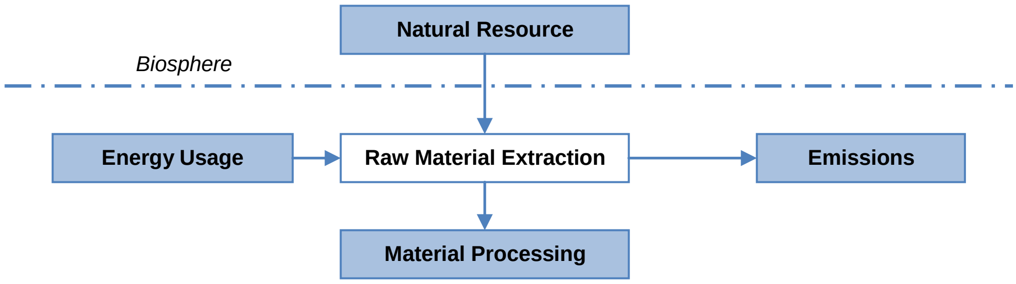

Figure 8 – Raw Material Extraction

Prior to extraction, raw materials lie outside the system boundary and will not impact the carbon footprint of the TECS, however the process of extracting and mining raw materials will produce emissions that will contribute towards the total CO_2. PAS2050 provides detailed information of the level of detail required of the emissions arising from this process:
"The GHG emissions resulting from all processes used in the transformation of raw material shall be included in the assessment, including all sources of energy consumption or direct GHG emissions.
"*Note: GHG emissions from raw materials include, but are not limited to: GHG emissions from mining or extracting raw materials (solids, liquids, and gases; such as iron ore, crude oil, and natural gas), including emissions from machinery, consumables as well as exploration and development; waste generated at each stage of the extraction and pre-processing of raw materials.*
"Note: Raw materials have zero GHG emissions associated with them when they have not been through any external process transformation, e.g. iron ore before it has been extracted."
While these details are fairly comprehensive for dealing with the emissions arising from the production of raw materials, they do not consider the emissions arising from the use of capital goods, including mining machines, diggers and other tools. PAS2050:2008 does not contain any details for accounting for these capital goods, and as a result it has currently been excluded from this revision. However, the following note indicates that position is due for review:
"*Note: the treatment of emissions arising from capital goods will be considered further in future revisions of this PAS*."
In the construction of a tidal stream array, it is unlikely that the raw material extraction will be performed by the company manufacturing the TECS, and ideally, the data should be provided by the suppliers. If this data is unavailable, then the model defined in this document should be used.

5.2 Material Processing

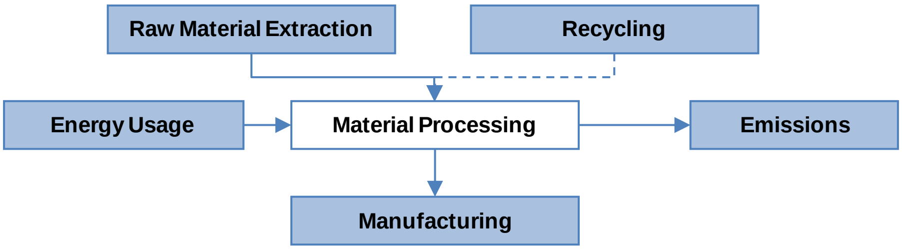

Figure 9 – Materials Processing

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Processing of materials should be part of suppliers responsibility to provide accurate data to the TECS manufacturer, however if data is unavailable, then reasonable data can be obtained from the material databases. A number of databases exist, and are used by existing LCA tools to provide the libraries of data needed to create the model. A range of different databases exist, some are global databases, such as ecoinvent and DEAM^{TM}. These provide a wide range of datasets and can be used to model a variety of different processes. Other databases provide industry-specific or country-specific data, and so can be used for more specialised processes. These databases include both the emissions arising from the materials themselves, as well as some of the more general processing operations. As well as the emissions arising from the processing of materials, it may be required to calculate the impact of emissions arising from the production and use of any capital goods used during the process. PAS 2050 states that these emissions are currently excluded from the assessment of the GHG emissions of the life cycle of a product, but this is under consideration for revision in future iterations of the PAS. As a result, it may be considered worthwhile to account for these emissions.

It is considered likely that the majority of components on a TECS will be constructed from different grades of steel, due to the low cost, high strength-to-weight ratio and structural properties. As a result, values will be required for the emissions arising from the extraction, processing and fabrication of steel components. Average values have been created for steel production by the World Steel Association [55]. This gives average emissions for production of steel, as well as the different impacts caused by different methods of production.

		Steel Fabrications				
	Average Steel	Plate	Sections	Tubes	Hot Dip Galvanised	Purlins and Side Rails
CO_2 (t/t steel)	0.464	0.919	0.76	0.857	1.35	1.10

Table 2 – Average steel production values [55]

The emissions arising from the material processing phase may be reduced if there is a lower dependency on resources produced from raw material. This would require a source of recycled material, either from the product stream itself in the form of previous TECS being recycled, or from external product systems. If the materials are provided directly from recycling a previous TECS, then the mass of raw material required will be reduced, which will reduce the carbon footprint of refining new material, although the carbon cost of recycling the material will be required (see Section 5.12). If materials are recycled from external product systems, then the recycling costs can be neglected, as they do not form part of the product stream.

5.3 Manufacturing

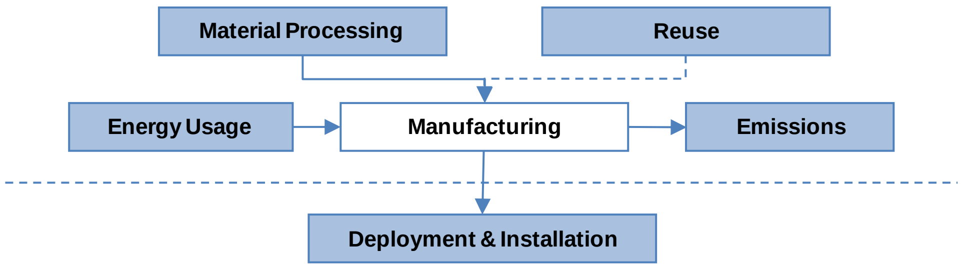

Figure 10 – Manufacturing

The manufacturing process represents a range of different processes, as this phase covers the manufacturing of the different elements of the TECS from component level up to assembly of the device prior to deployment. There are two broad categories of processes that need to be accounted for in regards to emissions arising from manufacturing:

- High-value processes – processes that produce large amounts of GHG in relation to the duration of the process, and as a result, these should be modelled individually. Examples of high-value processes may include casting, welding or hot forging.
- Stock processes – the majority of processes that form the manufacturing process can be treated as a single stock process for the purpose of simplifying the calculation of the carbon payback interval. The emissions arising from the individual processes can be averaged to provide an estimate of the average GHG produced by stock processes.

A threshold value of GHG emissions will need to be set in order to be able to quantify a process as either a high-value process or as part of the average stock processes.

For the manufacturing processes performed in-house, it should be possible to obtain accurate data for the emissions arising from the processes used. For all processes that are carried out by suppliers or subcontractors, it may prove more difficult to obtain accurate data for the GHG emissions, as this does not currently form part of an industry requirement. If this proves impossible, then the GHG emissions from the manufacturing phase will have to be estimated from any currently existing documented processes, such as data provided by Corus for the production of steel [55], until more accurate data can be obtained.

The emissions arising from the manufacturing phase may be reduced if components and systems can be reused, instead of fabricating new components for each device. Reused components are more likely to be sources from within the product stream, although it may be possible to use components from different products. By reusing components, the carbon cost of fabricating and manufacturing the components can be neglected, although if the components are sourced from the same product stream, then the emissions arising from repairing components prior to reuse would have to be included (see Section 5.11).

5.4 Deployment & Installation

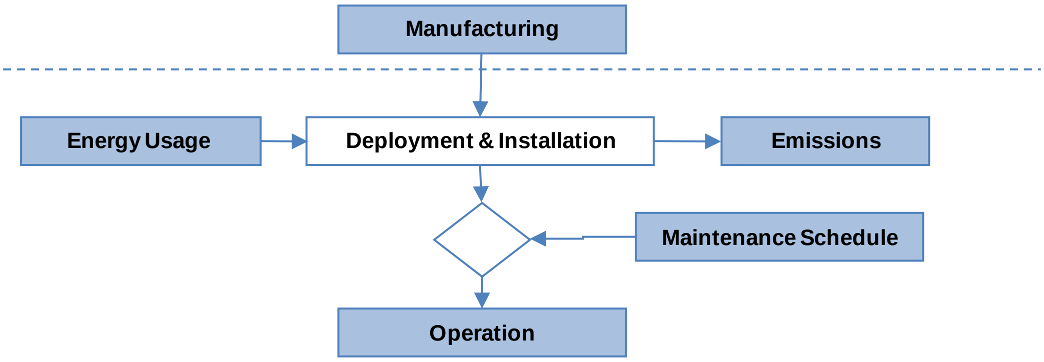

Figure 11 – Deployment

A model for deployment of a TECS will be influenced by the characteristics of a particular site, as there are a number of variables that will contribute towards access to the site (see Section 7). Until a site has been defined for an array of TECS, then the site conditions will have to be based on the idealised site (see Section 7.1).

Installation of a device at a site may include the installation of a foundation or anchor to position the device on the seabed, and connecting of the generator to the electricity grid Point of Contact (POC). This may be achieved through either individual cables, or by connecting a number of generators to a subsea junction box, and then running a single cable to the POC, and will depend of the size of the array and any product-specific design requirements.

5.5 Operation

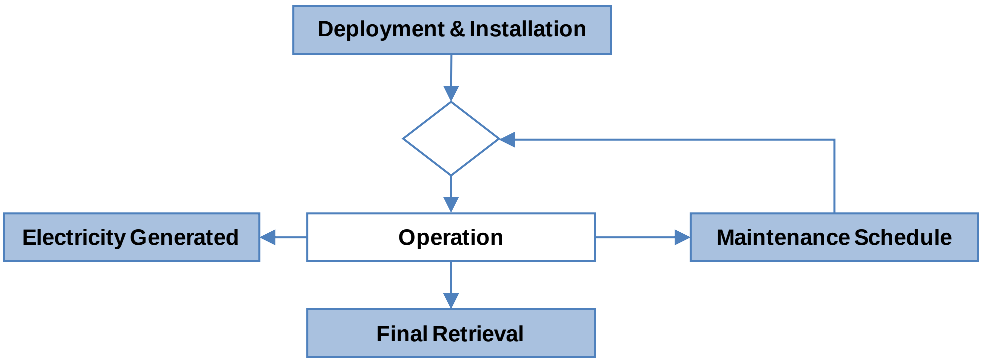

Figure 12 – Operation

The operation phase of a tidal stream generator differs from the 'Use' phase of an LCA, as detailed in ISO14040, ISO14044 and PAS2050. In the traditional LCA models, the 'Use' phase accounts for a degree of the emissions arising from the life of the device, however during normal operation, a tidal stream generator will not create any emissions. It is this phase of the life cycle that provides the carbon offsetting, as the amount of electricity generated (in kWh) can be multiplied by the average carbon cost of generating electricity per kWh in order to quantify the volume of CO_2 offset by the operation of the tidal stream generator (see Section 8.1.1).

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5.6 Maintenance Schedule

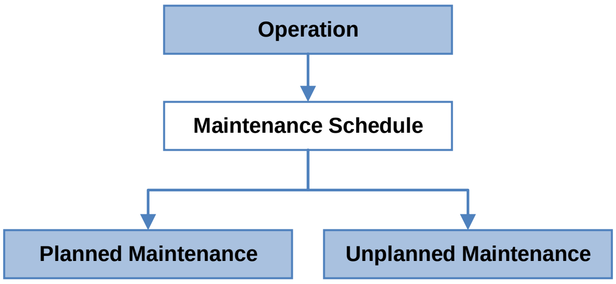

Figure 13 – Maintenance Schedule

The Maintenance Scheduling process is used to detail the breakdown and frequency of the various planned and unplanned maintenance operations required for the operational life of the tidal stream array.

Maintenance Scheduling has been included on the process flow diagram, but is not strictly a process, as it requires no energy to function, and does not produce emissions, as this will been defined in the actual maintenance task. Instead, it should attempt to cover all predicted inspection and maintenance activities. For unplanned activities, an estimate of the probability of occurrence should be used to calculate the expected number of unplanned maintenance activities over the lifetime of the array. This estimate may be used to evaluate the expected emissions from the unplanned activity over the course of the array life cycle, and hence determine whether the activity should be included within the assessment according to the cut-off criteria (see Appendix Section A.4).

5.7 Planned Maintenance

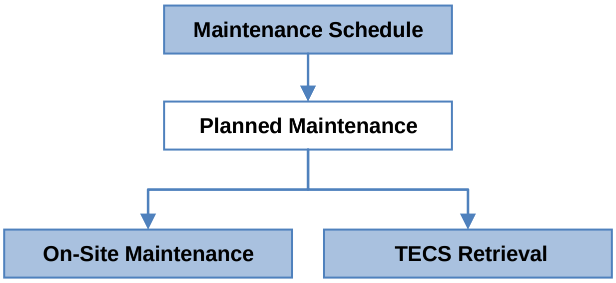

Figure 14 –Planned Maintenance

Planned Maintenance covers all expected routine inspection and maintenance activities that will occur during the life of the tidal stream array. This includes any inspection or maintenance activities that will be possible while the device is deployed, including the foundation and cables, as well as more substantial operations once the TECS has been returned to shore. Further details about procedures both on-site and on-shore are included in the following sections along with their impact to the carbon footprint of the device.

5.7.1 On-Site Maintenance

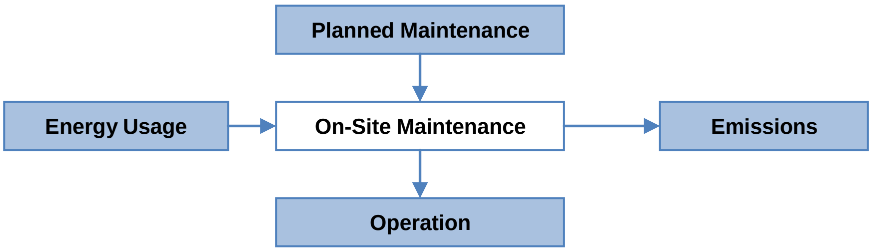

Figure 15 – On-Site Maintenance

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On-site maintenance will be required for the inspection of the TECS while it is still deployed, as well as maintenance of items that cannot be readily returned to shore for overhaul, such as foundations of the device and any sub-sea cables or connectors. The main source of emissions for this operation is likely to be the use of vessels to inspect or maintain the array, as a suitable vessel may be required to hold position over the site for a number of days, and so the fuel consumption may form a key element of the carbon footprint of this process.

5.7.2 TECS Retrieval

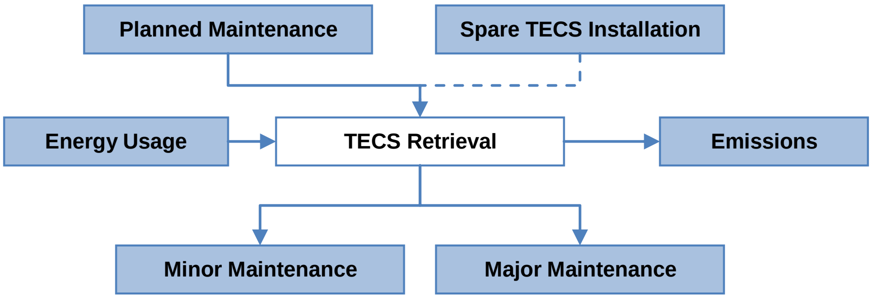

Figure 16 – TECS Retrieval

Typically, planned maintenance will require the retrieval of the device in order to return it to a shore-based repair facility for a thorough inspection or maintenance process. The TECS will need to be shipped to a suitable location, which should ideally be as close as possible to the array location to minimise transport time and costs. In calculating the carbon footprint, both the distance from the array to the repair facility, and the means of transport required will have to be considered. Further details about the transportation are included in Section 5.21.

The removal of a TECS requires a window of opportunity in the tide and weather conditions long enough to perform the operation, if this window is unavailable, then time until the optimal conditions may result in a loss of generating capacity, and as a result lengthening the payback period of the array. If the TECS is to be removed, and the time until replacement is significantly long, then it may be possible to install a spare TECS when the original device is removed, as this will minimise the outage conditions faced by the array, and so limit the impact to the payback period. The carbon cost of producing and maintaining spare generators will then have to be included in the life-cycle model.

5.7.3 Minor Maintenance

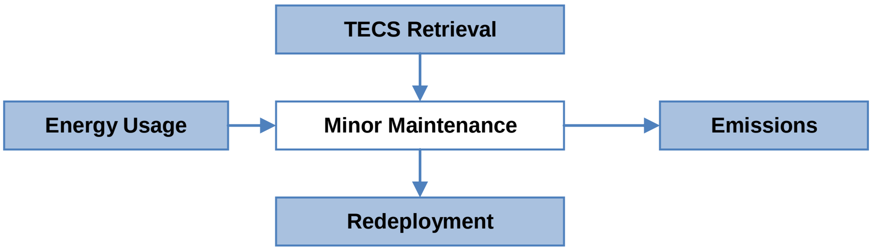

Figure 17 – Minor Maintenance

Minor Maintenance covers a range of simple and low risk maintenance and inspection operations that will need to be carried out during the operational life of a TECS. Minor processes are likely to include the replacement of consumables, minor repairs and replacements of simple systems as well as inspection and checking of systems. Consumables on a TECS may include, but are not limited to include seals, oil and lubricant.

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5.7.4 Major Maintenance

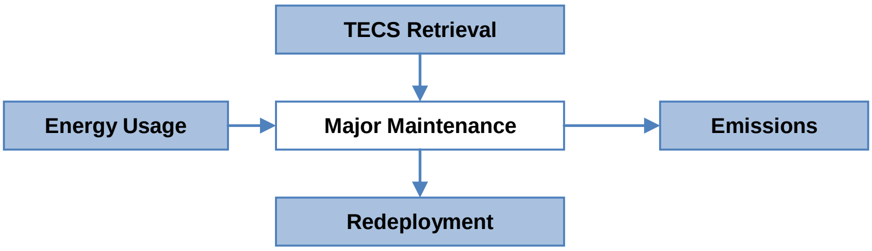

Figure 18 – Major Maintenance

Major Maintenance encompasses any large, complex, or technical repairs necessary to ensure the continued operation of the tidal stream array. This may include the repair or replacement of large structural items within the device, for example gearboxes, main shafts, frequency converters and transformers.

5.7.5 Redeployment

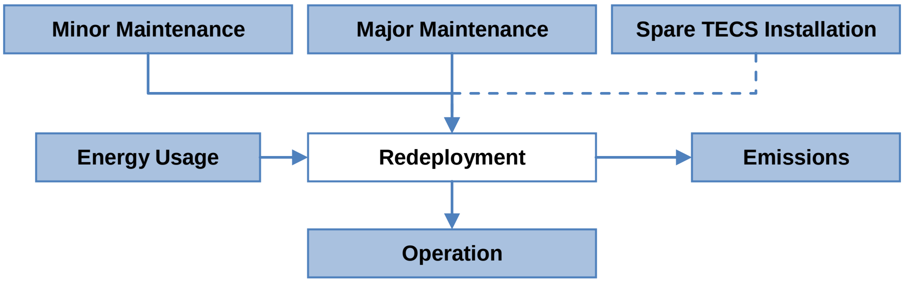

Figure 19 – Redeployment

The redeployment of a TECS will follow a similar process to the initial retrieval of the device. The machine will have to be shipped from the repair and overhaul facility to the array site, and then returned to its foundations to enable it to continue to generate electricity.

The carbon footprint of the redeployment phase is governed by the distance that the device has to be transported, and the means of transport used. The emissions arising from redeployment are also related to the weather and water conditions of the site, as if these cause the access to the site to become restricted, or cause the procedure to take longer than a standard operation, then the fuel consumption of the vessels used will increase, leading to a larger carbon footprint.

5.8 Unplanned Maintenance

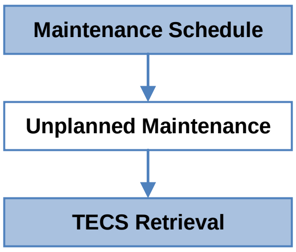

Figure 20 – Unplanned Maintenance

Unplanned Maintenance covers all maintenance operations that cannot be scheduled and do not occur at a regular frequency during operation. This covers any emergent situations on the device, such as malfunctions or failures. It may also include any upgrades or overhauls arising from regulations, redesigning, or other factors, although these may also be implemented as part of the planned maintenance schedule.

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5.8.1 TECS Retrieval

The process of TECS retrieval for unplanned maintenance is identical to the process identified for planned maintenance. See Section 5.7.2 for further details of the process.

5.8.2 Maintenance

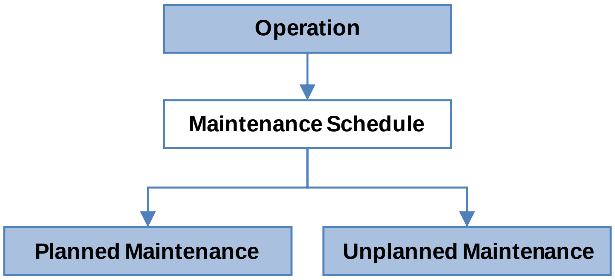

Figure 21 – Maintenance

The processes that form the maintenance phase cover all operations that are required as part of unplanned maintenance. This can cover repair and replacement of major items, minor items and consumables. If the scale of maintenance only requires the replacement of minor components and systems, it is possible that the processes can be carried out at a local repair facility. If a more thorough maintenance operation is required, or if major components from the device needs to be repaired or replaced, then it may be required to transport the machine to a larger overhaul facility. This additional transport distance will have to be modelled as well as the emissions arising from the processes used in the maintenance processes.

5.8.3 Redeployment

The process of TECS redeployment following unplanned maintenance is identical to the process identified for planned maintenance. See Section 5.7.5 for further details of the process.

5.9 Final Retrieval

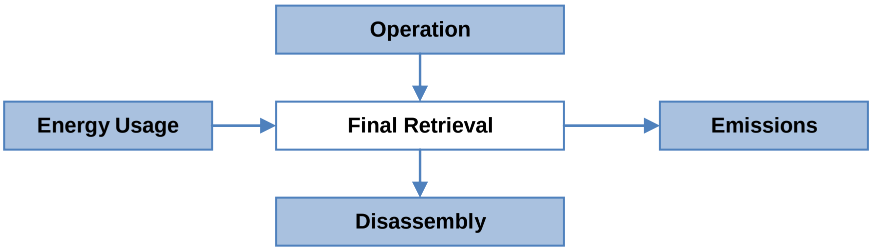

Figure 22 – Final Retrieval

The final retrieval of the TECS requires the complete removal of the device, including the foundations and all cabling up to the point of grid connection (POC). The retrieval of the device can be treated as the same process that was required to retrieve the device for maintenance (see Section 5.7.2).

The requirement for tidal power devices under UK government legislation is to remove all traces of the TECS back as far as the original level of the seabed which was present prior to deployment. This process will require a number of vessels to remove and transport the foundation of the device, as well as any cutting processes that are required to allow the base structure to be removed. There will also be a requirement to inspect the site following removal to ensure that the seabed is in a suitable condition.

Finally, there will be a requirement to remove all the sub-sea cables from the foundation to the grid POC, including any junction boxes.

