Optimising Tidal Lagoons: An Environmental Focus

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Declaration

I declare that this thesis has been composed solely by myself and that it has not been submitted, either in whole or in part, in any previous application for a degree. Except where otherwise acknowledged, the work is entirely my own.

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Abstract

Tidal lagoons could help towards meeting ambitious global and national renewable energy and carbon reduction targets, contributing towards tackling climate change through the displacement of fossil fuel generation. Lagoons have additional benefits over other forms of renewable energy which include: predictability, use of proven technology, long expected life spans (100 years) and the ability to be strategically located to provide a base load supply of continuous energy. Despite these advantages there are no tidal lagoons in the world to date, the key barriers to lagoon development have been cost and environmental concerns.

This research shows how to optimise tidal lagoons in terms of the environment, considering the wider socio-economic implications of lagoon developments as multi-use facilities. Through industry engagement, the research provides a snapshot of industry perspectives, allowing presentation of the key environmental impacts and benefits of tidal lagoons. It then uses systematic literature review to investigate transferable solution options from other relevant coastal and marine industries to address these key impacts. Finally, the research demonstrates use of a potential methodology to select and assess solution options which allows for consideration of the wider environmental, socio-economic implications of lagoons.

Unlike many other large-scale marine energy projects tidal lagoons have the potential to be multi-use, multi-benefit facilities which are likely to have far reaching environmental, social and economic impacts, both positive and negative. The lagoon sector is in its infancy with recent political debates arising over the 'value for money' of lagoons and the cost of developments to both the tax payer and to the environment. Independent research addressing the uncertainty surrounding the environmental impacts of lagoons and considering how to optimise lagoons in terms of the potential value they could provide to society is now more important than ever.

Acknowledgements

Thanks to my Grandma for showing me the value of hard work, to my parents for teaching me to do the right things and to do things right, to my friends for encouraging me along whatever path I choose to follow and to my siblings for reminding me not to get too big for my boots!

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Contents

List of Figures

List of Tables

List of Acronyms

BEIS	Department for Business Energy and Industry Strategy
CBA	Cost Benefit Analysis
CBL	Cardiff Bay Lagoon
CICES	Common International Classification for Ecosystem Services
DCO	Development Consent Order
DUKES	Digest of United Kingdom Energy Statistics
EIA	Environmental Impact Assessments
EsS	Ecosystem Services
PM	Particulate Matter
PRISMA	Preferred Reporting Items for Systematic Meta-Analysis
SBL	Swansea Bay Lagoon
SEA	Strategic Environmental Assessment
TLP	Tidal Lagoon Power Ltd
UK	United Kingdom
UKNEA	UK National Ecosystem services Assessment

1 Introduction

1.1 Brief Research Context

The deployment of renewable energy is regarded as a strategy to combat climate change through the displacement of fossil fuel energy sources and therefore the reduction of carbon emissions. There have been several global agreements aiming to mitigate the impact of climate change, the most recent being the 2015 Paris Agreement. To date, 172 of 197 parties have signed this historic agreement and begun to adopt climate change strategies into their own national agendas [1]. Nationally, the UK has a target to reduce its greenhouse gas emissions by 80% by 2050, relative to 1990 levels [2] and to provide 15% of its energy needs from renewable sources by 2020 [3]. There needs to be an increase in the rate of deployment of renewable energy in the UK if it is to achieve this target within the next 2 years. Under ‘business as usual’ conditions it will fail to achieve this target [4].

There are a variety of renewable energy options that the UK could deploy to meet these ambitious targets. Often overlooked is the vast amount of marine energy available around the UK coastlines, the majority of which is currently untapped. The UK has the greatest tidal energy resource in the world [5]. It is expected that a national fleet of tidal lagoons could supply 8% of the UK’s electricity [6]. Additional features of tidal range energy include reduced uncertainty through the use of proven technology, a high level of predictability [7], the ability to phase shift energy to provide a continuous base load supply [8] and a long expected project life spans (100 years) [9,10]. These features give lagoons the potential to be an attractive renewable energy option for the UK

Developments in the sector, including the awarding of a Development Consent Order (DCO) to Tidal Lagoon Swansea Bay in June 2015 [11] and the positive outcome of the Government Review into the feasibility of tidal lagoons for the UK in 2016 [12] created an increase in lagoon specific research activity. The recent government rejection of Swansea Bay Lagoon [13,14] and rebuttals from the Welsh Government and Tidal Lagoon Power (TLP) [15] mean it is now more important than ever to independently consider lagoons as potential key players in the national energy market. Due to the relative infancy of the lagoon industry, the field is constantly and rapidly changing. High quality, focused research at this stage is vital to ensure strong knowledge foundations for the industry if lagoons are going to progress into deployment.