5.10 Disassembly

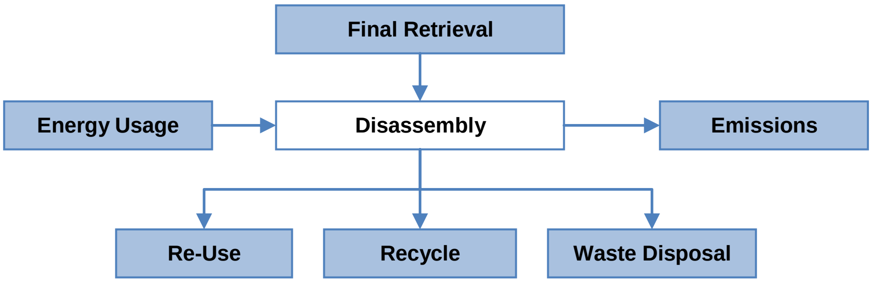

Figure 23 – Disassembly

Disassembly covers all of the processes required to take the TECS apart and then strip the device down to the component level so that parts can be either reused (see Section 5.11) or recycled (see Section 5.12) if possible. Any components that cannot be easily reused or recycled should be sent for final waste disposal (see Section 5.13)

5.11 Reuse

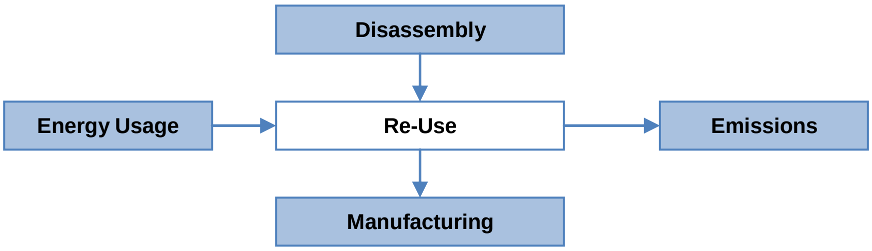

Figure 24 – Reuse

For the purpose of this report, reuse has been defined as the deliberate avoidance of manufacturing processes during later life cycles, due to the lack of disassembling components in an earlier life cycle. For a TECS, components may be re-used within multiple life cycles, within a single product stream. It has been foreseen that highly significant components such as foundation structures and turbine blades could be re-used, and therefore it is essential to define how this re-use should be included within the scope of the carbon payback analysis. If components are reused in different product streams to the original TECS, then the emissions offset by reusing the components would have to be allocated to the new product stream.

The re-use of components may include refurbishment activities between life cycles. If this is the case, rules for allocating the emissions associated with these activities must be defined. Examples of different scenarios for component re-use are illustrated in Figure 25.

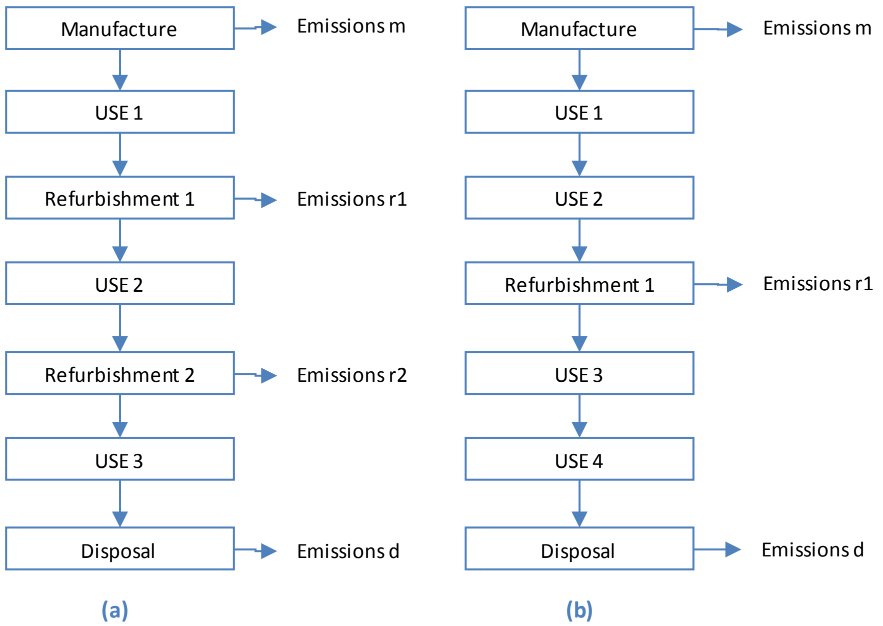

Figure 25 – Flow diagrams illustrating re-use for two different components

For the purposes of the carbon payback analysis, it is appropriate to include all emissions associated with the manufacture, *M*, and disposal activities, *D*. This is in accordance with the definition of the payback interval as defined in Section 1.5.2 and Section 9 (see Figure 41). The logic behind including these emissions is due to the fact that they are necessary for the functional unit to be delivered, and that by manufacturing a tidal stream array the generation of emissions associated with its ultimate disposal have been allocated.

For completeness, the carbon emissions arising from the refurbishment activities (*R1, R2,* etc) should be included in the scope of the study where it can be shown that these may arise. Not all of the components may be reused, but it may be possible to determine a list of systems that could be reused within the life cycle, and thus calculate a predicted carbon footprint associated with the overhaul of these components prior to reuse. By calculating the carbon cost of reusing components compared to manufacturing new components, it can be seen whether the reuse of a particular component offers a better carbon footprint. The carbon emissions offset by reuse of components would be included into the manufacturing phase of a future lifecycle (see Figure 41 in Section 9.1) as the reuse of components will reduce the requirement for components to be manufactured for a future TECS. It should be noted that the emissions arising from the process of reusing components and systems has been allocated to section F of the curve shown in Figure 41.

5.12 Recycle

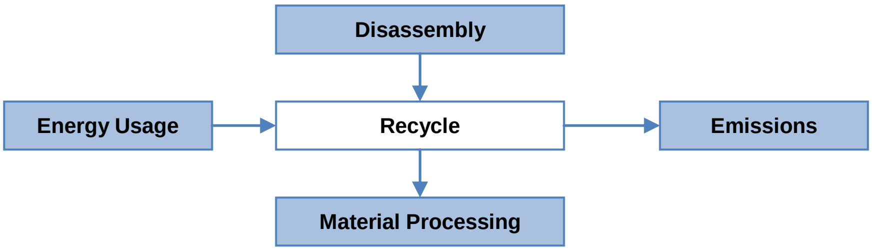

Figure 26 – Recycling processes

Any components or systems from a TECS that cannot be reused will have to be disposed of unless the material can be recovered and recycled. Waste materials can be classified into one of four categories:

A. Recyclable material (does not degrade in quality, see Section 5.12.1)

B. Recyclable material (degrades in quality, limited number of re-uses, see Section 5.12.2)

C. General non-recyclable waste (typically sent to landfill, see Section 5.13.1)

D. Other waste (e.g. hazardous waste, see Section 5.13.2)

The process of recycling materials can be considered to displace a similar amount of raw material from manufacturing and production processes. A flow chart illustrating this model is shown in Figure 27.

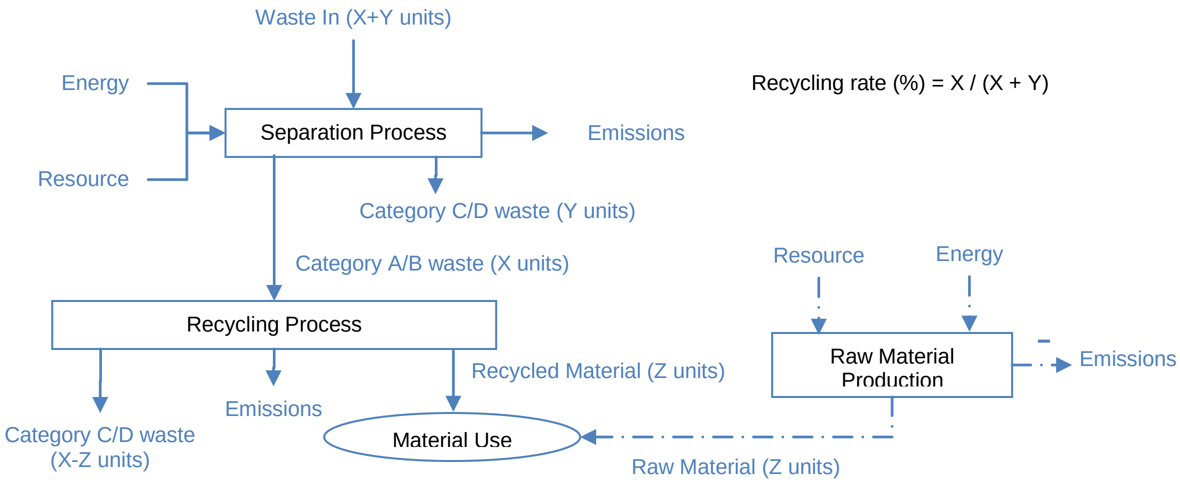

Figure 27 – Modelling of Category-A/-B waste using displacement of virgin material

The dotted lines in Figure 27 represent the flows of raw material that are avoided by using recycled material, and these flows should be the same processes that were used for the modelling the material usage prior to the introduction of recycled material for the consistency of accounting.

The recycling rate determines how much category-A and category–B waste is recovered during the separation processes. Separation processes may include breaking down components to separate materials, grinding to remove paint or sorting of waste. Un-recovered waste should be treated as category-C (see Section 5.13.1) or category-D (see Section 5.13.2). As the appropriate recycling rate in any situation is dependent upon how easily different materials may be separated after use, it is highly product-specific so an appropriate value should be chosen. Similarly, the emissions arising, and resources associated with the separation process should also be evaluated.

It has to be assumed that the recycled materials are reprocessed for future use on TECS, as if the recycled material is used for other products then it will prove difficult to account for the carbon offset by the recycling process. In reality it may prove that this view is unrealistic, but this should provide an acceptable estimate for the carbon payback.

5.12.1 Closed Loop Recycling

Materials that can be recycled indefinitely, that is without degrading the quality of the material during the recycling process can be described as following a Closed Loop recycling process. This covers materials such as steel, copper, aluminium and glass. As shown in Figure 27, the material production process including recycled materials should provide the same level of material to the original raw material production process used during the manufacturing stage. This is required to prevent inconsistencies between the use and disposal of materials.

The CO_2 emissions associated with the processing of selected closed loop recyclable materials are shown in Table 3 [21][22][23][24]. It may be assumed that all other GHG emissions are negligible. These values should be used unless product-specific data is available.

Material	Recycling Process Emissions (kg CO_2/kg category A/B waste)	Recycle Yield (kg Raw material offset/ kg category A/B waste)
Iron/Steel	0.46	0.90
Aluminium	0.86	0.79
Copper	0.59	0.88

Table 3 – Emissions associated with processing of recycled materials

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For glass, the recycling process is complicated by the necessity to include a certain proportion of virgin raw materials to the recycling mix. For recycled glass materials, ~0.25kg CO_2 should be assumed for the combined recycling process and virgin material displacement emissions for 1kg of category-A glass waste[25].

5.12.2 Open Loop Recycling

For materials with open-loop recycling properties (i.e. where the quality or grade of the material diminishes between subsequent uses), the boundary of the product life cycle is more challenging to define. The assessment should therefore include the recycling process from which the raw material was sourced, or in the case of the first life cycle the production of virgin material. Referring to Figure 28, 'Use 1' should include 'Extraction of raw material', 'Use 2' should include 'Recycling process 1' and 'Use 3' should include 'Recycling process 2'.

The treatment of recyclable materials with a limited number of re-uses poses a challenging allocation problem for LCAs. This type of recycling is termed 'open-loop', as the waste material is degraded in quality and therefore does not directly displace raw material use. A discussion of the relative merits of different open-loop recycling models is presented in Baumann et.al. 2004 [9] p114-119. Figure 28 illustrates the open-loop allocation problem for a material suitable for three uses.

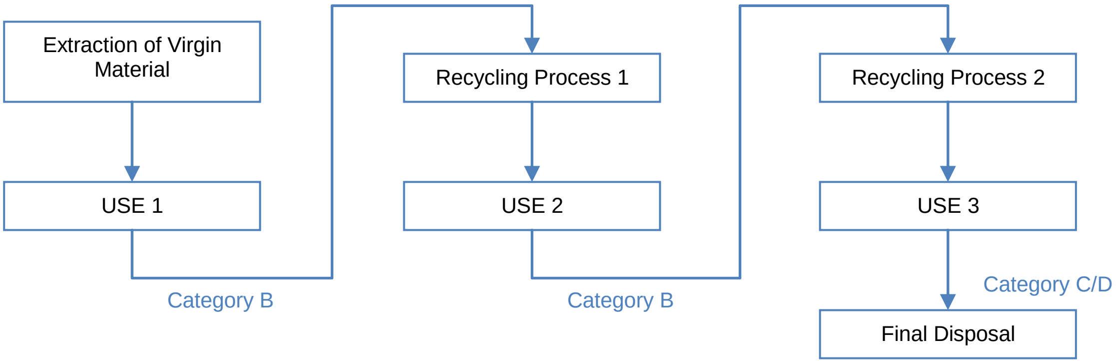

Figure 28 – Open-loop recycling processes

In allocating the downstream emissions associated with category-B waste, the following arguments were considered:

- The consideration of a large number of downstream processes increases the workload, as the scope of the assessment is widened significantly;
- The extraction of virgin material is necessitated by the first life cycle, and thus emissions associated with this process may reasonably be attributed to the first life cycle only;
- The final disposal is necessitated by the final life cycle, and thus emissions associated with this process may reasonably be attributed to the final life cycle only;
- The recycling processes are caused by the need to re-use the material for a different product. It therefore seems reasonable to allocate the emissions for the recycling processes entirely to the product life cycle that uses the recycled material.

By considering the above allocation in relation to Figure 28, it is apparent that the downstream processes associated with category-B waste are not considered, and therefore recycling of category-B waste after separation should be assumed to have zero emissions.

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5.12.3 Downstream Life Cycles

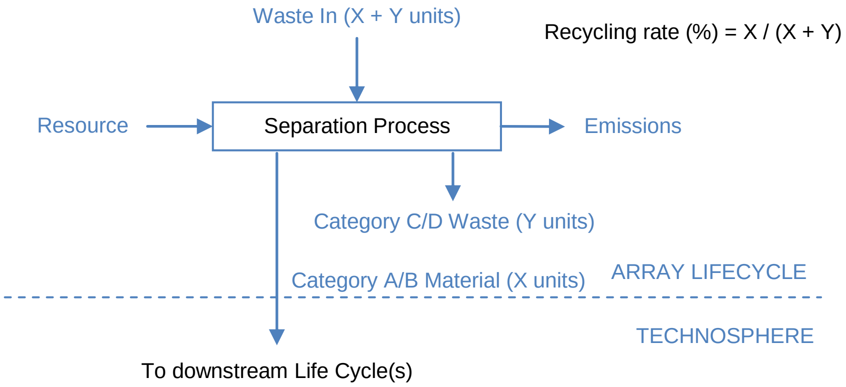

Figure 29 – Flowchart for modelling of Category-B waste disposal

As mentioned in Section 5.21, an assumption can be made that all materials recycled are kept within the product life cycle. However this assumption is not very realistic, as recycled materials may be used in a totally different product life cycle. This presents problems when accounting for the carbon offset by recycling material, as the impact to the carbon footprint by replacing raw materials with recycled material will not be measured by the LCA of the tidal stream array. If any materials from a TECS are to be recycled then the emissions offset should not be included as part of the decommissioning process, and instead form part of the next product lifecycle to use the recycled materials. As a result, if any recycled materials are used in the manufacture of a TECS, then the emissions offset by their use can be used to negate a proportion of the material processing emissions.

While the use of recycled materials offers an opportunity to reduce the carbon footprint of the manufacturing process, there is no credit provided should a company choose to recycle a TECS, unless recycling leads to a smaller carbon footprint than outright disposal. This lack of incentive could be perceived as a weakness in this accounting method, which is nonetheless technically correct where emissions are concerned.

5.13 Waste Disposal

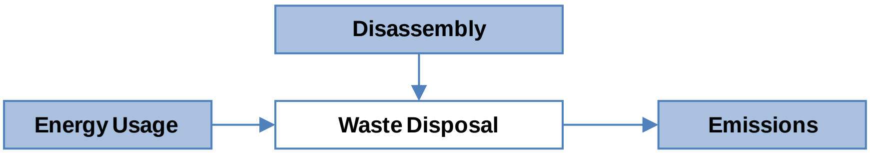

Figure 30 – Waste Disposal

5.13.1 Landfill

To model the disposal of category-C waste, disposal in landfill sites has been assumed. In the UK over 90% of non-recyclable waste is currently disposed of in landfill[26]. The percentage of waste being disposed of in this way is being steadily reduced due to the EU landfill directive. By 2020, it has been estimated that 25% of the non-recyclable waste within the UK will be incinerated instead [26]. For most types of waste, the global warming impact of landfill is greater than incineration, due to the higher proportion of methane released from organic decomposition [27]. For this reason, landfill represents a worst-case non-recyclable waste disposal scenario. Due to the prevalence of the use of landfill in the UK, it is reasonable to assume that this should be used as the means of disposing of non-recyclable waste from the tidal stream array for the purpose of calculating the carbon payback interval. Assuming landfill as the model for disposing of non-recyclable waste avoids the allocation issues associated with the energy recovery from waste incineration.

Three processes are considered to model the GHG emissions arising during the disposal of landfill waste. Two of the sources of GHG emissions arise from technical processes; the transportation of waste to landfill, and the fuel used to compact waste at landfill. The third source of GHG emissions from landfill is driven by the decomposition of organic material within the waste, which only applies to biologically degradable waste products (cardboard, paper, textiles).

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Sample data for the GHG emissions arising from the transportation and compacting of landfill waste was obtained from Baumann et.al. Appendix 1 [9]. The transportation data is based on municipal collection in Sweden, where the average transportation distance to a landfill was 18km. If a medium-sized truck is assumed, this equates to an emission of 2.5g CO_2 /kg for transportation. Compacting waste requires 40kJ / tonne, in the form of diesel fuel [9], and assuming 0.62g CO_2 /kJ, this equates to a CO_2 emission of 2.5g CO_2 /kg. Emissions of other GHG are not significant.

The GHG impact associated with waste disposal in landfill sites is dependent upon the type of waste under consideration, and the time horizon over which the emissions are considered. The global warming impact of landfill waste is due to the aerobic or anaerobic decomposition of organic waste, which releases CO_2 and CH_4 into the atmosphere. A small quantity (less than 2%[27]) of landfill gas is released as other hydrocarbons, but these are neglected as insignificant.

Waste initially decomposes rapidly under aerobic conditions, releasing primarily CO_2. This is followed by a long-term anaerobic decomposition, which releases a mixture of CO_2 and CH_4 into the atmosphere. Existing studies have shown that the amount of CH_4 and CO_2 released from landfill is comparable (typically 50% to 60% of landfill gas is CH_4 [27]). As the GWP of CH_4 is significantly larger than that of CO_2 (see Annex G), it is appropriate to predominately consider the global warming effect of CH_4 emissions.

Bjarnadóttir et.al. 2002 [28] provide a breakdown of potential CH_4 emissions over an infinite timescale, for different types of landfill waste. Table 4 presents an extract from this reference, which assumes 50% collection and combustion of CH_4 (this is approximately correct for UK landfill sites [27]).

Organic Material	Landfill Methane Emissions (kg CH_4 / kg Y)
Wood	0.126
Cardboard	0.120
Paper	0.123
Textiles	0.080
Other Degradable	0.033

Table 4 – GHG emissions from landfill by waste type [28]

A flow diagram for the disposal of category-C waste is shown in Figure 31, based upon the data for transporting and compacting of waste from Baumann et.al. appendix 1 [9], and disposal of waste in landfill from Bjarnadóttir et.al. 2002 [28].

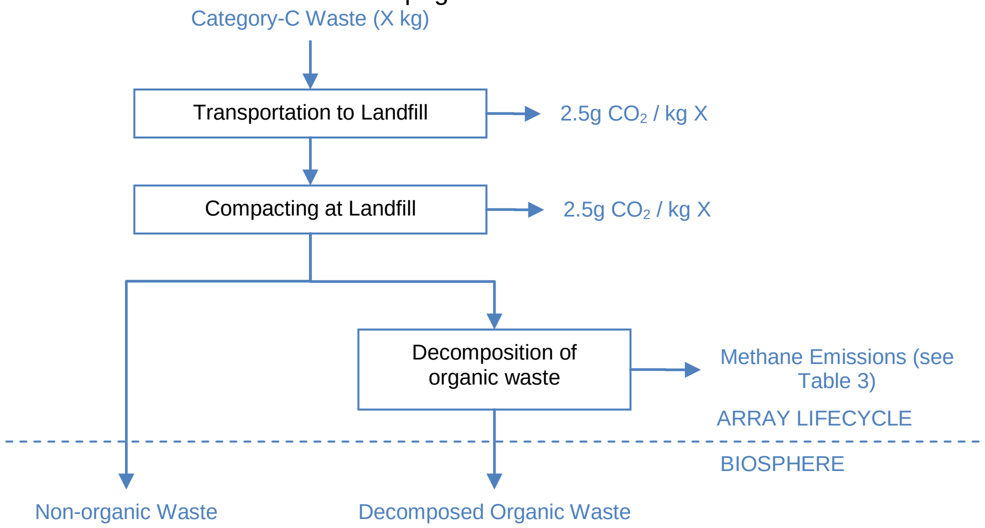

Figure 31 – Flowchart for modelling of Category-C waste disposal

5.13.2 Hazardous Waste

Hazardous waste is the term used to describe any waste that may present substantial or potential threats to public health and the environment. It covers a wide range of harmful and hazardous materials, and must be disposed of in accordance with local laws and regulations. More details as to the definition and classification can be found in 'A Guide to the Hazardous Waste Regulations and the List of Waste Regulations in England and Wales'[32] and 'The Interpretation of the Definition and Classification of Hazardous Waste'[33], both produced by the Environmental Agency. A table detailing the definitions of hazardous waste [33] has been included in Appendix Section C. It should be noted that nuclear waste falls into a separate category, but it is considered extremely unlikely that any radioactive waste should be generated during the life cycle of a TECS.

5.14 Transport Activities

Transportation of materials, components and products should be included within the study scope, unless excluded by the cut-off criteria specified in Appendix Section A.4. The functional unit of transportation is usually the product of the mass transported and the transportation distance. In this report, units of tonne kilometres (t.km) or kilogram kilometres (kg.km) are used.

5.14.1 Transportation Distance

Whenever possible, product-specific data should be used for the transportation distances associated with the tidal stream array life cycle. In the cases where this is not possible, the transportation distances may be estimated using the methods described in this section, or derived from similar LCA studies. All assumptions made regarding unknown transportation distances should be stated during the reporting of the final results.

5.14.2 Recommended Transport Modelling Technique

It is recommended that three processes be used to represent transportation activities. The first process specifies the transportation requirement within the product life cycle, and has a functional unit related to the component or material being transported (e.g. 1 component, 1kg of material, 1 litre of fluid). The transportation requirement (in t.km) is specified as an input to this process. A second process relates the transportation requirement (in t.km) to a fuel requirement (in MJ) and emissions associated with fuel combustion. This process is specific to the transport vehicle. A third process relates the fuel use (in MJ) to the associated GHG emissions from fuel production (see Section 8.1). A diagram illustrating this type of model is shown in Figure .

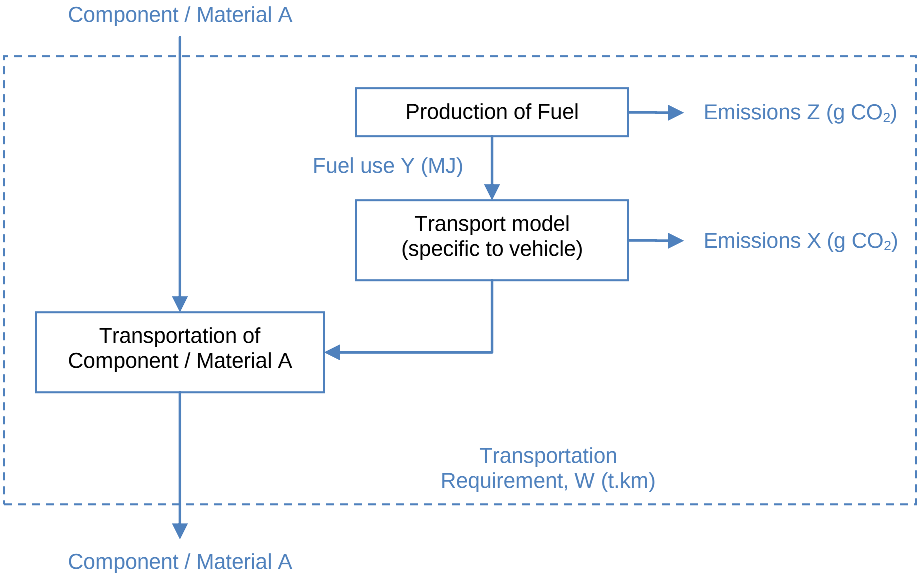

Figure 32 – Recommended Transportation Model

This model structure allows for flexibility in the modelling process. The mode of transportation may be changed retrospectively, and the same vehicle-specific transport process may be re-used. This type of model also provides visibility of the most significant transportation requirements within the life cycle, which is useful for analytical purposes.

The production of fuel may be omitted for rail transportation, as the use of both electricity and diesel powered trains prevents the inclusion of a specific fuel production process, instead a UK average value for the emissions arising from train journeys should be used, preferably in terms of kg.km.

Specific details regarding domestic and international travel, and different means of travel have been included in Appendix Section C.

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6 TECHNOLOGY LEVEL RATIONALE

LCA techniques were originally developed for existing products and processes, and require a defined level of technology readiness to create a suitably accurate model of the behaviour of a product over its entire life cycle. A new methodology has been suggested to allow a tiered approach to the technology levels used in the LCA carbon footprint model. This methodology introduces simplifications to enable an LCA to be created at a much earlier stage in product development but at a reduced level of accuracy. Successive tiers allow for more accurate models to be created, and so a detailed picture of the expected lifecycle emissions can be created. This methodology also enables a much simpler means of comparison between different TECS designs, as devices at a similar level of development can be compared more accurately.

6.1 Description of levels of fidelity

It is difficult to perform a detailed and accurate carbon payback calculation until the design has been exactly detailed. However this level of detail means that the model cannot be calculated until late in the design process. Instead a new approach is defined, in which it is possible to calculate the carbon payback for different levels of detail from the model.

This methodology defines a series of tiered Product Readiness Levels (PRL), which are linked to the Technology Readiness Level (TRL) system. The PRL form a gated means of calculating the carbon footprint of TECS at different levels of product readiness. The reasoning behind this methodology is to provide a clearly defined system for estimating the relative carbon emissions arising from a TECS when accurate product details are unavailable due to lower levels of technology readiness.

The chief advantage of this new method is the ability to create a carbon footprint model of a tidal stream array far earlier in the development phase than is currently possible. This allows potential areas for the reduction of carbon emissions to be identified, and to begin quantifying the amount of carbon it will be possible to offset with a given device. This method offers a further key advantage in that it will allow for a comparative assessment of different designs at similar levels of technology readiness.

As a design for a tidal generator progresses through the different TRL levels, more it will be possible to make a more accurate assessment of the CO_2 footprint of the device, as there is a greater degree of certainty over the materials and processes used during manufacture, operation, and disposal of the device. As a result, differences between two TECS designs at the same level of PRL can be compared, but it would be invalid to cross-compare designs across boundaries, as one will be a more accurate picture than the other. Without this technique, the existing methodology for calculating the carbon footprint of a product over its life cycle does not have any accommodation for designs with low technology readiness.

Currently, a system using four tiers of PRL is defined, as many more than this would add an unnecessary level of complication to the process, and limit the ability to compare competing designs, as well as requiring an excessive amount of additional data to produce meaningful models.

It has been decided that gates are required between the different PRL to provide a measurable point that the design has evolved from the lower level to the next level up. The gate mechanisms have been set as the points where it is most likely for a change to the predicted levels of carbon emissions, following greater technical experience with a device. As a result, the gates have been set to construction milestones:

- The first gate between Preliminary Design and Manufacture Prototypes is the construction of the first prototype, as prior to this event, the behaviour of the TECS is entirely predicted with no quantitative or qualitative results as to actual performance.
- The second gate from Manufacture Prototypes to Full-Scale Testing is the point at which the first test array is constructed, as this will allow for more accurate details about the production system to be included, as single prototypes are more likely to be bespoke individual units.
- The third and final gate between Full-Scale Testing and Production Design is defined as the point at which full-scale production design begins, as all of the factors involved throughout the life cycle of the TECS will now be defined to a suitable level of accuracy.

PRL	TRL	Gate Mechanism
1 – Preliminary Design	0-3	Start of project
2 – Manufacture Prototypes	3-6	First prototype constructed
3 – Full-Scale Testing	6-9	Demonstrator array built
4 – Production Design	9	Full-scale production

Table 5 – PRL Levels

As well as covering the different stages of technology readiness, a site will need to be specified, either to calculate the carbon payback interval of a single tidal stream array design, or to compare between two different TECS designs. As there is no commonality between the characteristics of different sites, a generic site design has been created, and this should be used for all different levels of fidelity (see Section 7.1). This allows for a model to be created before a deployable site has been established.

The PRL system should have a further benefit in allowing the carbon payback period of the device at PRL 4 to be estimated from earlier PRL levels. This estimation of the actual carbon footprint will be dependent on previous experience in footprinting devices in order to provide realistic scaling factors which can be revised at each subsequently higher PRL.

6.2 Preliminary Design

The LCA model constructed in the first tier of Preliminary Design is the most simplistic model of carbon emissions from the TECS. It will simply be built up from expected weight of materials, disregarding emissions arising from manufacturing processes. Considering the ideal site, it shall be assumed that there is no delay due to weather or conditions, and the only transport values that shall be considered will be the assumed distances to and from the ideal site.

6.3 Manufacture Prototypes

Once the first prototypes have been constructed, it will be possible to create a much more accurate model, using either real data from manufacture and installation, or extrapolating values from those obtained from the prototypes. It should be noted that if prototypes are manufactured at a smaller scale than the predicted final size of the generator, then the findings can still be used, but will have to be scaled up by a factor to allow for meaningful calculations to be carried out.

6.4 Full-Scale Testing

The full-scale testing allows for reasonable estimates of the carbon emissions from the production system to be included in the LCA model, as by this stage a first test array will have been manufactured and installed. As the prototype generators created will have been individual bespoke devices, it is likely that the methods of production will change to allow for a larger scale production system, and in doing this, there will be a change to the emissions produced during manufacture.

6.5 Production Design

The production design tier is equivalent to the existing standard for creating LCA models, as by this stage, all of the manufacturing, deployment and disposal phases will be defined to a high level of accuracy. It is also possible that by this stage that the actual site for the deployment of the full array will be known, and as a result, the idealised site conditions can be replaced in favour of the actual site conditions.

7 TIDAL STREAM ARRAY SITING CONSIDERATIONS

A number of different variables influence the design of a tidal stream array site and limit the upper number of devices that can be deployed in a given area. These variables create problems in defining an average site, as individual sites behave very differently to each other, as a result of the impact of the geographical, geological, ecological, tidal, meteorological, and social factors of the different sites. To allow an LCA to be performed for a TECS device far earlier in its development phase and estimate the carbon footprint, or to create a better means of comparison between different TECS designs, an idealised site has been defined. This will allow an LCA to be created independent of actual site data, and allows for different tidal stream profiles to be applied to the site.

7.1 Defining an Ideal Site

The choice of site for a TECS array is one of the key factors in the suitability of tidal stream energy. There are a number of factors that can influence the size of array possible for a given location, which in turn influences the amount of electricity that can be generated. Due to the number of variables that exist, it is not possible to approximate real sites to an idealised model. While the majority of the carbon produced during the life cycle of a TECS will be during the manufacture and disposal phases, there will be a measurable contribution arising from the choice of site. To allow for a comparative number of the carbon footprint to be calculated at different stages of the design, it will be useful to create an idealised site. The advantage of this idealised site is that it enables a carbon footprint model to be created for a tidal stream generator far earlier in the design process than is currently possible with the existing methodology, and it can also provide a means of comparison between different tidal stream technologies at similar levels of development.

The ideal site shall be set out here in its most general sense, and as required numbers can be substituted in to allow for LCA to be performed. It shall be assumed that the deployment site for the generators is a perfectly flat and level site, devoid of marine life and adverse geotechnical features, with the seabed consisting of flat bedrock. It shall also be considered that the site is regular area, sized of fixed dimensions across the flow and along the flow.

The tide in the ideal site shall be assumed to flow uniformly through the site so that all of the flow energy can be extracted by the generators without losses for the flow coming in at an angle to the array. It should also be assumed that the tide will reverse in direction by exactly 180°. In real sites, the direction of flow may not be as consistent, for example at the Fall of Warness site used by EMEC, the tide reverses to a lower degree.

It shall be assumed that the point of connection to the grid (POC) shall be set as being on the nearest point on the shore to the device, with the sub-sea cabling routed in a straight line between the array and the POC. The model shall allow for different means of power transfer, such as separate cables from each generator, or a collective cable from a sub-sea junction box.

The overhaul facility for the idealised array shall be modelled as being on the shoreline, but further from the site than the POC. For the purpose of the idealised site, it shall be assumed that there are transport links between the POC and the overhaul facility, either by land or water. For this idealised site, there should be options to transport the generator directly from the array to the overhaul facility, or to transport the generator to the overhaul facility via the grid POC. A schematic for the idealised site has been shown in Figure 33.

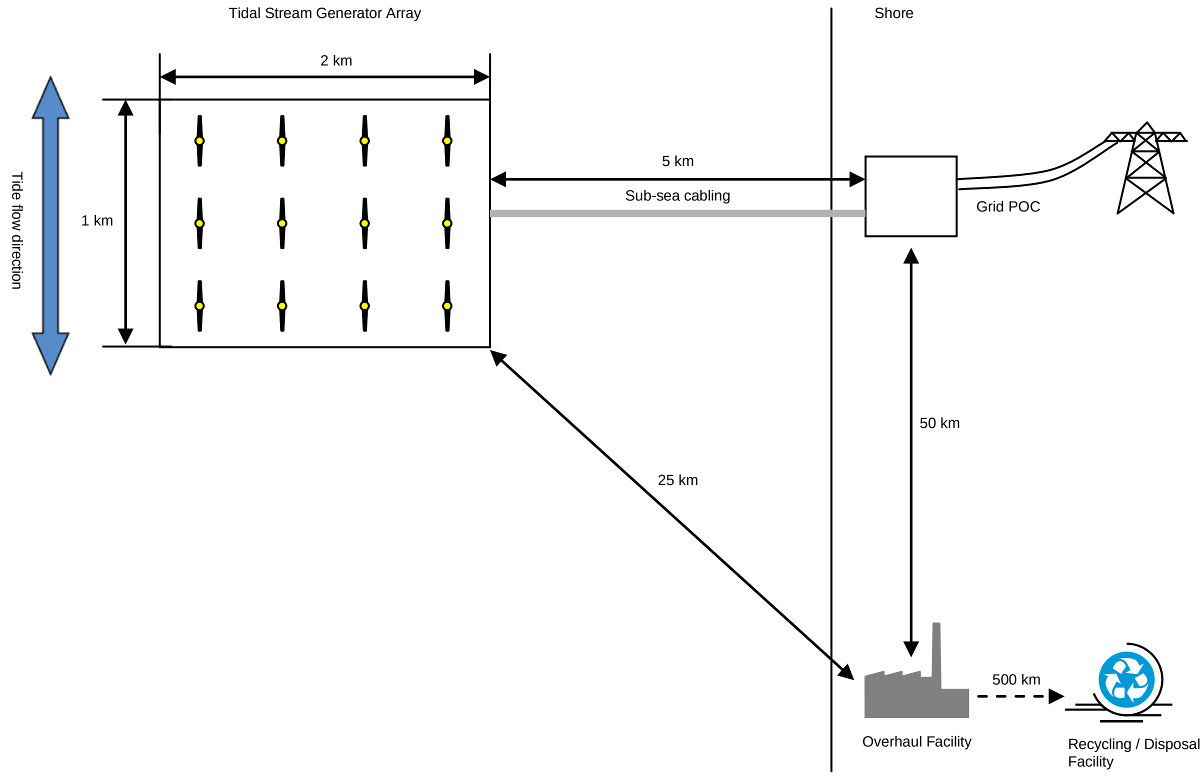

Figure 33 – Idealised Site for Tidal Stream Array

7.2 Array Location and General Site Conditions

The location of the array influences various aspects of the product life cycle. In particular, parameters such as the length of the sub-sea cable(s) and the shipping distance required for deployment, maintenance and retrieval vessels is highly dependent upon the geographical location and site conditions of the array. This level of details increases the complexity of the model, as there is no real commonality between potential array locations, and so the carbon payback model should either be created using the idealised site conditions detailed above, or on a site-specific basis. The use of the idealised site conditions will decrease the overall accuracy of the study, but will allow for a comparative assessment between different technologies.

7.2.1 Geographical Location

As mentioned, the geographical location of a tidal stream array can vary, and conditions are very subjective to the site selected. In considering the geographical properties of the site, the geotechnical conditions of the seabed must be considered, as well as the distance to shore, the available transports links, and weather conditions. These are detailed further over the following sections.

7.2.2 Seabed Geotechnical Features

In the idealised site detailed above, the site was assumed to possess flat level bedrock throughout the site. This removes the need to model a wide range of features that exist at different actual sites, such as loose rock, hard clay or fine silt, and the overall attitude of the seabed, as it may not be consistently flat and level. If further support to a TECS is required, then mud mats may be used under the foundations to increase stability. It should be noted in the decommissioning phase that these mud mats will need to be removed along with the generator in order to return the site to its original state.

For defining the site features of an actual site, it will be necessary to conduct a site survey, and then the impact of the seabed features can be measured by the restrictions placed on the number of TECS that it will be possible to install on the site.

7.2.3 Depth of Array

The typical depth for TECS deployment in UK waters varies between 40m and 80m deep, it can be assumed that for the idealised site, an average value of 60m can be used. This average value will also account for TECS which may feature a number of devices vertically stacked onto a single foundation.

7.2.4 Distance to Shore

The distance to shore refers to the distance to the nearest suitable condition for the POC to the electricity grid, as this is the ultimate point that will fall under the scope of the carbon payback model. The infrastructure for the electricity grid, including the sub-station needed to transform the power from the tidal stream array is outside of the scope of a tidal array, and so shall be discounted. However, the cabling leading to the sub-station must be accounted for, including the design-specific choice of whether there will be a single cable routed from the array, and a sub-sea junction box for all of the cables from the individual devices, or whether each machine will be connected to the grid individually.

If the idealised site conditions are to be used, then a fixed distance of 5 km can be used for the distance to shore, which can be based on a range of typical distances to shore for existing tidal stream sites in the UK. In the case that actual site details are used, then the actual figure for the distance to shore should be used. The means of connecting the array to the grid POC should be assumed to be a single subsea cable, with each device in the array linked in via a subsea junction box unless the design clearly states that a different means of connecting the array to the grid has been selected and modelled.

7.2.5 Nearest Port

The nearest port to the tidal stream array should be considered to be the nearest port of a suitable size for a given array. It should also be assumed for the idealised site that any required maintenance during the life of the TECS should be able to be performed at this location. The suitability of a port can therefore be determined by any restrictions that the port places on the size of components that can be transferred, the ability of the port to handle required sizes of vessel, and the access to maintenance facilities at or near to the port.

For the idealised site detailed previously, the port shall be assumed to be 25 km from the tidal stream array. It should also be noted that for this site, there is also a transport link between the grid POC and the port, and so it may prove more advantageous to transport items to the POC and then by alternative means to the port for maintenance. This distance may well be longer than the direct route to the harbour, but may offer a saving in emissions. This may be advantageous if there is a rail link between the POC and the repair facility, as this may have a lower fottprint than the carbon cost incurred by using a vessel.

When using real site data, the actual distances from the array to the port should be used, although it may still be possible to use alternative routes between the array and the port, and will rely on the location of the array.

7.2.6 Recycling / Disposal Facility

A distance of 500km has been assumed as a relatively conservative distance from the Maintenance Facility to a Recycling and/or Disposal destination. This distance has been estimated based on the distance from EMEC to Edinburgh which is at the upper-end of transport distances from UK coastal sites to major industrial hubs. The distance represents a once-per-turbine journey near the end of the lifecycle and is chosen to encompass a wide range of tidal sites and recycling facilities.

7.2.7 Weather Conditions

The weather conditions for the site of a tidal stream array can influence the array in a number of ways. Access to site to install or remove generators (both for maintenance and disposal) will be dependent on both the tidal conditions and the weather conditions. This can result in extended periods of inactivity, and impact on the payback interval of the array if a turbine is awaiting maintenance or overhaul.

The reporting of the carbon payback interval should comment upon the level of storm protection designed into the tidal stream device under consideration, and any implications that this might have for quantitative comparison between different technologies. The effect of the weather conditions on the maintenance intervals should be investigated during the development phase to establish how they will affect retrieval of turbines, such as issues with sea state and visibility. While there is no direct emissions associated with delays to turbine retrieval, a longer period of turbine inactivity will increase the carbon payback interval.

7.2.8 Marine Life

The idealised site has been assumed to have no impact on the marine life of the locality, and conversely, it has been assumed that marine life, such as growths, will not impair the operation of the array. However planned inspection and maintenance activities to remove marine growths from the array have remained within the scope of the idealised site to allow for a consistent maintenance schedule to be applied, regardless of site choice.

Marine life specific to an actual site must be considered in more depth, with studies being carried out to ensure the ecological impact of the array is minimised. The emissions arising from these studies may contribute towards the overall carbon footprint of the array, although their contribution may fall under the threshold line, and so they could be safely neglected. The threshold value below which contributions to the carbon footprint can be neglected should be set at 0.1% of the carbon footprint. However if the combined value of all neglected factors exceeds 0.5%, then these should still be included.. The inspection schedule for the array in an actual site will have to be adapted based on the rate of marine growths on the generators. This rate may depend on overall geographic location, but also be compounded by a seasonal variation.

7.2.9 Disturbance to Shipping

For the carbon payback study of the idealised site, it shall be assumed that the installation site will not contain any shipping lanes, and as a result there will not be any additional emissions arising from the re-routed shipping that will need to be accounted for in the model.

This model may not prove valid for real sites, and each site should be investigated to determine whether the installation of a tidal stream array would result in a disruption to existing shipping lanes. It may be decided that the shipping lane cannot be moved, and then the resultant impact to the array site can be investigated, to determine whether the site can still be used for an array. Alternatively, the impact to the carbon payback interval of re-routing the shipping lane could be calculated to determine the additional impact caused by the tidal stream array.

Comments should be made during the reporting of the carbon payback interval regarding the likely effects of the specific technology upon shipping routes, and this should be considered when comparing the assessed carbon payback interval with other technologies.

7.3 Array Spacing

For a given site, the number of TECS that can be installed will be fundamentally limited by the size of the suitable area of seabed for TECS installation. A larger area will allow more TECS to be installed, and more power extracted from the tidal stream, however, the number of TECS is also constrained by the spacing required between individual devices. To ensure that each TECS operates at optimal conditions, there must be sufficient space, both around the device, and also the disturbance to the flow caused by any units in front must be minimised. The spacings for each design will vary depending on the size of the TECS and means of extracting energy from the flow, and will be specific to each design. For axial flow turbines, this spacing is currently thought to be 2 rotor diameters between turbines in the same row, and 5-10 rotor diameters between rows of turbines:

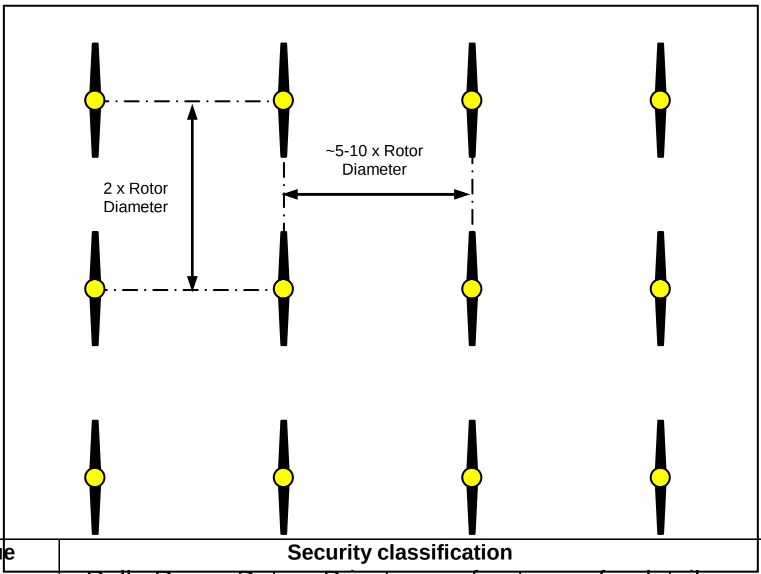

Figure 34 – Array Spacing

7.4 Array Sizing

The greatest possible size of a tidal stream array is limited by the factors outlined above, particularly the available area of seabed for TECS, and the space required between devices. A number of other factors have a bearing on the overall size of the array, including the required power of the array, as this may require fewer turbines than the maximum possible for a given site. Also it is important to consider the total energy that can be extracted from the tidal stream in a given area.

For specific sites, there will be a requirement for either a number of devices or an output power from the customer, and this can be used to populate the array accordingly. For an idealised site, the array size defined in Figure 33 should be used in order to generate the maximum electricity from the size.

Finally, the size of the array may have a bearing on the possible method and production for the array, which will accordingly have an impact on the carbon emissions produced during the life cycle of the array. The change to the carbon emissions will have to be calculated depending on the processes, as while the monetary cost of the project will decrease by establishing a production line, the effect on the carbon footprint would still need to be analysed.

7.4.1 Selection of Array Size

Different methods were considered to allow the average electrical power output of the array to be calculated. The first step in calculating the average electrical power of an array is to establish how many generators can physically be installed at one location, using the conditions and variables described previously. The assumed tidal stream flow model for the site could then be established for the site, and if no actual site data is available, an assumed low-, medium-, or high flow speed tidal array can be used for the site, depending on the optimal performance of the generator. By defining the power output of the generators of the array over the tidal stream velocities, the power produced by the array can be calculated.

This approach was used for several reasons. Firstly, it avoids the concept of 'rated power', which is a quantity that may be defined differently across a range of tidal stream technologies. Secondly, it uses the area of the array site as effectively as possible by fitting as many devices as possible onto the site, which is the most practical means of using the available area. Thirdly, while the third method specifies a power required from the array, and then selects a number of generators accordingly, this is not a conventional means of sizing arrays. Typically, a developer for a site will decide both on the type and number of TECS to be deployed on site, based on the size of site available, and the level of funding, and from the size of the array, the average power output can be estimated.

A number of different methods were also considered for sizing a TECS array, and these alternatives are detailed below. One approach involved specifying the number of machines within the array, and to calculate the average output power based upon the knowledge of the machine rated power and load factor. Thus the number of machines determines the farm size.

A third approach was to specify the average output power directly, and to specify a standard tidal current profile. If the power output of the tidal stream devices over the range of tidal current velocities were known, this would allow the number of machines within the array to be calculated.

7.5 Standard Tidal Current Histogram

To establish the average power output of a tidal stream array, the individual energy yield of the tidal stream generators will have to be calculated, either from estimated tidal stream velocity models, or from actual site-specific data of the tidal stream velocities. Once the power output from a single generator has been modelled, this can be factored up to estimate the performance of the whole array.

The tidal stream current velocity should be assumed to be uniform for all machines within the array, however it is unlikely that every device will have been designed to work optimally at the same flow speed. Some devices may have been optimised for certain specific conditions, such as the high tidal stream flow occurring at the Race of Alderney, or low tidal stream flow, to create a device that is able to be installed in a wider variety of locations. To allow for idealised site conditions to be used for a carbon footprint model, three different general flow conditions have been provided. These have been created to provide ideal flow conditions for generators that respectively work better in low, medium, or high flow conditions.

As previously mentioned, high flow conditions exist at the Race of Alderney, and while a site-specific velocity profile could not be found, data has been estimated, based on the data found for the maximum average flow speed of 4.4m/s [17]. The medium flow speed data was derived from simplified data obtained from EMEC[13] for

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the current test site at the Fall of Warness. The low speed flow data has been estimated, assuming an average flow speed of around 1m/s. While no site-specific data for this profile has been found, it is currently deemed to be suitable enough for the purpose of this report, as there are a number of sites that exist with flow speeds of around 1/ms, including Carmel Head, Islay, and the Isle of Wight [16].

The tidal current profiles have been assumed to conform to relative probability distributions, and this has been represented graphically in Figure 35 and Figure 36. The data has not been measured directly, with only the data for the medium flow speed profile being directly derived from actual site data obtained by EMEC. The data has been solely provided for the purposes of modelling, and to assist with the definition of the idealised site properties.

Marine current resource modelling is a highly site-specific and detailed process. Guidance upon carrying out such an assessment of a specific site is available in a report from EMEC [15].

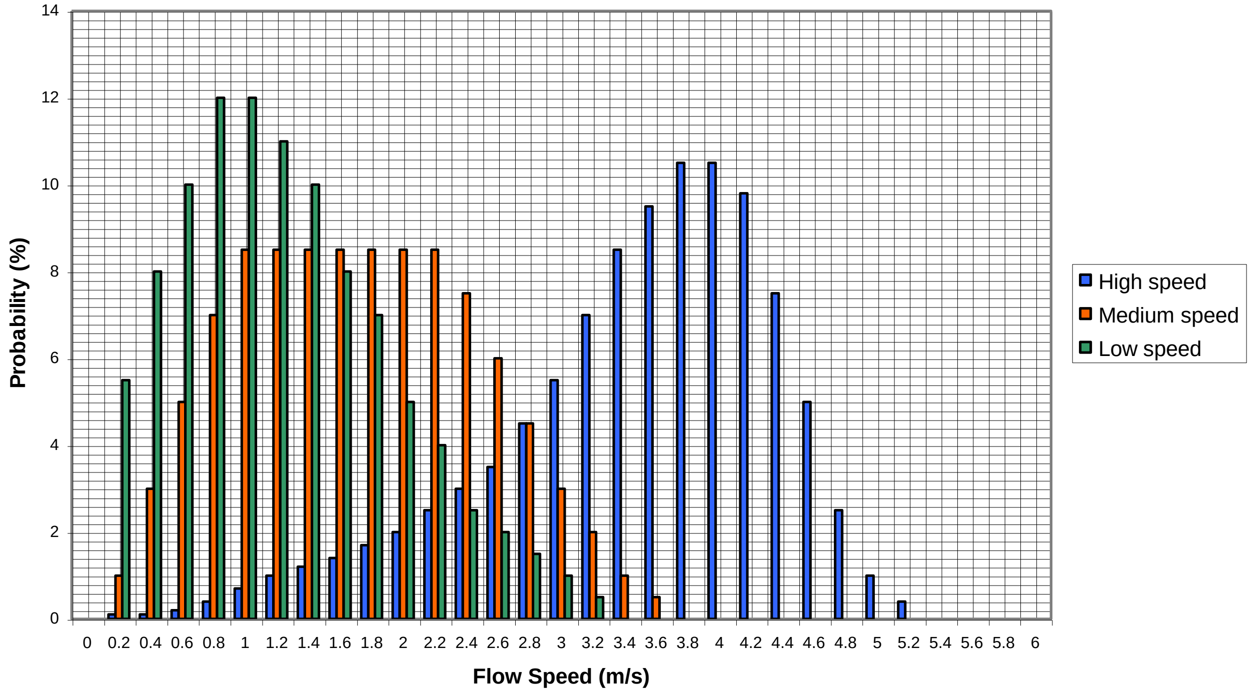

Figure 35 – Tidal Current Histogram (% Probability)

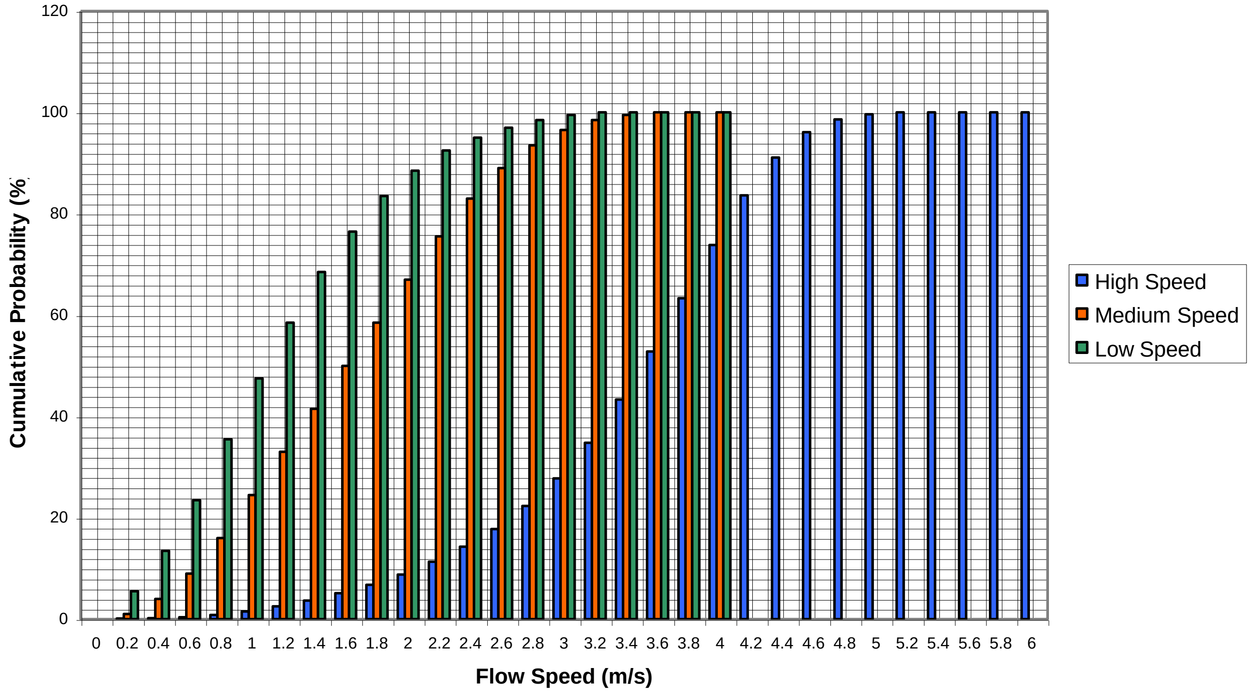

Figure 36 – Tidal Current Histogram (% Cumulative Probability)

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7.6 Calculating the Power Output from an Array

The average output power of a tidal stream generator can be calculated by using a relevant tidal current histogram. This can be based on real site data or if actual data is not available then the histograms defined in figures 35 and 36 that are best suited to the machine in question should be used. The output power of the generator must be known for a given range of speeds in order to calculate the average output power.

The average assumed power of a generator can be found by multiplying the machine power at a given flow speed by the probability of that speed occurring (for example from Figure 35). These values are then calculated for the full flow speed range and then summed, and divided by 100% to obtain the average power output of each machine. An example of a fictional machine to demonstrate the process has been shown in Table 6, Table 7, Figure 37, and Figure 38. For the purpose of this example, it has been assumed that the device will be running in medium-speed tidal stream flow conditions, and the machine power at given flow speeds has been estimated.

Flow Speed (m/s)	Availability (%)	Machine Power (kW)	Power × Availability
0.0	0.0	0	0
0.2	1.0	0	0
0.4	3.0	0	0
0.6	5.0	0	0
0.8	7.0	0	0
1.0	8.5	0	0
1.2	8.5	100	850
1.4	8.5	200	1700
1.6	8.5	300	2550
1.8	8.5	400	3400
2.0	8.5	500	4250
2.2	8.5	600	5100
2.4	7.5	700	5250
2.6	6.0	800	4800
2.8	4.5	900	4050
3.0	3.0	1000	3000
3.2	2.0	1000	2000
3.4	1.0	1000	1000
3.6	0.5	1000	500
3.8	0.0	1000	0
4.0	0.0	1000	0

Table 6 – Example calculation of average power of fictional Tidal Stream Generator

	Power (kW)
Sum (Power × Availability)	38450
Average Power (kW)	384.5

Table 7 – Average power of fictional Tidal Stream Generator

Figure 37 – Power curve of fictional TECS

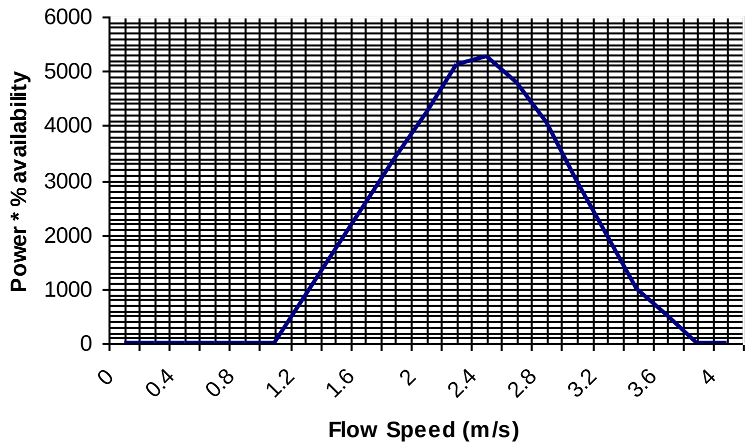

Figure 38 – Curve showing peak power availability for fictional TECS

Figure 37 provides a graphical representation of the power curve of the fictional TECS detailed in Table 6 and Table 7 which has been assumed to increase in power linearly until it reaches the maximum power of the device, assumed to be 1MW. A more useful curve is shown in Figure 38, which indicates the optimal flow speed for the device, based on both the expected power for a given flow speed and the probability of that flow speed occurring for the tidal stream at the site in question.

In calculating the average machine power output for a tidal stream array, it is required to account for the machine availability. Machine availability during operation will cover lost time due to planned and unplanned activities, and an approximate value for the availability factor should be calculated during the creation of the maintenance schedule. In the example of the idealised tidal stream array, if it is assumed that the TECS should be available 95% of the time, then the resultant power output should be multiplied by a factor of 0.95 to account for the lost availability.

As well as accounting for the availability of the devices, the seasonal variation of the tidal stream will need to be accounted for in determining the power output from a TECS. This data will be site-specific, with no opportunity to average this between locations. Possible effects of seasonal variation could include changes to the maximum flow speed of a site, changes to the probability distribution of flow speeds, and alterations to flow direction, including changes to the bi-directionality of the tidal stream flow. The effect of these changes may impact on the power output from the TECS, but investigations will need to be carried out to determine the size of this impact, as this may positively or negatively impact the output of the generator. These factors have been neglected for the case of the idealised site.

Assuming that the number of TECS to be deployed on a given site is known, the average power yield of the array can be estimated by multiplying the average power for a single machine by the number of devices to be

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installed in the array, based on the method defined in Section 7.4.1. Once the average power yield for the array is known, this can be used to calculate the offset GHG emissions arising from electricity generation (see Section 9.5)

7.7 Shore Connection and Other Infrastructure

In order to model the complete tidal stream array, it is not sufficient to model a specified number of tidal stream turbines. Supporting infrastructure such as sub-sea cables, transformers and electrical switchgear also has to be included for the model to accurately reflect reality. This section describes the approach that should be taken to model this infrastructure.

7.7.1 Electrical Shore Connection – Grid frequency AC

In the case of a technology that uses electricity at grid frequency (50Hz in the UK) to transport power to the shore, this may include sections of sub-sea cable, a sub-sea or land-based transformer and junction box, and a number of dry-mate or wet-mate connectors to join the TECS to the electricity grid.

If the array is at a stage of development where the electrical interconnection to be used is known, then this technology-specific infrastructure arrangement should be used for modelling.

If the technology under investigation is at an early stage of development where the required electrical infrastructure for a large array is unknown, then the connections defined by the idealised array should be used.

7.7.2 Other type of Shore Connection (e.g. DC electricity, hydraulic fluid)

For the case of tidal stream technologies that do not transfer power to the shore using a grid frequency AC electrical connection, the required infrastructure should be modelled based upon the best estimate of the structure of a large array. This model should include any on-shore equipment necessary for the production of grid electricity from the power transfer medium (for instance a DC to AC converter).

7.7.3 Other Offshore Infrastructure

Other offshore infrastructure which may be considered within the model include the use of scour prevention measures and warning buoys. The inclusion of such infrastructure is design-specific, and it should be decided whether these fall under the scope of the product system, or are instead essential technical processes. Further guidance on the cut-off criteria needed to define where these processes fall can be found in Appendix Section A.4.

7.7.4 Onshore Infrastructure

Onshore infrastructure should be included within the scope of the study if it is considered necessary for the delivery of the functional unit. An example of on-shore infrastructure that would be included is a DC to AC power electronic converter, or an on-shore transformer. Attention is drawn to the cut-off criteria specified in Appendix Section A.4.

8 SPECIFIC MODELLING CONSIDERATIONS

This section aims to provide coherent guidance for modelling activities within the array life cycle. It builds upon Section 4, in which the general structure and form of the model was described. The purpose of this section is to provide a standard set of modelling assumptions, which would allow the results of separate studies to be compared quantitatively.

The quantitative data provided in this section is intended for use only when more appropriate data is not available, such as actual device performance data or site-specific deployment data. Alternative quantitative data should be used if it is available and fulfils the quality requirements specified in Appendix Section E and if:

- The alternative data is product specific, process specific, or location specific (primary data or secondary data that was collected for the specific process under consideration);

Or:

- The alternative data is specific to the country in which the process occurs (if not within the UK), and is consistent with the boundary conditions specified in Section 3.2.3;

Or:

- The alternative data is based upon assumptions relating to the array lifecycle that are considered more reasonable for the study in question;

Or:

- A sensitivity analysis has indicated that the choice of data has a greater significance than has been assumed for the idealised case (with the exception of the production of electricity).

The use of alternative data should be stated and justified within the final report, and a sensitivity analysis should be performed to determine the extent to which the choice of alternative data has influenced the outcome of the study.

8.1 Energy Use Modelling

Energy use within the product life cycle should be modelled using energy carrier flows. An energy carrier flow may be a quantity of electricity or specific fuel that is measured in terms of its energy content (e.g. in J, kWh, BTU etc), and is used within another process as a source of heat energy. The purpose of this sub-section is to provide guidance on the modelling of energy use, and to provide standard data for the emissions associated with the combustion of fuels for energy, which may be used if product-specific data is not available.

8.1.1 Electricity Production

Electricity production within the UK has been assumed to generate 0.43kg CO_2 / kWh based on the UK average grid mix, as it is not possible to break this down to the contributions arising from different means of generation. All other GHG emissions associated with electricity should be neglected, as stated in the guidance issued by DEFRA[8], and personal communication with the Carbon Trust. The assumed CO_2 arising from electricity production can be used to provide the basis for calculating the carbon offset by the operation of a tidal stream generator:

$$\text{Emissions offset} = \text{kWh generated during operation} \times (CO_2 / \text{kWh})$$

When reporting the final results, the value selected must be stated, and justified. More thorough details can be found in Appendix Section 12. The production of electricity can be represented by a process flow diagram, as shown in Figure 39.

Rolls-Royce Data - Private, see front page for details

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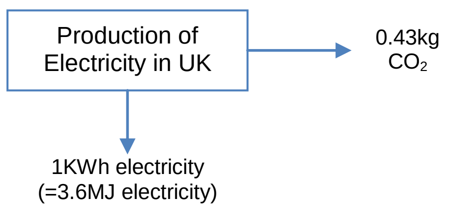

Figure 39 – Energy use from electricity flow diagram

8.2 Activities Modelling

All activities that are not excluded by the cut-off criteria should be included. For each planned activity a unit process model should be defined, which quantifies the required flows associated with that process, such as energy use, transportation requirements or material requirements. The process unit of the individual process should be chosen, as considered appropriate (for example, the process unit may be defined as the cleaning of the blades of one turbine). An example of a process for the cleaning of turbine blades is illustrated in Figure 40.

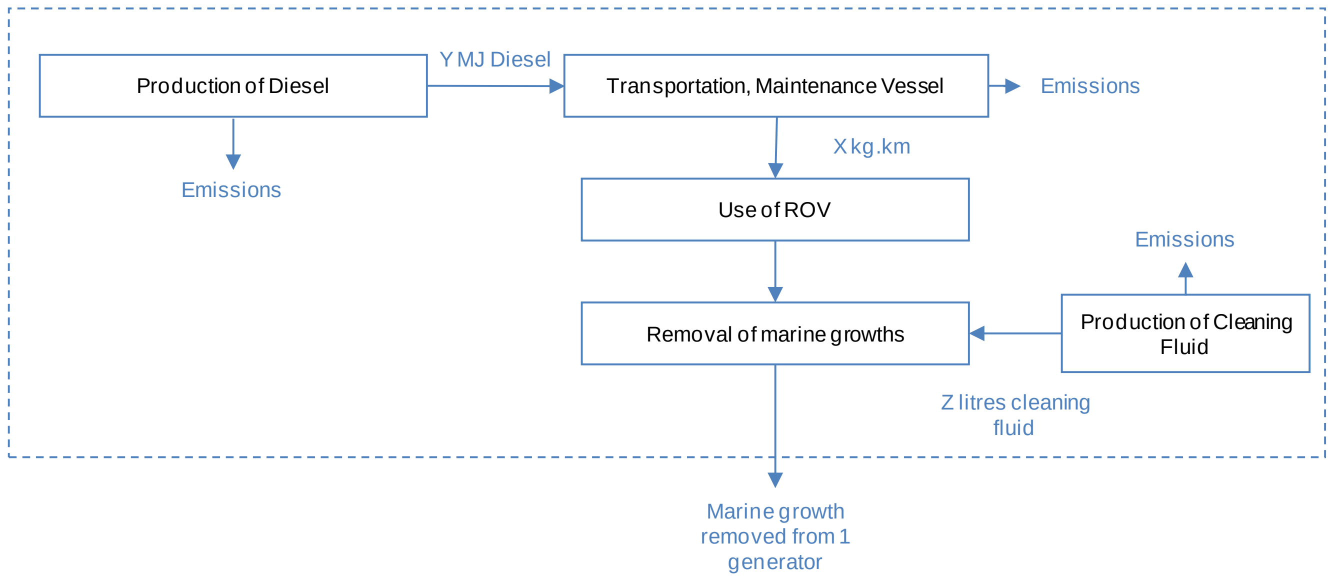

Figure 40 – An example maintenance activity model

8.2.1 Modelling the occurrence of activities

To include the inspection and maintenance activities within the impact assessment, a model for the undertaking of planned and unplanned activities over the course of the life cycle needs to be constructed. This should take the form of another unit process, containing the expected number of occurrences for each activity. It is suggested that parameters may be used within this model, to allow changes to the inspection and maintenance schedule to be accommodated.

8.3 Modelling Overhaul Activities and Spare Parts

For many tidal stream technologies, it may be planned to overhaul or re-fit the array one or more times during the product life cycle. In a similar manner to the inspection and maintenance activities, this may be modelled as a collection of unit processes within the 'operation' phase of the product life cycle. If spare parts are required during the overhaul, the manufacture of these parts should be included. In many instances, this may be readily achieved by duplicating the original processes included in the 'manufacture' phase.

8.4 Data Collection Considerations

To provide guidance of data collection for the study a series of considerations for the data collection process have been developed, and these can be found in Appendix Section E.

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9 CALCULATION OF CARBON PAYBACK INTERVAL

This section details a method for calculating the carbon payback interval from the results of the LCA. It is assumed that the LCA has been conducted in accordance with the guidance presented in previous sections, and that the necessary cut-off conditions have been met. An overview of the calculation method was originally defined in Section 1.6, and shown in Figure 3.

Following the calculation of the carbon payback interval, a number of other calculations are detailed, so that the GHG abatement potential, the total emissions from manufacture and disposal, the upkeep emissions rate and the avoided emissions can be found for the life cycle of a TECS array.

9.1 Calculation of Carbon Payback Interval

A simplistic diagram illustrating the GHG emissions over the life cycle of a tidal stream array is shown in Figure 41. The areas A to G represent the total GHG emissions at different stages of the life cycle, measured in kgCO_2e.

A	Emissions from Manufacture (kgCO_2e)
B	Emissions from Maintenance {before payback} (kgCO_2e)
C	Displaced Emissions from Electricity Generation {before payback} (kgCO_2e)
D	Emissions from Maintenance {after payback} (kgCO_2e)
E	Displaced Emissions from Electricity Generation {after payback} (kgCO_2e)
F	Emissions from Disposal (kgCO_2e)
G	Disposal Emissions from Reuse and Recycling (kgCO_2e)

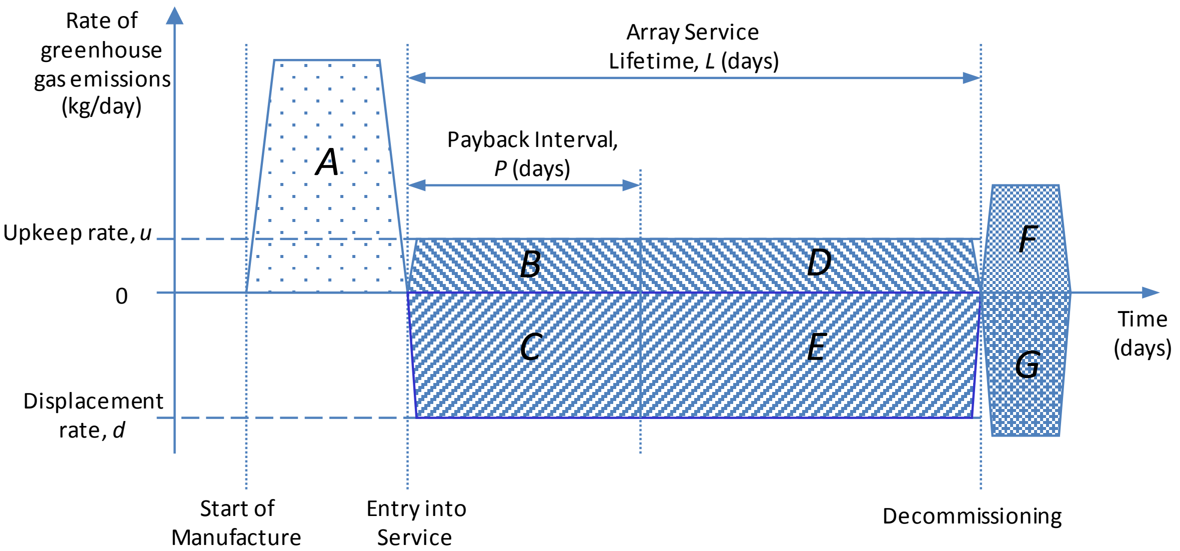

Figure 41 – Sources of GHG emissions over lifetime of tidal stream array

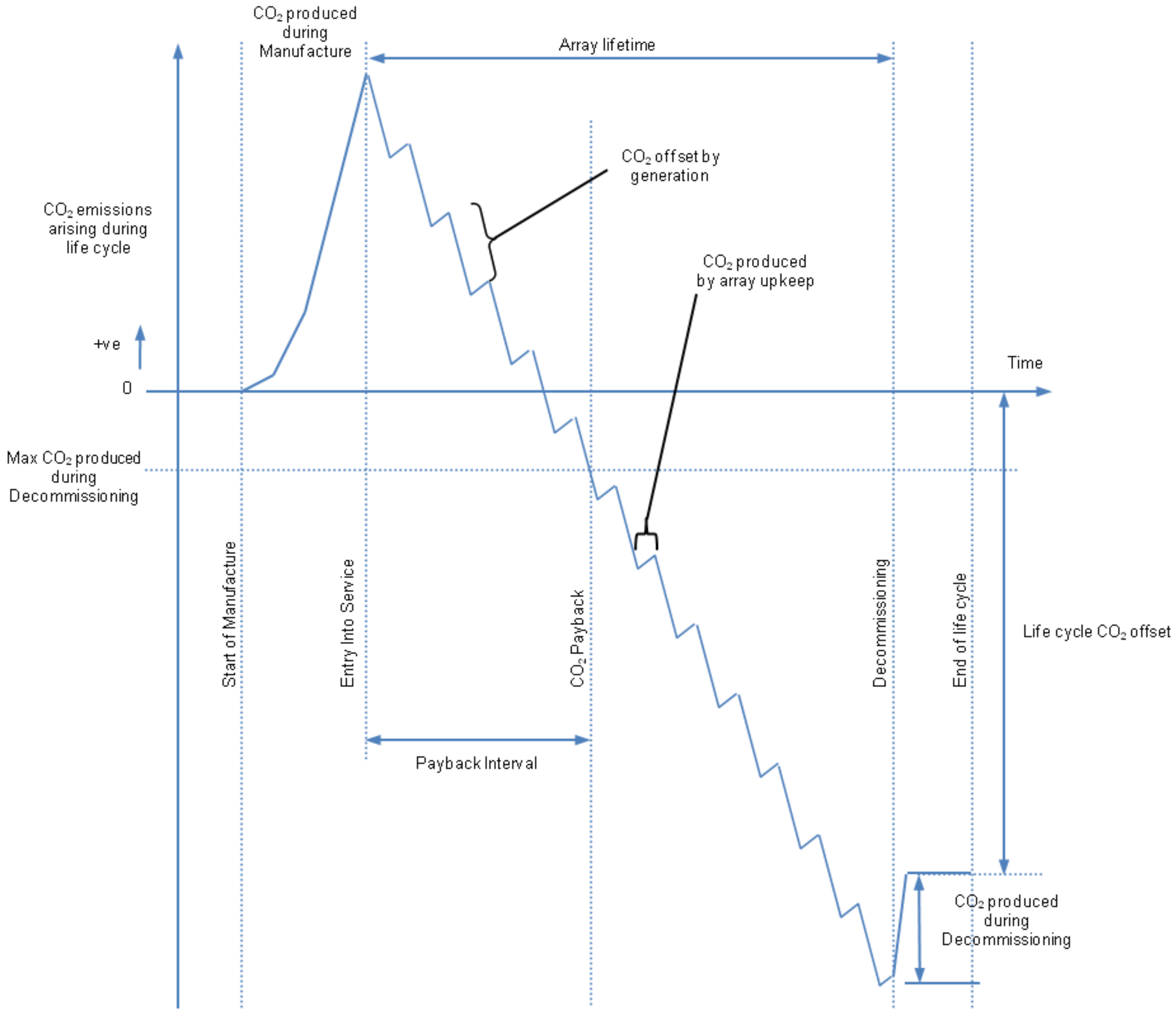

Figure 42 – Curve showing lifetime GHG emissions offset by tidal stream generator

The data shown in Figure 41 can also be represented in Figure 42. This shows the actual CO_2 emissions arising during the life cycle, as opposed to the rate of CO_2 produced. It has been assumed for this model that the TECS generates electricity at a constant rate and that maintenance occurs at a regular rate, producing a consistent amount of GHG with every operation. It should be noted that the payback interval has not been measured as the point at which the curve recrosses the line of zero CO_2 emissions, as the final carbon cost of decommissioning the device has not been accounted for at this point. In the example the emissions arising from the end of life process is already known, and it is assumed that no emissions are offset through reusing and recycling components. By knowing the amount of carbon produced in the decommissioning process, it has been determined that when this value has been offset is the TECS, after the initial carbon costs have been accounted for, that the device will have paid back the carbon costs of operating itself, and will begin to offset more CO_2 than it cost.

Depending on the level of reuse and recycling during the disposal of the tidal stream generator, the size of the offset emissions from disposal, area *G*, may change in size in relation to the emissions from disposal, area *F*. If it is possible to reuse or recycle every component on the device, then the offset emissions from disposal will be maximised. If all the components and materials are reused and recycled, there will still be emissions arising from disposal, to account for the processes involved in recovering and separating the materials prior to reuse or recycling.

The payback interval is measured from the time of entry into service to the time that the TECS has offset all emissions arising from the full life cycle, including manufacture and disposal. The device will most likely continue to operate after this point, and while there may be more emissions arising from further maintenance instances, these will not affect the payback interval. Continued emissions from maintenance and inspection activities will reduce the overall volume of carbon offset by the array, but should not substantially alter the scale of offset CO_2.

In order to calculate the point at which carbon payback occurs, an equation can be set up in terms of the areas used in Figure 41, assuming that at the instance of carbon payback, the sum of GHG emissions arising and offset must be zero:

$$C = A + B + (F - G) \quad [1.1]$$

Substituting the payback interval (*P*), displacement rate (*d*) and upkeep rate (*u*) of GHG emissions for areas *B* and *C* allows the equation to be rewritten:

$$P.d = P.u + A + (F - G) \quad [1.2]$$

Rearranging the equation to put in terms of the payback interval (P):

$$P = \frac{A + (F - G)}{d - u} \quad [1.3]$$

Expressing this result in words:

$$Payback\ Inverval(days) = \frac{Manufacturing\ Emissions\ (kgCO_2e) + Disposal\ Emissions\ (kgCO_2e)}{Rate\ of\ displacement\ (kgCO_2e/day) - Rate\ of\ upkeep\ (kgCO_2e/day)}$$

If the expected array lifetime is known, then the rate of emissions due to upkeep may be found by dividing the total emissions in the use phase due to maintenance (the sum of areas B and D) by the expected lifetime of the array, in days. Thus:

$$Payback\ Inverval(days) = \frac{Manufacturing\ Emissions\ (kgCO_2e) + Disposal\ Emissions\ (kgCO_2e)}{Rate\ of\ displacement\ (kgCO_2e/day) - \left(\frac{Upkeep\ Emissions\ (kgCO_2e)}{Array\ Lifetime\ (days)}\right)}$$

This is the approach that will be adopted in this report for calculating the payback interval. The total emissions due to manufacturing, disposal and maintenance will be calculated using a LCA of one array. The rate of displacement is a function of the size of the array, and a suitable method for calculating this rate is presented. Using the formula shown above and an estimate of the array lifetime, the payback interval may be inferred.

9.2 GHG Abatement Potential

Calculation of carbon payback interval alone is not sufficient to compare the global warming merits of different technologies; consideration must be made of the expected lifetime of the system. The avoided emissions due the installation of the tidal stream array is represented by the sum of areas *A* to *G* in Figure 40; for the purposes of this report this is termed the 'abatement potential'. It represents the global warming impact avoided as a direct result of installing the tidal stream array. By summing the areas *A* to *G* in Figure 40, it may be shown that:

$$Abatement\ Potential\ (kgCO_2e) = (Rate\ of\ displacement\ (kgCO_2e/day) \cdot Array\ Lifetime\ (days)) + (Disposal\ Emissions\ (kgCO_2e) + Manufacturing\ Emissions\ (kgCO_2e) + Upkeep\ Emissions\ (kgCO_2e))$$

This result may be readily derived from the same LCA used to calculate the carbon payback interval.

As well as conducting the LCA to establish the GHG abatement potential, a cost model of the array should also be conducted, although this currently falls outside the scope of this report. From the LCA of the carbon footprint and a cost model, it will be possible to show the cost of abatement, as this is a ratio of the lifetime cost of a tidal stream array to the abatement potential that can be achieved by the array. This relationship is shown below:

$$Cost\ of\ Abatement\ (£/kgCO_2e) = \frac{Array\ Lifetime\ Cost(£)}{Abatement\ Potential\ (kgCO_2e)}$$

9.3 Calculation of Total Emissions from Manufacture and Disposal

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The process for calculating the emissions from manufacture and disposal of the tidal stream array is based upon an impact assessment of the relevant stages of the LCA. In the case of GHG emissions, the impact assessment process requires the emissions from different processes within the life cycle to be converted into a total global warming impact, measured in kg CO_2e. This requires GWP constants defined in Appendix F. Figure 43 illustrates the calculation of the global warming impact from the manufacture stage of the life cycle. It consists of summing the emissions of individual GHG over all products, and weighting each by a GWP constant.

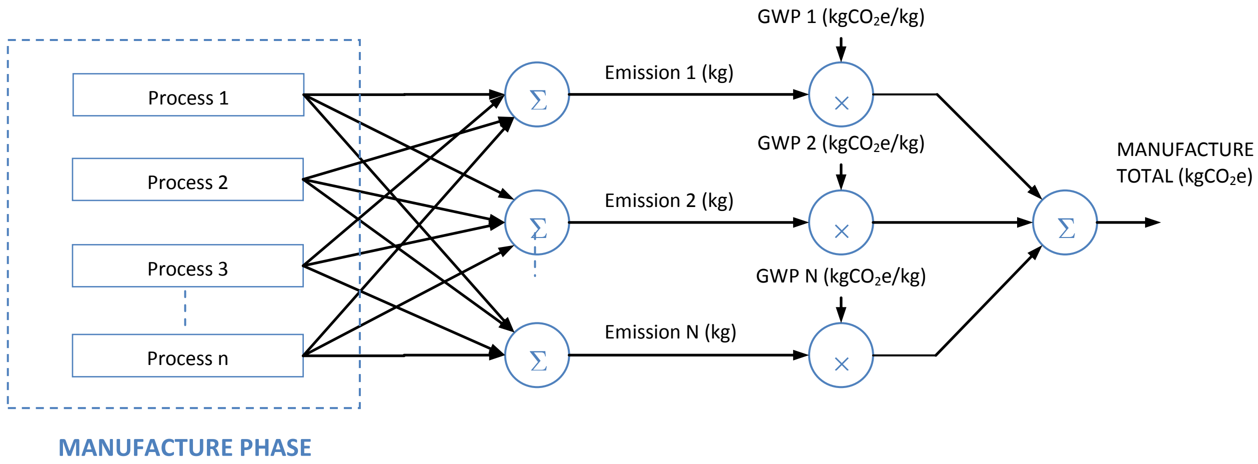

Figure 43 – Calculating the emissions from the 'manufacture' phase model

This can also be expressed as follows:

Total GHG Emissions (kgCO2e) = ∑[(Emissionx(process1 + process2 +……)×GWPx) + (Emissiony (process 3 + process4 +……)×GWPy)]

The process for calculating the total GHG emissions from the disposal phase of the product life cycle is identical. It is likely that the total emissions due to disposal are negative, due to emissions credit from material recycling (see Section 5.21). Upon the completion of this process, two numbers should be available that correspond to the total GHG emissions for the manufacture and disposal phases, corresponding to areas *A* and *E* within Figure 40.

Most LCA software tools are able to perform the impact assessment for these calculations automatically. Care should be taken to ensure that the emissions from the correct processes are used.

9.4 Calculation of Upkeep Emissions Rate

The upkeep emissions rate associated with the operation phase of the array life cycle is calculated by dividing the total emissions due to inspection, maintenance and overhaul activities (see Sections 5.7 and 8.3) by the array lifetime used for the estimation of those emissions. This process is illustrated in Figure 44.

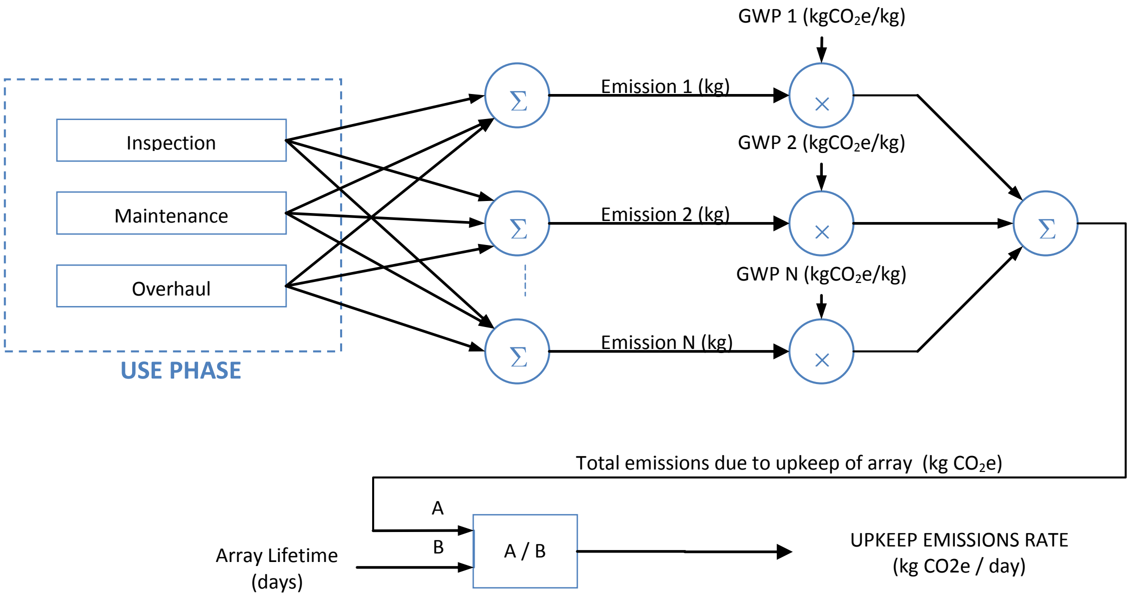

Figure 44 – Calculating the emissions rate from the 'use' phase model

The upkeep emissions rate represents the average daily GHG emissions associated with running the tidal stream array.

9.5 Calculation of Avoided Emissions due to Electricity Generation

The avoided emissions due to electricity generation may be calculated by using the average electrical power output of the array, as calculated in Section 7.6 for an idealised array. This should be converted into units of KWh / day, and multiplied by an estimated 0.43kg CO_2 / kWh, to obtain a rate of avoided emissions in kg CO_2 / day. This process is illustrated in Figure 45.

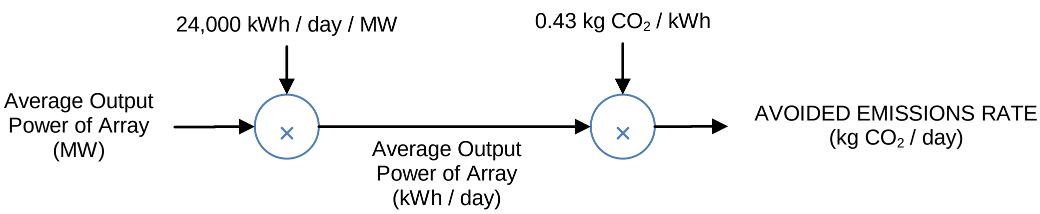

Figure 45 – Calculating the avoided emissions due to electricity generation

The average Array Power can also be shown in the equation below:

$$Array\ Power(MW) \times 24{,}000 = Average\ Array\ Output(kWh/day)$$

$$Average\ Array\ Output(kWh/day) \times 0.43 = Avoided\ Emissions\ Rate(kgCO_2e/day)$$

9.6 Calculation of Payback Interval

For reasons discussed in Section 1.5, the payback interval is measured in days, and is calculated according to the following equation (see Section 9.1)

$$Payback\ Inverval(days) = \frac{Manufacturing\ Emissions\ (kgCO_2e) + Disposal\ Emissions\ (kgCO_2e)}{Rate\ of\ displacement\ (kgCO_2e/day) - \left(\frac{Mantainance\ Emissions\ (kgCO_2e)}{Array\ Lifetime\ (days)}\right)}$$

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This calculation is illustrated diagrammatically in Figure 46.

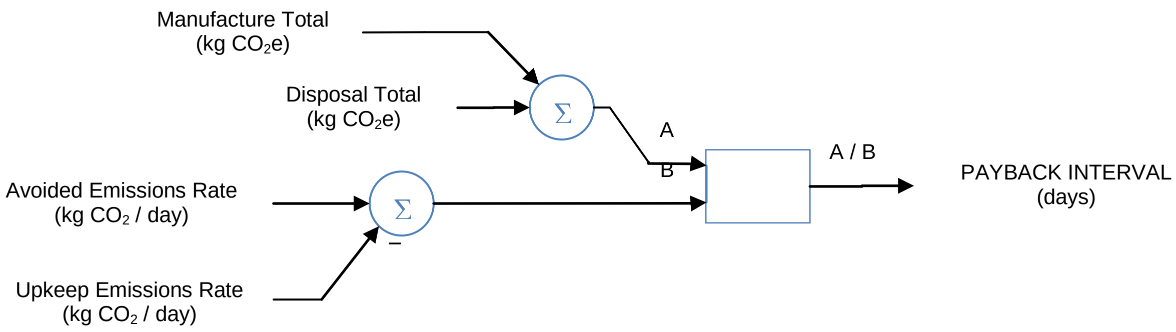

Figure 46 – Calculation of Payback Interval

The payback interval represents the length of time taken for the total avoided emissions due to electricity production from the array to equal the total emissions due to manufacture, disposal, inspection, maintenance and overhaul of the array.

9.7 Calculation of GHG Abatement Potential

It was stated in Section 9.2 that consideration of the carbon payback interval alone is not sufficient for evaluation of the global warming merits of a tidal stream electricity generation system. In addition, the avoided GHG emissions due to the installation of the array should be calculated. This is termed the GHG abatement potential, and may be calculated using the following expression:

$$Abatement\ Potential\ (kgCO_2e) = (Rate\ of\ displacement\ (kgCO_2e/day) \times Array\ Lifetime\ (days)) - (Disposal\ Emissions\ (kgCO_2e) + Manufacturing\ Emissions\ (kgCO_2e) + Upkeep\ Emissions\ (kgCO_2e))$$

It should be apparent that the abatement potential is equal to the mass of GHG emissions avoided by electricity generation minus the total emissions associated with the manufacture, upkeep and disposal of the array. This calculation is illustrated diagrammatically in Figure 47.

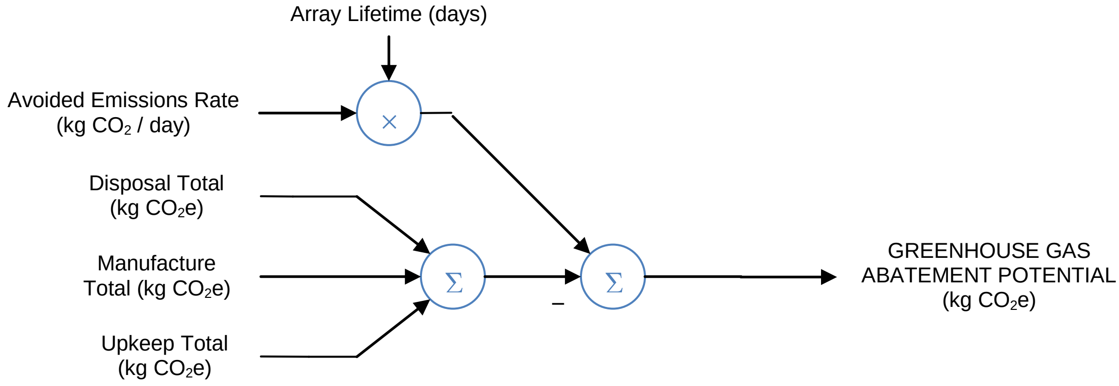

Figure 47 – Calculation of GHG Abatement Potential

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9.8 Recording of Results

The results of the carbon payback calculation should be recorded. This record as a minimum should contain the following:

- A complete flow diagram illustrating all unit processes considered
- An aggregated GHG emissions inventory for the 'manufacture', 'disposal' and 'operation' stages of the product life-cycle
- A record of the assumed life-time of the array
- A record of the payback interval (in days) and the GHG abatement potential (in kgCO_2e).
- A description of the perceived limitations of the result.

In addition to the above, it may also be helpful to record details of particular assumptions or key data sets, and a review of the allocation of emissions between different processes within the life cycle. Further information on the reporting of results is provided in Section 11.

10 EVALUATION AND REVIEWING OF RESULTS

This section aims to provide guidance upon the results evaluation and checking processes. It is based upon the requirements of the LCA standards ISO14040:2006 [2] and ISO14044:2006 [3]. The intention of the evaluation process is to validate the outcome of the study. Upon the completion of the evaluation process, the results of the analysis should be comparable with similar studies.

10.1 Results Evaluation Process

Most life-cycle assessments are iterative processes, and are refined based upon the outcome of quality assessments and audit reviews. This sub-section describes a suitable structure for this evaluation process, which is illustrated in Figure 48. The refinement of the model includes any activities identified during the evaluation of the results of the report. This may consist of changing the structure of the model, changing system boundary assumptions or changing sources of data.

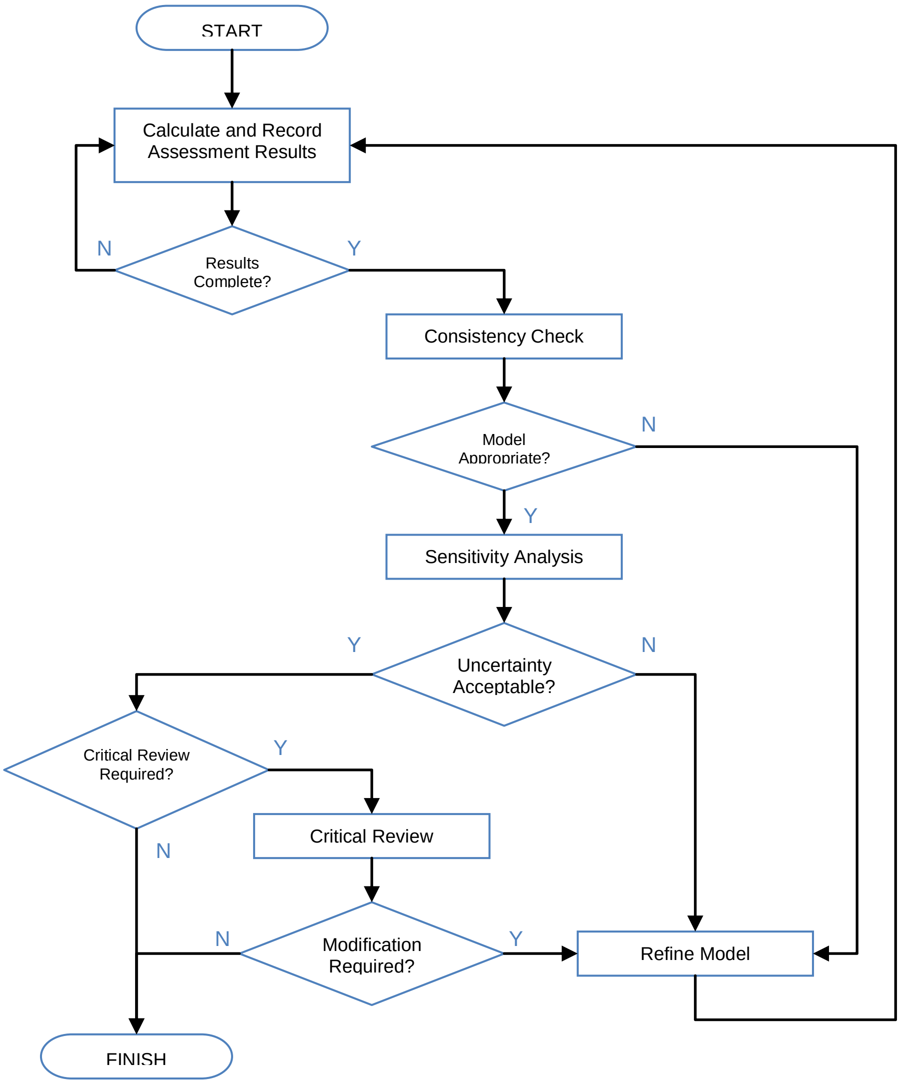

Figure 48 – Results evaluation and review process

The remainder of this section provides specific guidance regarding the activities identified in Figure 48, and their application to the carbon payback study.

10.2 Completeness Check

The first check that should be performed upon the results of the study is a completeness check. The purpose of this check is to ensure that the calculation of the payback interval has been conducted correctly. A completeness check should as a minimum ensure the following:

- The payback interval and GHG abatement potential have been calculated in accordance with the calculation method specified in Section 9;
- All relevant processes within the different life cycle stages have been considered in the calculations as defined in Section 9;
- The emissions of all GHG as specified in Appendix G have been considered in the calculations as defined in Section 9;
- The results of the study have been recorded according to Section 9.8.

The results are considered complete when all the above criteria are met. If any of the above points are not fulfilled, the study should be considered incomplete and the results should be re-calculated.

10.3 Consistency Check

The purpose of the consistency check is to ensure that the life cycle model used for the calculation of the results is consistent with the goal and scope of the study. A consistency check should as a minimum ensure the following:

- The studied tidal stream array is representative of a realistic deployment scenario of the technology in question;
- The modelling techniques described in Section 4 have been used throughout the study;
- All flows are accounted for to the minimum level specified by the PRL for the device (see Section 6);
- The boundaries of the study are compliant with the guidance provided in Section 3.2.3;
- The studied array is either consistent with the standard array specified in Section 7 or is representative of a realistic deployment scenario;
- The modelling guidance provided in Section 8 has been followed;
- For the processes that do not conserve mass between input and output flows, these inequalities are explained and justified, based upon the goal of the study;
- All process data is stored in accordance with the guidance of Appendix Section E.7 and in accordance with the standard defined in ISO14044 [3];
- The same value for the array lifetime has been used throughout the study.

The results of the study are considered consistent when all the above criteria are met. If the study is inconsistent, this should be rectified by modification of the life cycle model or methodology.

10.4 Sensitivity Analysis

10.4.1 Purpose and Scope

The purpose of the sensitivity analysis is to quantify the dependence of the payback interval upon:

- Allocation assumptions;
- Recycling rate assumptions;
- The frequency of maintenance, inspection and overhaul activities;
- Assumed transportation distances;
- Other assumed parameters used within the life cycle model.

By evaluating the sensitivity of the payback interval to these parameters, the most critical assumptions may be identified. This may be used to identify any assumptions within the model that may require further investigation.

10.4.2 Method

Sensitivity analysis is conducted by applying a small change in a parameter value within the model. The sensitivity of the carbon payback interval to a parameter is termed the 'significance' of that parameter, and is defined as the absolute relative change in the payback interval of the array divided by the absolute relative change in the value of that parameter.

To avoid repeatedly evaluating the payback interval calculation, the sensitivity of the payback interval to different processes may be calculated using constants, which represent the sensitivity of the payback interval to the GHG emissions associated with each stage of the product life. The parameters k_M , k_D and k_O represent the increase in the array payback time per kg CO_2e of increased emissions within the 'manufacture', 'disposal' and 'operation' phases respectively. The use of these sensitivity analysis parameters avoids repeatedly re-calculating the payback interval.

10.4.2.1 Calculating the significance of parameters

To calculate the significance of different parameters within the life cycle model, it is necessary to estimate the effect of that parameter upon GHG emissions within the different life-cycle stages. This should be achieved by increasing the value of that parameter by a small amount (for example, 1%) and recording the resultant change in GHG emissions at each lifecycle stage. The relevant sensitivity analysis parameter may be used to convert these differences in emissions into a difference in payback interval, by summing the contribution from each life cycle stage. By dividing the fractional change in emissions by the original change, here assumed to be 1%, the significance of that parameter may be calculated. This process is illustrated in Figure 49.

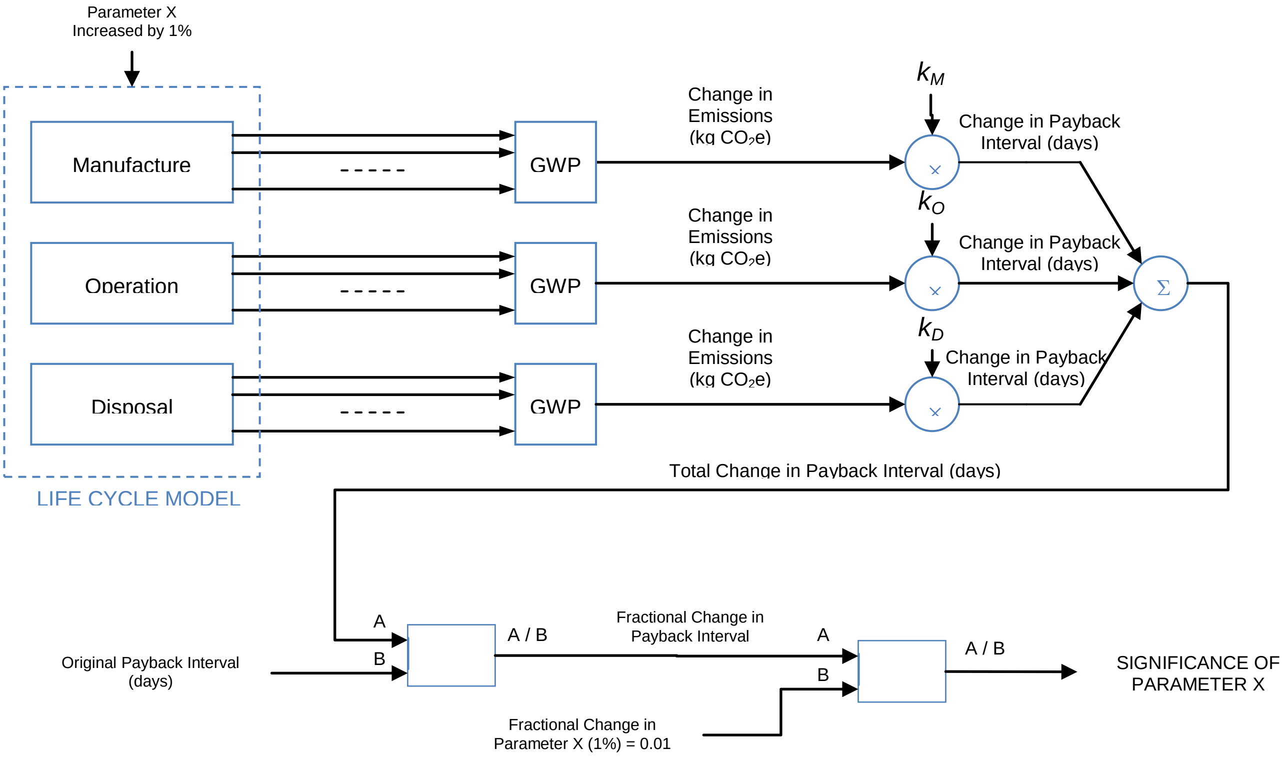

Figure 49 – Calculation of parameter significance

The significance of a parameter represents the ratio of the relative change in payback interval to the relative change in that parameter. If the significance term for a given parameter is found to be a large positive or negative value, this provides an indication that the study is highly sensitive to deviations in that parameter, and as a result, this will have a significant impact on the payback interval of the array. Conversely, a small value for the significance of a parameter implies that a parameter is less critical to the payback interval.

10.4.3 Conducting a sensitivity analysis

The aim of the sensitivity analysis is to rank the parameters within the model by significance, and to determine whether additional modelling or data is required for the most significant parameters. It may be appropriate to exclude insignificant parameters for the purpose of simplifying the process. A parameter may be assumed as being insignificant if its significance is found to be less than 0.002, implying that for a 50% change in the value of the parameter, there is less than a 0.1% change in the payback interval of the array.

A suitable value for the total uncertainty introduced to the final carbon payback interval by the parameters should be selected, which will also indicate the cut-off point at which the costs involved in the additional modelling become unreasonable. An example of the impact of the parameters can be shown by an fictional parameter with an estimated 10% uncertainty and a significance of 0.1. This parameter would introduce an overall uncertainty of 1% to the payback interval, and if the total uncertainty is assumed to be 10%, then the fictional parameter would constitute a tenth of the total permissible uncertainty for the model.

10.4.4 Recording and interpretation of sensitivity analysis results

The outcome of the sensitivity analysis should be a table containing parameters within the model, ranked by the uncertainty introduced in the final result. The total uncertainty introduced by all parameters should be used to determine whether additional modelling is required. The ranking of parameters should be used to determine where additional modelling depth or an improved data source is required. An example of a results table for a sensitivity analysis is shown in Table 8.

Rank	Parameter	Modelled Value	Tolerance of Value	Significance	Uncertainty Introduced
1	Steel Recycling Rate	95%	5%	0.25	1.25%
2	Mass of Steel in Foundation	50000kg	7%	0.15	1.05%

Table 8 – Example sensitivity analysis results table

The results of the sensitivity analysis work carried out during the carbon payback calculation should be recorded in a suitable format, so that it may be accessed later.

10.4.5 Inclusion of sensitivity analysis results within report of results

The report containing the results of the study should contain a section describing the results of the sensitivity analysis. As a minimum, a list of the ten most significant parameters and a list of the ten parameters that introduce the greatest uncertainty should be included. This forms a list of the key dependencies of the model. The implications of these parameters upon the validity and interpretation of the result should be discussed.

10.5 Critical Reviewing of Results

If the results of the carbon payback study are to be publicly disclosed, a panel of interested parties, chaired by an independent external life-cycle assessment expert, should review the study. This is in accordance with ISO14044 [3]. The panel of interested parties should consist of at least three members, and include at least one expert on the tidal stream device under consideration, such as the chief designer or chief engineer.

The purpose of the audit review is to review the validity of the model, including the LCA methodology and its application to the tidal stream array.

Recommendations made by the panel should be recorded, and included within the carbon payback report. It may be necessary to refine the model based upon the guidance of the panel; in this case an additional critical review should be conducted upon the completion of these modifications.

11 REPORTING AND INTERPRETATION OF RESULTS

This section describes how the results of the carbon payback study may be communicated to an external audience, including a description of how the results of the study may be analysed and interpreted. As a minimum, the communication of results should include the generation of a final report, but other communication techniques may be used in addition. This section focuses on providing guidance on the contents of the final report; for other reporting formats, the guidance should be adapted as appropriate.

Figure 50 illustrates the information that may be included within the final report. Information that should be included is shown as solid arrows, and dashed arrows represent optional information. The following sub-sections provide guidance upon the inclusion of this data within the final report and details on ensuring conformity and gaining accreditation.

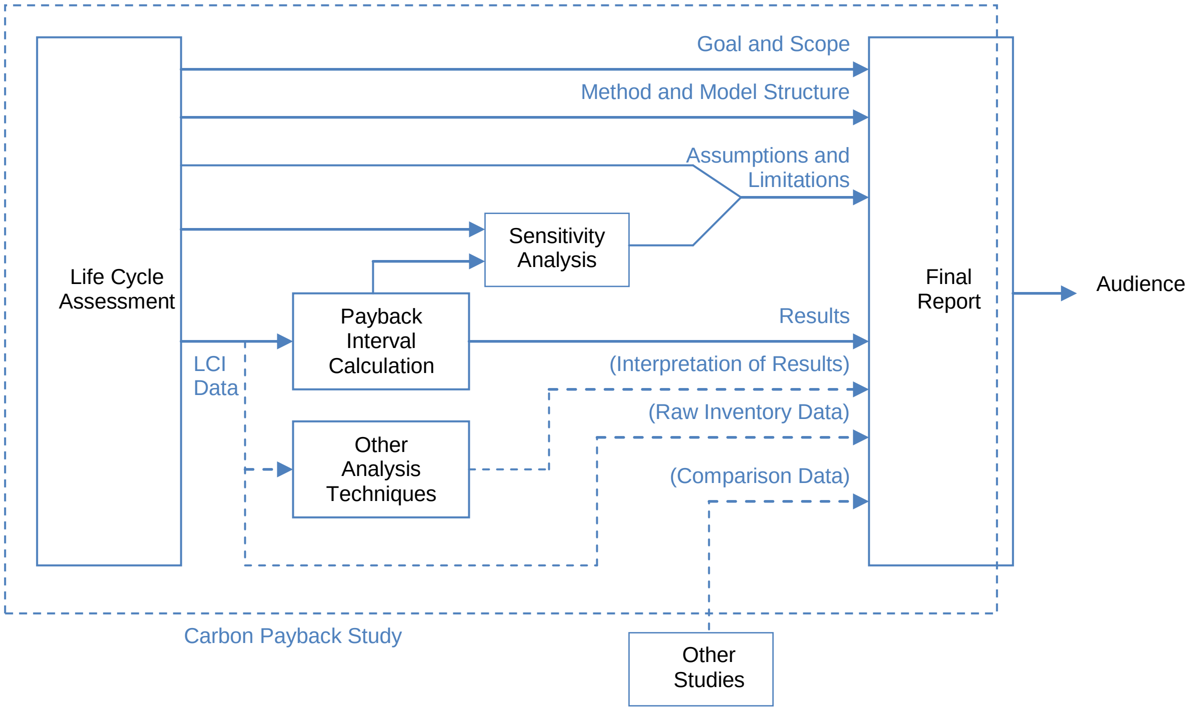

Figure 50 – Information sources for the final report

11.1 Required Report Contents

This sub-section provides guidance upon the inclusion of information that should be present within the final report.

11.1.1 Payback Interval

The carbon payback interval should be stated within the final report, stated in days to the nearest whole day. If the payback interval is presented in units of months, a conversion factor of 30.42 days/month should be used. If the payback interval is presented in units of years, a conversion factor of 365 days/year should be used.

11.1.2 Goal and Scope of the study

A section summarising the goal and scope of the study should be included within the final report. As a minimum, this should include:

- A description of the tidal stream technology studied;
- The reasons for carrying out the study;
- The intended end use of the results;
- The intended audience or end user of the results;
- The functional unit of the study;

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- A description of the boundaries of the study;
- A description of how the modelling was carried out.

These should be based upon the original goal and scope as defined for the carbon payback study, and should be reported in accordance with the guidance specified in ISO14044 [3].

11.1.3 Method and model structure

A description of the method used to calculate the carbon payback interval should be included within the final report. This should include a short summary of LCA, and a description of the calculation method presented in Section 9.

In addition to the description of the method, an overview of the life cycle model used to calculate the GHG emissions associated with the different stages of the life cycle should be included. This model should illustrate the significant top-level processes within the life cycle, although individual unit processes may be omitted for clarity. The reporting of the model structure should include a description of how transportation, energy and waste management activities were modelled.

11.1.4 Assumptions and Limitations

All assumptions and limitations associated with the life-cycle model should be stated within the final report. This includes but is not limited to:

- Limitations associated with the data used within the model;
- Limitations due to the use of linear LCA modelling;
- Assumptions relating to system boundaries;
- Choice of average or marginal data;
- Cut-off criteria
- Limitations associated with modelling activities, including transportation, energy production and waste disposal;
- Allocation assumptions;
- Sensitivity analysis results, including lists of significant parameters;
- Limitations introduced by the use of a standard tidal stream array;
- Limitations associated with the calculation methods used;
- Assumptions made regarding the supply chain structure;
- Interpolation or scaling assumptions;
- Availability and generation capacity assumptions
- Assumptions related to the choice of product life-cycle;
- Assumptions related to the modelling of repair, maintenance and overhaul activities.

The purpose of stating limitations within the final report is to prevent misinterpretation of the study results, to aid comparison with other technologies and to assist future studies. Justification of decisions and assumptions made during the modelling or calculation process should be included. It may prove beneficial to combine the description of the limitations and assumptions with the sections of the report describing the goal and scope of the study, or the sections describing the method and model used to carry out the study.

11.1.5 Referencing Data

All significant sources of data used for the calculation of the payback interval should be referenced within the final report. This includes both primary and secondary data sources, and includes any data used during the analysis that was included within a LCA software package.

11.2 Conformity and Accreditation

This document has been prepared based upon the guidance of ISO14040:2006[2], ISO14044:2006[3] and PAS2050:2008[4]. However, the completion of a carbon payback study according to this document does not imply compliance with either the standards or the specification, instead the document offers a current best-practise model based on their guidance as well as industry-specific factors to adapt existing models to the application of a tidal stream generator.

Currently there is no mechanism of seeking accreditation for the carbon footprint model for a renewable energy device, however it is recommended that the carbon payback study be conducted according to the principals of PAS2050, ISO14040 and ISO14044, as it is likely that these will provide the basis for the means of obtaining accreditation in the future. By seeking compliance with these standards, a formal review process will be required if results are to be publicly disclosed.

APPENDIXES

A SYSTEM BOUNDARY DETAILS

A.1 Types of System Boundary and Interaction

The main system boundaries of the product system exist cover the product system and technological processes, known as the Technosphere, other boundaries exist between the product system and natural processes, termed the Biosphere, and between the product and financial processes, called the Value Sphere. As previously mentioned, the Value Sphere is not applicable to modelling the carbon footprint of the life cycle of a tidal stream array, and has been neglected.

Further system boundaries exist within the Technosphere between the product system and the essential and non-essential technical processes. The boundary between the product system and the essential technical processes is termed 'cut-off criteria', as the essential processes still form a key element of the life cycle of the array, despite not being directly involved in the manufacture, operation, or disposal of the array. The boundary between the product system and the non-essential processes is termed 'allocation criteria' and details how emissions are to be allocated between different product life cycles, such as may arise with the recycling or reusing of components or materials.

The point at which the processes of the product system interact with the natural processes is termed the environmental impact, and covers both any emissions released to the environment (gas, liquid and solid wastes) and any natural resources required by the product system.

The inbound technical flows to the product system have been termed Resource. Typically resource flows enter the product system from essential technical processes, such as material production, however resources can also come from non-essential processes in the case of material recycling or reuse. Outbound flows from the product system to other technical processes are termed as outputs, when they contribute towards the product, waste when they do not contribute towards the product, and by-products when they contribute towards non-essential processes. Flows can be further subdivided to include negligible flows, where the impact of the flow is so minimal that they can be discounted from the carbon footprint model. A diagram illustrating the different types of system boundary is shown in Figure A.1.

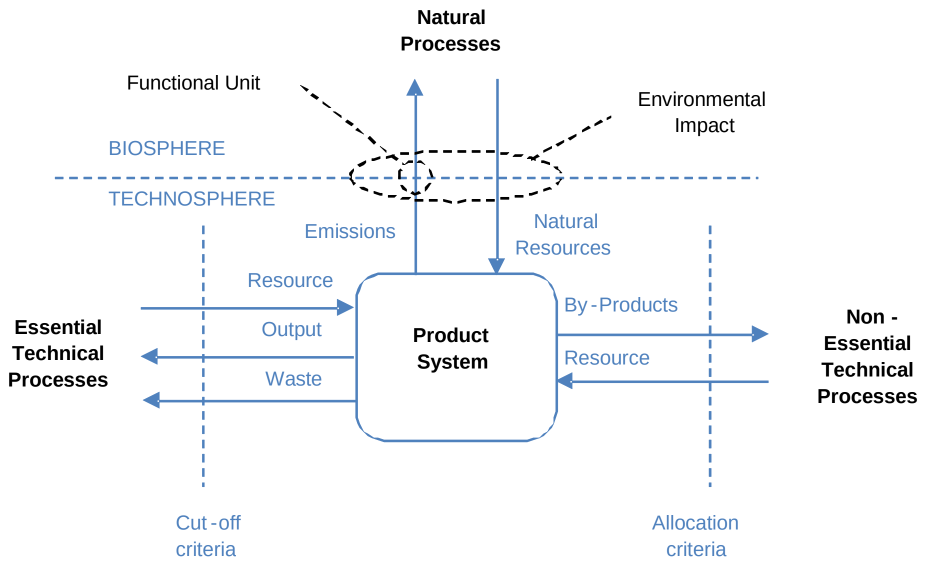

Figure A.1 – Different types of system boundary

Rolls-Royce Data - Private, see front page for details

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Process/Flow	Example
Natural Process	Formation of tides
Natural Resource Flow	Extraction of iron ore from ground
Emission Flow	Release of carbon dioxide into atmosphere from inspection vessel
Essential Technical Process	Production of blades for TECS
Essential Technical Process (negligible)	Production of bolts for mounting electrical equipment
Essential Technical Process (irrelevant)	Distribution of electricity from array
Resource	Steel for construction of TECS
Resource (negligible)	Solder for electrical connections within nacelle
Resource (irrelevant)	Natural gas for heating design offices
Waste	Scrap metal from machining
Output	Delivery of electricity from array to national electricity grid connection point
Non-Essential Technical Process	Generation of heat from combustion of landfill gas from waste
By-Product	Production of gravel from mining of iron ore

Table A.1 – Examples of excluded processes and boundary flows for a tidal stream array

It can be seen that the environmental impact of a product life cycle system is a function of its natural resource usage and emissions. The exact quantification of 'environmental impact' from the quantities of emissions and natural resource usage is termed 'life cycle impact assessment' (LCIA). In the case of a carbon payback study, the environmental impact is specified in kg CO_2e. Examples of different types of external natural process, external technical process and boundary flow within the context of tidal stream electricity generation are presented in Table A.1.

The primary purpose of a LCA is to quantify the ratio of the environmental impact to the output, which is expressed as environmental impact per functional unit. It can be seen that the choice of cut-off criteria and allocation criteria is critical to this assessment.

A.2 Other types of Boundary

Two other types of boundary need to be specified, to allow different studies to be compared quantitatively. A geographical boundary needs to be defined, which represents the geographical location of different processes. It is necessary to define the location of all processes for which product-specific data is not available, to ensure that similar assumptions are made within each study.

It is also necessary to specify the boundary associated with time. Environmental impacts are considered within a specified impact timescale, and a standard needs to be adopted between studies to make the results comparable. This is especially true of disposal processes for solid waste, such as landfill. Decomposition and environmental impact can occur over an extremely long time-span, and therefore the environmental impact associated with such activities is sensitive to the length of time over which the impacts are considered.

A.2.1 Boundaries with Non-Essential Technical Processes – Allocation

Where boundaries between the product system and other 'non-essential' technical processes (i.e. other product life cycles) exist, it is necessary to define the method by which emissions are allocated to the product system. This may occur where processes are 'shared' between the product system and other systems, as illustrated in Figure A.2.

The situation illustrated in Figure A.2 (a) shows a common upstream process that feeds into the product system. This process could represent operations such as reuse or recycling of components from other product systems or the refining of oil, where there will be more resultant products than will be needed for the TECS device. In this case, the proportion of original resource allocated to the TECS will need to be defined.

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The Figure A.2 (b) illustrates a shared downstream process, which is fed by three separate flows. This process could be used to represent processes such as final waste disposal through landfill, as this will be the final process for a number of different products. The amount of emissions that should be apportioned to the flow from the TECS device needs to be defined.

Figure A.2 (c) shows a shared transport process, where the means of transport is used to transport components or systems for multiple product systems. The proportion of emissions that may be apportioned to the product life cycle will need to be defined in relation to the quantity of TECS components being transported, by volume, value, or by number of components, and the means of selecting the method of apportioning the emissions should be created as required.

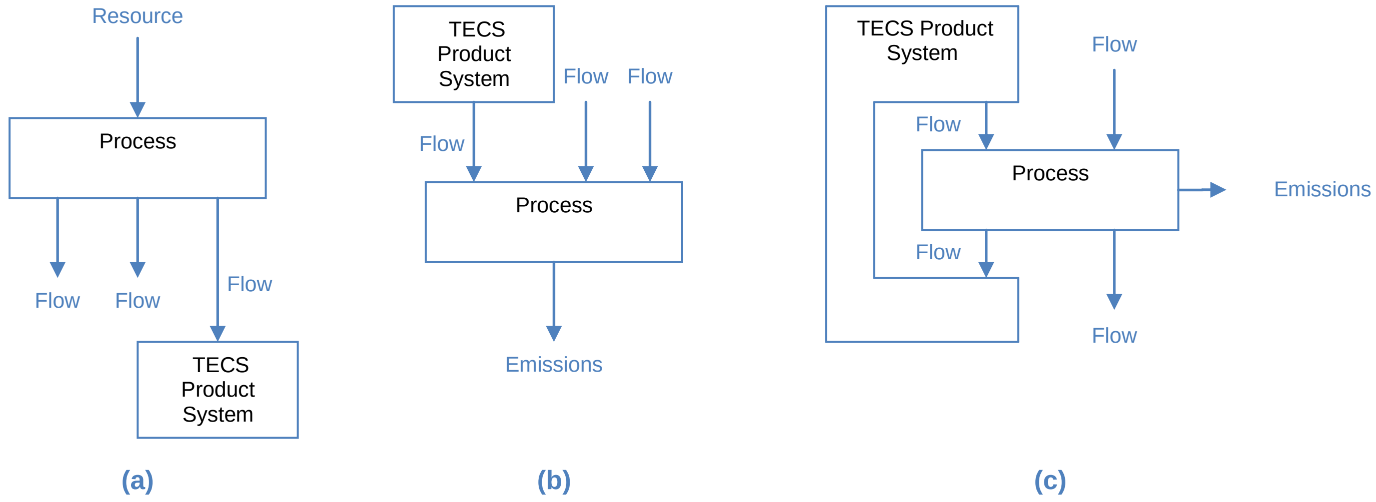

Figure A.2 – Examples of shared processes for which allocation must be used

Allocation should be conducted in the manner specified in PAS2050 Section 8.1[4]. Initially, expansion of the process to avoid the problem of allocation should be considered. If this is not possible, then expansion of the system to include additional functions related to the co-products should be considered. If neither approaches are practical, then allocation of resource use and emissions should be conducted based upon the economic value of the respective flows.

All choices of allocation method should be commented upon within the final report. Further information about the correct choice of allocation technique may be found in PAS2050 [4] or the PAS2050 application guide [5].

A.2.2 Geographical Boundaries

In assessing the GHG emissions associated with the manufacture and disposal of a tidal stream array, the geographical location of these stages of the product life cycle is highly relevant. The GHG emissions associated with energy usage, waste management and material extraction processes can differ significantly with geographical location, as well as the effect on changing the transportation distances and methods. In an ideal situation, the location of all the processes within the product system would be known, and for the idealised site detailed in Section 7.1, distances have been assumed from the array to the grid POC and overhaul facilities, however little information is known about the location of the various maintenance and disposal facilities.
Until accurate data from suppliers can be obtained in regards to their location, and thus allow transport methods and distances to be calculated, assumed average data should be used. This data can be found in Appendix Section C.1. It should be assumed that all processes occur within the UK unless there is design-specific to the contrary, and should be assumed that all transport prior to deployment is carried out by road or rail. In creating the model, the breakdown of transport should be estimated, which may include some components being transported by road, some by rail, and some by a combination of road and rail.

Results for existing cradle-to-grave studies may be used for materials extraction and processing. Such data may be readily obtained from commercial LCI databases. All modelling assumptions used within any existing study should be stated within the final report. Upstream transportation should be considered, based upon the specified location of the 'gate'? for the existing study. Table A.2 summarises the location to be assumed for various processes within the life cycle.

Life Cycle Stage	Process Type	Is Location Known?	Process Model	Location of Process
Manufacture	Material Extraction	Y/N	Existing cradle-to-later stage study	As specified in existing study
	Material Processing	Y/N	Existing cradle-to-later stage / stage-to-stage study	As specified in existing study
	Steel Production	Y/N	Specified in this document	UK
	Manufacture	Y	Custom process model / Existing study	Known location
		N	Custom process model / Existing study	UK
	Assembly	Y	Custom process model	Known location
		N	Custom process model	UK
	Test	Y	Custom process model	Known location
		N	Custom process model	UK
Operation	Deployment	Y/N	Custom process model	Orkney, UK
	Inspection	Y/N	Custom process model	Orkney, UK
	Minor Maintenance	Y/N	Custom process model	Orkney, UK
	Major Maintenance	Y/N	Custom process model	Orkney, UK
Disposal	Retrieval	Y/N	Custom process model	Orkney, UK
	Disassembly	Y	Custom process model	Known location
		N	Custom process model	UK
	Material Recycling	Y	Custom process model / Existing study	Known location
		N	Custom process model / Existing study	UK
	Waste Disposal	Y/N	Specified in this document	UK

Table A.2 – Choice of modelled geographical location

A.3 Boundaries with Natural Processes

In order to best define the location of the boundary between the product system and natural processes within the biosphere, it is most meaningful to divide the biosphere into three separate components. These are the land, the water system and the atmosphere. By doing this, the natural boundary between the product system and the biosphere is divided into three sub-boundaries, as illustrated in Figure A.3.

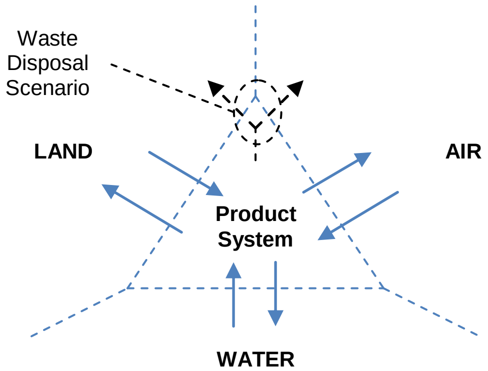

Figure A.3 – Sub-division of Natural Boundary into land, water and air boundaries

The sub-boundaries may be defined by considering the individual flows of inbound resource and outbound emissions, as represented by the six solid arrows in Figure A.3, representing the raw materials, solid waste produced, resource from the atmosphere, emissions arising from the processes, resources from water, and emissions released into the water. The particular case of disposal of solid waste is covered in Section 5.13, as the distribution of emissions between the land and the atmosphere can vary greatly between different disposal scenarios, and so this has been included separately on the diagram.

A.3.1 Emissions to the Atmosphere

Emissions to the atmosphere should be considered for all unit processes within the model. It is only necessary to consider the six classes of GHG, as specified in PAS2050 Annex A [4]. An emission is defined as a gas flow that has been released from the product system that has mixed with the air in a manner sufficient that it cannot be uniquely recovered. The boundary is defined as the point at which the irreversible mixing occurs.

A.3.2 Resource from the Land

The boundary for use of non-renewable natural resources such as mined ore or pumped oil is defined as the point at which that resource is extracted, i.e. the point at which it may be considered under human control and becomes property. All extraction processes should be considered within the scope of the study.

The boundary for renewable resources is defined as the point at which that resource enters or re-enters direct human control, by extracting or adding value to that resource in relation to the product life cycle. It is likely that the only significant renewable resource extracted from the land within the context of the carbon payback analysis will be the processes of felling trees for wood. In this instance, the point of resource extraction should be considered to be the felling of the tree; all preceding forestry and cultivation activities should be considered outside the study scope.

A.3.3 Water Resource

Many manufacturing processes use a significant volume of water. To fairly evaluate the GHG emissions associated with manufacturing processes, it is necessary to consider the indirect emissions associated with the storage, pumping, treatment and distribution of this water. It is important to state that indirect GHG emissions would only be associated with water from a public network supply. The use of groundwater or rainwater should not be considered as a source of GHG emissions.

A briefing note issued by the UK environment agency [10] estimated the GHG impact due to supply of domestic water to be approximately 0.3gCO_2e / litre. Based upon this, an indirect atmospheric emission of 0.3gCO_2 / litre should be assumed for water taken from a public network supply. Where water use is expressed by mass, the density of water should be assumed to be 1kg / litre.

A.3.3.1 Waste Water Treatment

The disposal of water into a public sewage network has associated indirect GHG emissions, due to the required wastewater treatment activities. The UK environment agency [10] estimate this impact to be 0.5gCO_2e / litre. Based upon this, an indirect atmospheric emission of 0.5gCO_2 / litre should be assumed for the disposal of waste water into a public network. The density of wastewater should be assumed to be 1kg / litre.

Disposal of wastewater outside a public network should not be considered as a source of GHG emissions.

A.3.4 Resource from the Atmosphere

The use of GHG from the atmosphere should be included within the scope of the study. The use of any GHG directly from the atmosphere should be treated as an avoided emission of that gas.

A.4 Boundaries with Essential Technical Processes – Cut-off

There are two reasons why an essential technical process may be excluded from the scope of the study. A process that contributes a negligible impact within the context of the entire study may be omitted on the grounds that its inclusion would not significantly influence the result. Production of small components such as fixings may be an example. This type of excluded process is termed ‘negligible’.

Secondly, the process may be omitted because it is not relevant to the intended use of the study. In the context of a carbon payback study intended to compare different tidal stream arrays, this may be because the process in question does not have any associated GHG emissions, or because that process would be identical for other methods of delivering the same functional unit and therefore would not influence the interpretation of the results (for example the construction of the national electrical distribution network). This type of excluded process is termed ‘irrelevant’.

For the carbon payback interval calculated by different studies to be comparable, it is apparent that there must be a limit to the quantity of processes that may be considered negligible. Furthermore, a method for establishing which types of process may be considered irrelevant is required.

A.4.1 Minimum level of inclusion

A minimum of 95% of the total mass of the tidal stream array must be considered within the scope of the study. Processes that are judged to be negligible may be excluded from the study, provided that the total mass of the components for which the downstream process are not studied does not exceed 5% of the total mass of the tidal stream array. During the study, a record should be kept of the total mass of the input flows that are considered negligible. This should be quoted within the final report.

A.4.2 Irrelevant Processes

The following processes are considered outside the scope of the study:

- Electrical grid re-enforcement activities;
- Research, Development and Design activities;
- Any activity related to personnel, for example transportation or housing of personnel;
- Manufacture of capital plant.

As these activities are considered common to all tidal stream arrays that may be studied, the inclusion of the above activities would not contribute to the comparison between technologies. When considering other processes to be excluded, the goal of the study as a comparative assessment between technologies should be considered.

It should be noted that activities listed above may be included if it considered technology-specific, and therefore relevant to a comparative study. An example might be the manufacture of custom tooling or vehicles.

B WASTE DISPOSAL

B.1 Hazardous Waste

The following table is a reproduction of the definitions of hazardous materials, as laid out by the Environmental Agency in 'Interpretation of the Definition and Classification of Hazardous Waste', page 7[33]

Number	Hazard
H1	"Explosive": substances and preparations which may explode under the effect of flame or which are more sensitive to shocks or friction than dinitrobenzene
H2	"Oxidising": substances and preparations which exhibit highly exothermic reactions when in contact with other substances, particularly flammable substances
H3A	"Highly Flammable": • Liquid substances and preparations having a flashpoint of below 21°C (including extremely flammable liquids), or • Substances and preparations which may become hot and finally catch fire in contact with air at ambient temperature without any application of energy, or • Solid substances and preparations which may readily catch fire after brief contact with a source of ignition and which continue to burn or be consumed after removal of the source of ignition, or • Gaseous substances and preparations which are flammable in air at normal pressure, or • Substances and preparations which, in contact with water or damp air, evolve highly flammable gases in dangerous quantities
H3B	"Flammable": liquid substances and preparations having a flashpoint equal to or greater than 21°C and less than or equal to 55°C
H4	"Irritant": non-corrosive substances and preparations which, through immediate, prolonged or repeated contact with the skin or mucous membrane, can cause inflammation
H5	"Harmful": substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may involve limited health risks
H6	"Toxic": substances and preparations (including very toxic substances and preparations) which, if they are inhaled or ingested or if they penetrate the skin, may involve serious, acute or chronic health risks and even death
H7	"Carcinogenic": substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may induce cancer or increase its incidence
H8	"Corrosive": substances and preparations which may destroy living tissue on contact
H9	"Infectious": substances containing viable micro-organisms or their toxins which are known or reliably believed to cause disease in man or other living organisms
H10	"Toxic for reproduction": substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may produce or increase the incidence of non-heritable adverse effects in the progeny and/or of male or female reproductive functions or capacity
H11	"Mutagenic": substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may induce hereditary genetic defect or increase their incidence
H12	Substances and preparations which release toxic or very toxic gases in contact with water, air or an acid
H13	Substances and preparations capable by any means, after disposal, or yielding another substance, e.g. a leachate, which possesses any of the characteristics listed above
H14	"Ecotoxic": substances and preparations which present or may present immediate or delayed risks for one or more sectors of the environment

Table B.1: Hazardous Materials

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C TRANSPORT DETAILS

C.1 Domestic Transport

In order to model the transport details for the manufacture, operation, and disposal of a tidal stream array, the distances and modes of transport must be known to calculate the effect on the carbon payback interval. Where these are not known, average data included in this section can be used. As previously stated, it is assumed that all processes occur within the UK unless there is specific data to the contrary, and so all transport data can be assumed to be domestic.

It is also important to include the link between road freight and rail freight. While there are sources of data for the average road and rail shipping distances, these cannot be treated as independent items, as goods may be transported by rail for a part of the journey before being transferred to road transport.

C.1.1 Domestic Road Transportation

Unknown domestic road transportation distances should be estimated using the UK statistics released by the Department for Transport (DfT) [38], which quantify the average road transport distance by commodity type in 2009. An extract from these statistics is provided in Table C.1.

Commodity	Average length of haul (km)	Million tonnes (Mt = $1x10^6$ tonnes)
Wood, timber and cork	121	32
Crude minerals	47	216
Ores	80	16
Crude materials	132	16
Coal and coke	96	10
Building materials	68	126
Iron and steel products	129	26
Petrol and petroleum products	79	61
Chemicals	139	38
Other metal products	137	20
Machinery and transport equipment	89	68
Miscellaneous manufactures	107	82
Miscellaneous articles	135	318

Table C.1 – Average road transportation distance in UK by commodity type, DfT 2009[38]

These statistics should only be used when obtaining product-specific data is not possible. The use of these statistics should be stated within the reporting of the results as a limitation of the study.

The emissions associated with road transportation are dependant on several factors. Firstly, the size of the vehicle has a very significant impact on the transportation emissions. Secondly, the emissions are dependant upon the utilization of the vehicle (defined as the ratio of the load mass (in kg) to the vehicle capacity (in kg)). Finally, the requirement of the vehicle to make an empty return trip (backhaul) should be considered.

Activity-specific and product-specific data should be used whenever it can be obtained. If this data is unavailable, the size of the road vehicle to be used should be based upon reasonable comparisons with similar transportation activities.

Data for the fuel consumption and emissions for different road transportation vehicles is presented in Table . This table is based upon life cycle data within the CPM LCA database, from studies originally conducted by NTM [40][41][42][43][44]. This data should be used only if product-specific data is unavailable. Diesel fuel is assumed for all vehicle sizes. Table C.3 features values for emissions and diesel emissions in terms of X/W and Y/W respectively, these were defined in Section 5.14.2.

Vehicle Type	Capacity (t)	Utilisation	Emissions X/W (gCO_2 /t.km)	Diesel use Y/W (MJ / t.km)
Heavy Truck	40	70%	46	0.61
Heavy Truck	26	70%	50	0.68
Medium Truck	14	70%	130	1.8
Light Truck	8.5	50%	170	2.3
Delivery Van	1.4	50%	660	9.0

Table C.3 – Emissions and diesel fuel use for different road vehicles

If the requirement for an empty return trip (backhaul) is unknown, then the additional transportation distance should be based upon average statistics for the UK. Statistics released by the Department for Transport (DfT) [38] reveal that 27% of goods vehicle journeys are unloaded. From this, it may be estimated that the distance goods are transported in km will incur total vehicular mileage of 1.27 times the distance travelled. Use something other than X's in this paragraph

C.1.2 Domestic Rail Transportation

In a similar manner to road transport, unknown domestic rail transportation distances may be estimated by commodity type. Statistics for the UK rail network were found in an archived DfT report on rail freight modelling [39], and are summarised in Table C.4. The data shown in Table C.4 should be treated with a degree of caution, as the data is not current. More recent data has been sought to update the report.

Commodity	Average rail transport distance (km)	Million tonnes (Mt = $1x10^6$ tonnes)
Coal and coke	115	45
Construction materials (aggregates)	166	17
Minerals	72	8
Metals (steel)	213	8
Oil and petroleum	195	6
Infrastructure	88	8

Table C.4 - Average rail transportation distance in UK by commodity type, DfT 2002[39]

These statistics should only be used when obtaining product-specific data is not possible. The use of these statistics should be stated within the reporting of the results as a limitation of the study.

If no specific data is available for the emissions associated with rail transport, a transportation emission (X/W) of 25gCO_2 / t.km should be assumed. This is based upon European average data within a 2008 UIC report [45] for both diesel and electric rail transport. Emissions of other GHG should be considered negligible.

C.1.3 Sea Transportation Data

Activity-specific and product-specific data should be used whenever it can be obtained. If this data is unavailable, ships should be classified by displacement weight according to Table C.5. If the type of ship is unknown, a medium ship should be assumed. Emissions and fuel use data for these categories of ships are available from the CPM LCA database[46][47][48], based upon research from NTM. This data is summarised in Table C.5, and should only be used when obtaining product-specific data is not possible. The use of this data should be stated within the reporting of the results as a limitation of the study.

Type of Ship	Size (dwt)	Emissions X/W (gCO_2 / t.km)	Heavy fuel oil use Y/W (MJ / t.km)
Small Ship	< 2000	30	0.4
Medium Ship	2000 – 8000	21	0.28
Large Ship	> 8000	15	0.2

Table C.5 – Emissions and heavy fuel oil use for sea transport by class of ship[46][47][48]

C.1.4 Other Domestic Transportation

Other forms of domestic transportation such as airfreight may be used in exceptional cases. If this activity is not excluded by the cut-off criteria, an appropriate model should be selected, with reasonable assumptions for modelling purposes. All assumptions should be stated within the reporting of the final results.

C.2 International Transportation

The geographical boundary conditions specified in Appendix Section A.1 stated that all processes for which the location is unknown and existing studies are not available should be assumed to take place within the UK. If any processes are known to occur outside of the UK, then reasonable assumptions regarding the international transportation distances, methods and emissions should be made. All assumptions made should be included within the reporting of the final results.

D TIDAL CURRENT PROBABILITY DATA

The tidal current profile data used in Section 7.5 in the histograms has been included in Table D.1, Table D.2, and Table D.3 for low-, medium- and high- tidal flow speed respectively. As mentioned in Section 7.5, the data has been estimated, and as a result a degree of inaccuracy must be assumed. The low-speed data has been estimated for a site with low tidal flow speeds, such as Carmel Head, Islay, or the Isle of Wight [16]. The medium-speed date has been derived from simplified data obtained from EMEC[13]. The high-speed data has been estimated, based on data found for the maximum effective tidal stream flow of the Race of Alderney of 4.4m/s [17].

Flow Speed (m/s)	Probability	Cumulative Probability (%)
0.0	0.0	0.0
0.2	5.5	5.5
0.4	8.0	13.5
0.6	10.0	23.5
0.8	12.0	35.5
1.0	12.0	47.5
1.2	11.0	58.5
1.4	10.0	68.5
1.6	8.0	76.5
1.8	7.0	83.5
2.0	5.0	88.5
2.2	4.0	92.5
2.4	2.5	95.0
2.6	2.0	97.0
2.8	1.5	98.5
3.0	1.0	99.5
3.2	0.5	100.0
3.4	0.0	100.0
3.6	0.0	100.0
3.8	0.0	100.0
4.0	0.0	100.0

Table D.1 – Low-Speed Tidal Current Probability Distribution

Flow Speed (m/s)	Probability	Cumulative Probability (%)
0.0	0.0	0.0
0.2	1.0	1.0
0.4	3.0	4.0
0.6	5.0	9.0
0.8	7.0	16.0
1.0	8.5	24.5
1.2	8.5	33.0
1.4	8.5	41.5
1.6	8.5	50.0
1.8	8.5	58.5
2.0	8.5	67.0
2.2	8.5	75.5
2.4	7.5	83.0
2.6	6.0	89.0
2.8	4.5	93.5
3.0	3.0	96.5
3.2	2.0	98.5
3.4	1.0	99.5
3.6	0.5	100.0
3.8	0.0	100.0
4.0	0.0	100.0

Table D.2 – Medium-Speed Tidal Current Probability Distribution

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Flow Speed (m/s)	Probability	Cumulative Probability (%)
0.0	0.0	0.0
0.2	0.1	0.1
0.4	0.1	0.2
0.6	0.2	0.4
0.8	0.4	0.8
1.0	0.7	1.5
1.2	1.0	2.5
1.4	1.2	3.7
1.6	1.4	5.1
1.8	1.7	6.8
2.0	2.0	8.8
2.2	2.5	11.3
2.4	3.0	14.3
2.6	3.5	17.8
2.8	4.5	22.3
3.0	5.5	27.8
3.2	7.0	34.8
3.4	8.5	43.3
3.6	9.5	52.8
3.8	10.5	63.3
4.0	10.5	73.8
4.2	9.8	83.6
4.4	7.5	91.1
4.6	5.0	96.1
4.8	2.5	98.6
5.0	1.0	99.6
5.2	0.4	100.0
5.4	0.0	100.0
5.6	0.0	100.0
5.8	0.0	100.0
6.0	0.0	100.0

Table D.3 – High-Speed Tidal Current Probability Distribution

E DATA COLLECTION CONSIDERATIONS

This section provides guidance upon the type and quality of data required, possible sources of data, the interpretation of data from previous studies and the treatment of incomplete or commercially sensitive data.

E.1 Data Requirements

The data required for a carbon payback study may be split into two categories. The first category is qualitative data, which is usually related to the structure of the life cycle model. The second type of data is quantitative data, which is used to populate the inventories of the processes within the life cycle model.

E.1.1 Data requirements throughout the modelling process

Modelling of the product life cycle starts with a rapid collection of qualitative data, resulting in the construction of an initial process model for the life cycle of the system. The second stage of data collection consists of collecting quantitative data for the modelled processes, evaluating this data against the cut-off criteria, and collecting qualitative data to increase the depth of study if the cut-off criteria are not met. The modelling process ends when all cut-off criteria are met. This process is illustrated in Figure.

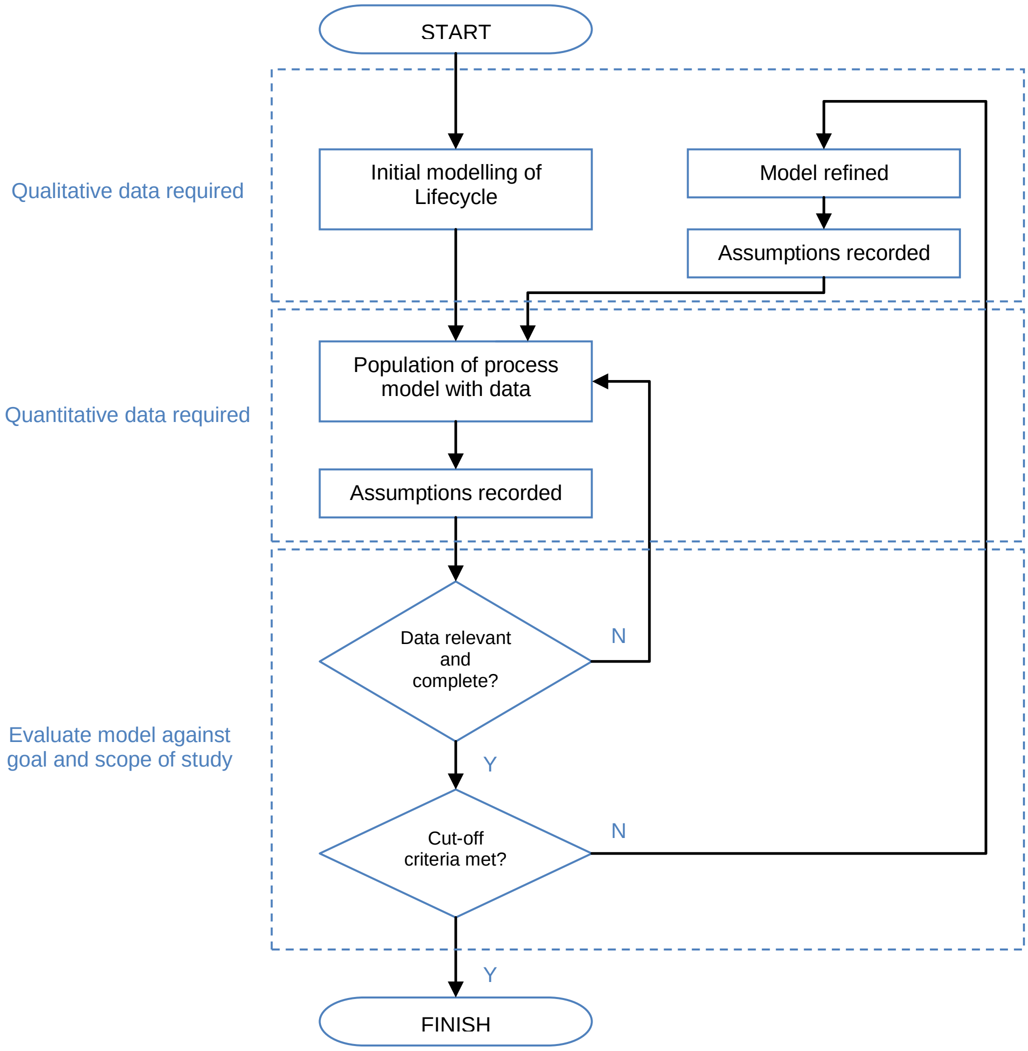

Figure E.1 – Modelling Process

E.1.2 Qualitative Data Requirements

Qualitative data is descriptive, and is used to construct process models. Examples of qualitative data includes information about how a process is conducted, the required inputs and outputs of that process, geographical location of the process and any transportation arrangements, handling of waste, and contact information for suppliers and contractors.

Quantitative data may be used for the following purposes:

- Determining what additional data is required to model a process;
- Constructing a representative process inventory;
- Choosing a representative functional unit for a process;
- Determining suitable boundaries for a process model;
- Determining appropriate allocation techniques;
- Understanding mathematical relationships between flows and processes;
- Understanding the significance of assumptions within previous studies;
- Interpretation and verification of quantitative data;
- Documentation of quantitative data.

Qualitative primary data is normally collected by personal communication from the original data owner, the designer, manufacturer, supplier or contractor. It is important to record this communication in a means that will enable it to be used for modelling and documentation purposes, but a suitable means of implementing the data recording must be introduced.

E.1.3 Quantitative Data Requirements

Quantitative data is used to populate the process models. This requires quantification of all inflows and outflows, and quantification of other parameters used within a model, such as transportation distance or efficiency. When modelling a specific process, the requirements for quantitative data are usually made apparent during the modelling phase, during the construction of a process inventory.

For further information regarding the required quantitative data to conduct a LCA, the reader is referred to the published ISO standards [2][3]. If a software LCA tool is used, the required data is usually made explicit upon the creation of a process model.

The collection of quantitative primary data may be best conducted by the use of questionnaires or spreadsheets, which are completed by the data provider. Examples of data collection questionnaires are provided in ISO14044:2006 [3]. Records of the data collected should be retained in a suitable format, as detailed in Appendix Section E.7.1.

E.2 Data Quality and Selection

E.2.1 The importance of data selection

The choice of data is one of the most challenging aspects of any LCA. Ideally, ‘primary’ data that is specific to the product life cycle and processes under consideration would be used throughout the whole study. However, resource and technology maturity constraints imposed upon the assessment will inevitably result in the use of non-specific ‘secondary’ data from outside the product system, which invariably requires assumptions to be made about the nature of the studied life cycle. This is caused by discrepancies between the modelled process and the process from which the data was derived.

The most suitable data will cause the most reasonable assumptions to be made, and therefore the definition of ‘most suitable data’ is highly process-specific. Furthermore, the sensitivity of the final result to these assumptions will vary greatly, depending upon the significance of the modelled process within the life cycle. For these reasons, it would be inappropriate to specify any kind of numerical weighting or selection method, and the selection of data is left to the judgement of the practitioner.

All secondary data used during the study should be evaluated, and the resultant limitations imposed upon the calculated payback interval should be stated and discussed alongside the reporting of the final results of the study.

E.2.2 Data selection considerations

The following criteria should be considered as a minimum when evaluating data:

- Age of data;

- Geographical differences between modelled process and studied process;
- Depth of study from which the data was derived;
- Assumed boundary conditions (included and excluded activities);
- Data tolerance and error range (if stated);
- Reliability of data source, and whether it has been reviewed.

The relevance of these considerations is process-dependant. This can be shown by considering the significance of the age of the data to be dependent upon the rate of technological development within the studied industry. These considerations should be applied on a case-by-case basis if it is judged as appropriate.

E.2.3 The data selection process

A process map illustrating the data collection process is shown in Figure . This process is intended for guidance only, and should not be considered mandatory.

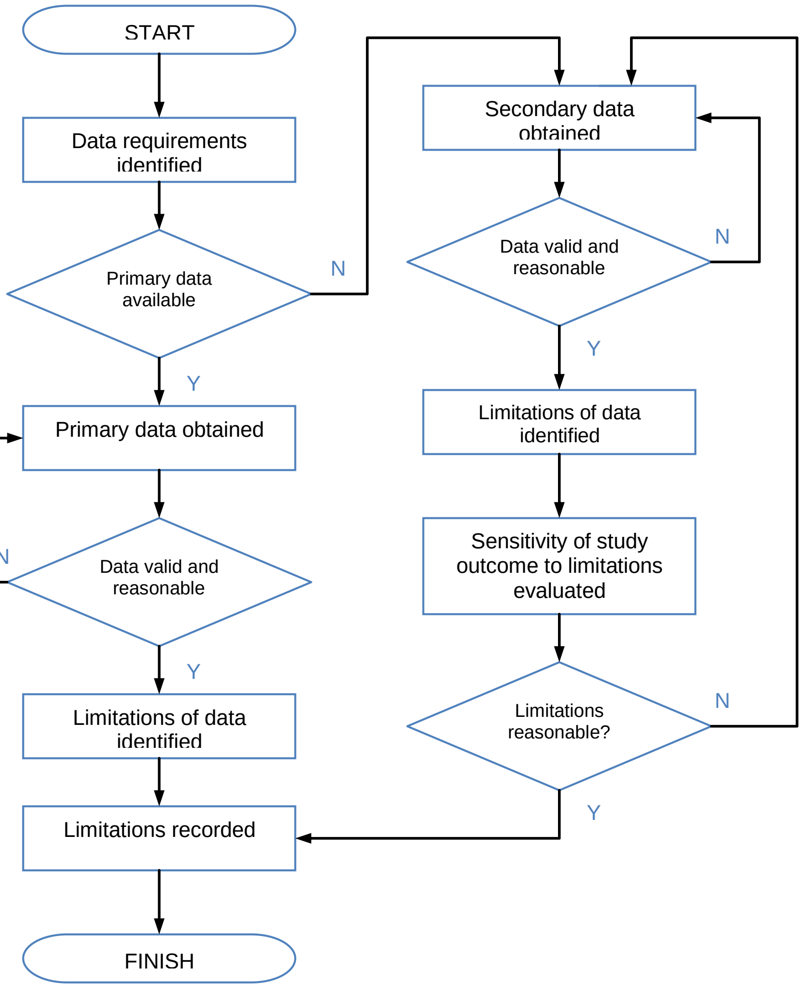

Figure E.2 – Data selection process

E.3 Data Sources

This section aims to provide a brief overview of data sources that may be considered; access to these type of sources may be considered a requirement of the study.

E.3.1 Sources of Primary Data

E.3.1.1 Data from the tidal stream turbine designers and manufacturer

Primary data may include assembly techniques, transportation methods, operating and maintenance procedures and disposal plans which occur under the direct control of the manufacturer. This information is usually product-specific, and is fundamental to designing an effective life cycle model.

In the case of a relatively recent industry such as tidal stream turbine design, primary data differs greatly between different technologies, and is usually only known at the required level of detail by a few individuals employed within the design team. Establishing a strong relationship with the product design team at an early stage is therefore crucial to the success of the study. Due to the nature of the industry, the primary data may also be proprietary or covered by intellectual property restrictions.

A recommended approach is to involve the product design team in an initial meeting, during which a rudimentary process map representing the product life cycle is constructed. This may be based upon existing cost modelling of the tidal stream technology.

One of the most important aspects of the modelling process is the design of the standard tidal stream array, as described in Section 7.1. The design of the array infrastructure for the standard array should be carried out with the guidance of the design team.

E.3.1.2 Data from suppliers and contractors

As the PRL level of the LCA increases, there will be a requirement to obtain a detailed picture of the product supply chain in order to allow a sufficiently accurate calculation of the carbon payback interval. It may be possible to obtain material or process data directly from suppliers and contractors in order to populate the model, although it should be noted that currently LCA is not a common process in the manufacturing industry, and as a result it may prove difficult to obtain accurate data from suppliers. Ideally, the suppliers and contractors should be engaged at the earliest opportunity, so that the modelling requirements can be detailed in order for the suppliers to provide appropriate data. The data from the suppliers should follow on from the qualitative information obtained from the designers and manufacturers of the TECS.

E.3.2 Sources of Secondary Data

If the collection of primary data is impossible or considered unreasonable, then data from secondary sources could be considered. A range of different sources exist that could be used to supply the information, which include, but are not limited to:

- Industry Bodies;
- Life Cycle Inventory Databases;
- Personal communication with industry experts;
- Published statistics and literature;

It should be noted that there is no implied order of preference in the naming of these sources. The selection of secondary data should be conducted based upon the quality requirements specified in Section E.2.

E.4 Aggregation of Data

For the purposes of clarity, multiple sources of data may aggregated. Aggregation is the process of combining the inventories of two or more processes into one common inventory. Aggregation is usually performed for the presentation of results, and typically, secondary data is usually provided in aggregate form.

In the context of a LCA there are two distinct types of aggregation, vertical and horizontal. Vertical aggregation involves combining the inventory of a process with upstream or downstream processes, and is commonly used for the presentation of results for 'cradle-to-later stage' studies. Horizontal aggregation implies that a set of data represents an average, taken across different processes that have the same functional unit, and this approach is often employed when representing transportation and waste management activities.

Unnecessary aggregation should be avoided during the construction of the life cycle model. Aggregation is a one-way process of simplifying the data, as the original inventories cannot later be retrieved from the combined dataset. Furthermore, aggregation requires assumptions relating to the structure of the model to be made, which makes the aggregate process inflexible to change and can make the data difficult to comprehend.

E.4.1 Use of Vertical Aggregation

Vertical aggregation of GHG emissions is necessary during the calculation of the carbon payback interval, as described in Section 9. It is also likely that vertically aggregated secondary data may be used, in the form of 'cradle-to-later stage' production processes or 'later stage-to-grave' waste management processes. In all other instances, vertical aggregation should be avoided.

E.4.2 Use of Horizontal Aggregation

Horizontal aggregation may be appropriate to systems that reside close to the boundaries with natural systems, such as raw material extraction. Processes with large variation such as transportation may also use horizontally aggregated data. As with vertical aggregation, horizontal aggregation should be avoided during the modelling stages of the assessment, due to the inflexibility associated with aggregated models.

E.4.3 Average and Marginal Data

One of the important decisions made whilst conducting a LCA is whether average or marginal data should be used for non-linear processes, as illustrated in Figure E.3.

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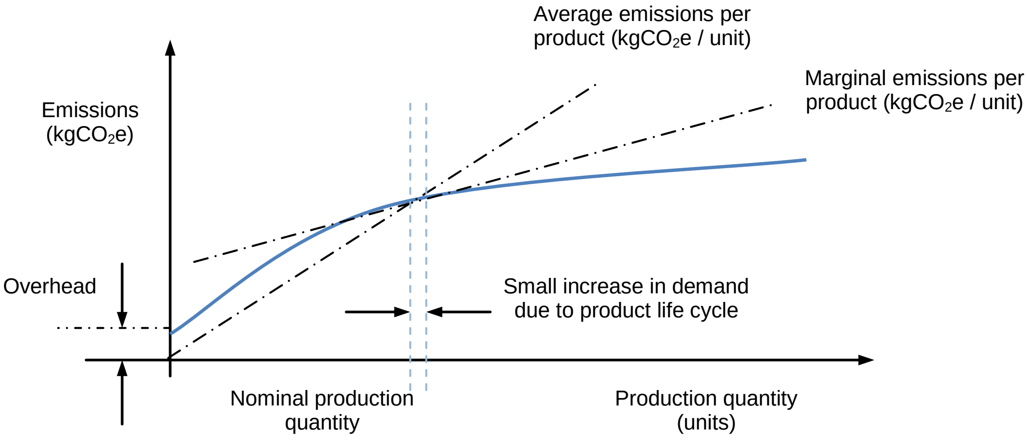

Figure E.3 – Average and marginal data for a non-linear process

If the change in demand introduced by the product life cycle under consideration is small relative to the original nominal demand, then it may be considered appropriate to use marginal data to model the consequence of the product life cycle. However, this method fails to account for economies of scale and overheads that may be associated with the process, and therefore does not reflect the true emissions associated with the average functional unit delivered.

In deciding which type of data is most appropriate, the goal of the study should be considered. For studies that intend to calculate the environmental impact that may be attributed to a product, average data would be appropriate. For studies that are intended to compare different options, marginal data would be more appropriate. The choice between average and marginal data must therefore be based upon whether accuracy or comparability of results is preferred.

The goal of the carbon footprint study is to calculate the carbon payback interval for a TECS array. By establishing this interval, it will be possible to compare and contrast the payback periods of different tidal stream technologies. To create a meaningful comparison between technologies, it will be required to have accurate data, as well as a comparable level of PRL. It is suggested that the role of the carbon footprint model should be to calculate the most conservative "worst case" scenario, and find the longest predicted payback period. The choice between marginal and average data should aim to give the highest associated emissions for each process. In most cases, this will require the use of average data.

The type of data used for each process model should be stated within the reporting of the final results, and a discussion should be included describing any implications for the interpretation of results that arise out of this. The choice between average and marginal data is a key limitation of the use of a linear life cycle model to calculate a carbon payback interval.

E.5 Checking of Data

E.5.1 Qualitative Data

Qualitative data should be checked by comparison of the model with models for similar processes. Where any discrepancies exist that cannot be explained by differences in the studied processes, these should be discussed with the supplier of the data.

E.5.2 Quantitative Data

Quantitative data may also be checked by comparison with similar processes. In addition, the total mass of inputs and outputs to unit processes should be calculated by summation of the individual flows. Ideally, mass should be conserved through the process, and the total mass of input and output flows should be equal. Where this is not the case, the source of the discrepancy should be identified, and these checks should continue until all relevant flows have been modelled. The documentation of the dataset should state whether mass is conserved, and provide reasoning and justification if this is not the case.

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E.6 Data Interpolation Techniques

It may be considered appropriate to use linear interpolation to estimate unknown parameters and flow quantities, based on existing details held on the model. Where interpolation is used, its use should be stated and justified during the final reporting of results.

E.7 Data Handling Considerations

E.7.1 Storage of data

Guidance upon the storage of data within a LCA and an example data storage format are provided by ISO14044 [3]. A discussion of this guidance is presented in Baumann et.al [9]. Data is usually stored in datasets, corresponding to unit processes within the product system. This is carried out automatically within LCA software tools. The limitations, boundary conditions and modelling assumptions associated with inventory data should be stored in the same location.

E.7.2 Uncertainty

For each dataset, a description of the uncertainty, tolerance or error associated with the data should be included in the analysis of the data, as this will vary from study to study. This is intended to prevent misuse upon re-distribution of the data, and to prevent misinterpretation of the data.

E.7.3 Data Referencing

The source of data should be recorded within each dataset. A modification record should also be kept within the same location. The purpose of this is threefold. Firstly, the process of reporting the results of the study is simplified. Secondly, any relevant copyright restrictions may be met. Finally, it will enable future studies to obtain information on the sources used in the model, simplifying these processes as well.

E.7.4 Treatment of Commercially Sensitive Data

Access to commercially sensitive data is likely to be required to complete the carbon payback analysis. A plan for the handling of this data should be reached with the relevant parties, before the data is used.

F GLOBAL WARMING POTENTIAL

(normative, 100 year horizon)

The following table provides a list of GWP constants for assessing the carbon payback interval of a tidal stream array. Values quoted are from PAS2050 Annex A [4], originally obtained from the IPCC 2007 report [1]. It is required to ensure that the actual values used for the study are current and correct; more recent GWP constants from the IPCC or Carbon Trust should be used in preference to the values presented in Table F.1.

Industrial Designation or Common Name	Chemical Formula	GWP for 100-year horizon (at date of publication
Carbon Dioxide	CO_2	1
Methane	CH_4	25
Nitrous Oxide	N_2O	298
NO_X (low estimate [49])	NO_X	120
NO_X (high estimate [49])	NO_X	470
Substances controlled by the Montreal Protocol		
CFC-11	CCl_3F	4,750
CFC-12	CCl_2F_2	10,900
CFC-13	$CClF_3$	14,400
CFC-113	CCl_2FCClF_2	6,130
CFC-114	$CClF_2CClF_2$	10,000
CFC-115	$CClF_2CF_3$	7,370
Halon-1301	$CBrF_3$	7,140
Halon-1211	$CBrClF_2$	1,890
Halon-2402	$CBrF_2CBrF_2$	1,640
Carbon tetrachloride	CCl_4	1,400
Methyl Bromide	CH_3Br	5
Methyl Chloroform	CH_3CCl_3	146
HCFC-22	$CHClF_2$	1,810
HCFC-123	$CHCl_2CF_3$	77
HCFC-124	$CHClFCF_3$	609
HCFC-141b	CH_3CCl_2F	725
HCFC-142b	CH_3CClF_2	2,310
HCFC-225ca	$CHCl_2CF_2CF_3$	122
HCFC-225cb	$CHClFCF_2CClF_2$	595
Hydrofluorocarbons		
HFC-23	CHF_3	14,800
HFC-32	CH_2F_2	675
HFC-125	CHF_2CF_3	3,500
HFC-134a	CH_2FCF_3	1,430
HFC-143a	CH_3CF_3	4,470
HFC-152a	CH_3CHF_2	124
HFC-227ea	CF_3CHFCF_3	3,220
HFC-236fa	$CF_3CH_2CF_3$	9,810
HFC-245fa	$CHF_2CH_2CF_3$	1,030
HFC-365mfc	$CH_3CF_2CH_2CF_3$	794
HFC-43-10mee	$CF_3CHFCHFCF_2CF_3$	1,640

Rolls-Royce Data - Private, see front page for details

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Industrial Designation or Common Name	**Chemical Formula**	**GWP for 100-year horizon (at date of publication**
Perfluorinated Compounds		
Sulphur Hexafluoride	SF_6	22,800
Nitrogen Trifluoride	NF_3	17,200
PFC-14	CF_4	7,390
PFC-116	C_2F_6	12,200
PFC-218	C_3F_8	8,830
PFC-318	$c\text{-}C_4F_8$	10,300
PFC-3-1-10	C_4F_{10}	8,860
PFC-4-1-12	C_5F_{12}	9,160
PFC-5-1-14	C_6F_{14}	9,300
PFC-9-1-18	$C_{10}F_{18}$	>7,500
Trifluoromethyl sulphur pentafluoride	SF_5CF_3	17,700
Fluorinated ethers		
HFE-125	CHF_2OCF_3	14,900
HFE-134	CHF_2OCHF_2	6,320
HFE-143a	CH_3OCF_3	756
HCFE-235da2	$CHF_2OCHClCF_3$	350
HFE-245cb2	$CH_3OCF_2CHF_2$	708
HFE-254fa2	$CHF_2OCH_2CF_3$	659
HFE-347mcc3	$CH_3OCF_2CF_2CF_3$	359
HFE-347pcf2	$CHF_2CF_2OCH_2CF_3$	575
HFE-356pcc3	$CH_3OCF_2CF_2CHF_2$	110
HFE-449sl (HFE-7100)	$C_4F_9OCH_3$	297
HFE-569sf2 (HFE-7200)	$C_4F_9OC_2H_5$	59
HFE-43-10-pccc124 (H-Galden 1040x)	$CHF_2OCF_2OC_2F_4OCHF_2$	1,870
HFE-236ca12 (HG-10)	$CH_2OCF_2OCHF_2$	2,800
HFE-338pcc13 (HG-01)	$CHF_2OCF_2CF_2OCHF_2$	1,500
Perfluoropolyethers		
PFPMIE	$CF_3OCF(CF_3)CF_2OCF_2OCF_3$	10,300
Hydrocarbons and other compounds – direct effects		
Dimethylether	CH_3OCH_3	1
Methylene Chloride	CH_2Cl_2	8.7
Methyl Chloride	CH_3Cl	13

Table F.1 – Global Warming Potential (GWP) constants for 100-year time horizon[4]

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