1.2 Statement of the Problem

Despite the potential advantages of tidal range energy, previous projects have been turned down in the UK, mainly due to lack of serious proposals, high capital cost and/or environmental concerns [16,17]. There are now several serious proposals, with TLP and others presenting a number of lagoon options for deployment in the UK. The high capital costs of lagoons were investigated in the 2016 government commissioned review, which concluded that lagoons did have a cost effective role to play in the UK [18], the cost of Swansea Bay lagoon specifically is currently being heavily debated in the sector. Although lagoons have previously been presented as a more environmentally sensitive alternative to tidal barrages [17], the environmental impacts are still a concern for the industry [10]. It can therefore be foreseen that environmental impacts may present additional hurdles to the industry's future development if the uncertainty surrounding them is not addressed further at this early stage of the sector's development.

There are no man-made, energy generating tidal lagoons in the world to date. As such, there is no operational data on their environmental impacts, little relevant lagoon-specific literature and no in-depth studies on potential solution options to address their impacts. Identifying the key environmental impacts of tidal lagoons and investigating potential solution options to address them is vital to reduce the uncertainty surrounding tidal lagoons and combat the concerns regarding environmental impacts as a barrier to the industry's development.

1.3 Aims & Objectives

This research has one overarching aim, which provides a clear focus and direction for the project. To achieve this overarching aim there are three main research objectives. These three objectives are later presented as three separate chapters (3,4 and 5) making up the core contribution of the research to the body of knowledge.

Overarching Aim**:** To optimise the selection of solution options to address the key environmental impacts of tidal lagoons

Objectives

- Identify the key impacts of tidal lagoons
- Determine solution options to the key impacts of tidal lagoons
- Select, assess and value solution option combinations for addressing the key impacts of tidal lagoons

A brief statement on scope is required here to provide indication of the boundaries of the research. This is particularly important given the lack of research to date on tidal lagoons and therefore the potential scope for new research. The identification of key impacts includes both positive and negative impacts to capture the concept of lagoons as multi-use facilities. The detail of this research is kept intentionally high level not related to one site or project, not going into ecological or biological species level impacts or into modelling of environmental processes. The research does not look at one particular lagoon, one particular impact or one particular solution, it is a holistic broader view of lagoons as a whole which is deemed to be more valuable for the sector in its present state as a young industry still in the planning stages.

The environmental impacts identified in the research initially consider regional and local level impacts at a high level e.g. changes to ‘sediment regime’ or ‘impacts to fish migration’. Later in the research when solution options to address impacts are considered a wider view and scale of changes to ecosystem services is taken, including consideration of global implications on society such as energy generation and displacement of carbon emissions.

1.4 Significance of the Research

Given the relative infancy of the lagoon industry, there is significant potential for new research to be high impact, this will be made clearer in Section 2.6.4 A Place for this Research. This research is significant in three main areas; knowledge advancement in the field, providing solutions to a sector problem and demonstrating the novel use of an established procedure.

1.4.1 Knowledge Advancement

The existing body of knowledge relating specifically to the impacts of tidal lagoons is very limited, and as such almost all of the research findings contribute towards new knowledge in the sector. This includes the identification and better understanding of the key environmental impacts and benefits of lagoons. The research provides a holistic snapshot of the industry’s current ‘state of the art’, highlighting potential areas of focus for future research. Through industry engagement new light has been shed on the industry perspectives, which provides insight into the sector’s development, challenges and critical future requirements.

Transferable environmental impact solution options are identified, assessed and valued in terms of their potential for application in the lagoon industry. This process enables the presentation of relevant knowledge surrounding solution options from other industries and pushes forward its potential application for the lagoon sector. Assessment and valuation of the solution options incorporating the ecosystem service approach allows new knowledge to be developed relating to the consequences of inclusion of the wider environmental parameters in solution option appraisal and optimisation.

The advancement of knowledge in the sector from this research includes the presentation of industry perspectives on the key environmental impacts of lagoons, the identification of solution options to address those environmental impacts from other relevant industries and learning from the outcomes of including or excluding the wider environment and society in lagoon environmental optimisation and appraisal.

1.4.2 Solutions to Problems

One of the biggest problems for the tidal lagoon sector is lack of knowledge. The contribution of this research to the creation of new knowledge in the sector is outlined above and discussed in more detail in Chapter 6. Along with new knowledge, this research develops practical and usable tools which aim to help address the key barriers currently facing the sector. These include an impact and opportunities register, a look-up database of solution options to address the key impacts of tidal lagoons, a basic solution selection tool based on key criteria and a template for assessment and valuation of solution options which includes the wider environmental, social and economic implications.

This research advances the knowledge in the sector and creates tools to allow practical application of the findings to address key sector problems, this helps towards reducing uncertainty in the sector. Uncertainty surrounding the environmental impacts and uncertainty surrounding the high capital costs of lagoons, are both currently seen to be major barriers for the sector. The industry engagement in this research is a preventative solution to reduce the chances of a future problem in the industry by early demonstration of the similarities and differences in perspectives of influencers and developers on the environmental impacts of tidal lagoons.

1.4.3 Novel Procedure Use

There are no tidal lagoons in the world to date. As such to investigate their key environmental impacts and potential solution options existing methodologies have to be applied in a novel tidal lagoon application. The research uses a systematic literature review, not just to pull the body of academic knowledge together to demonstrate current industry status, but to undertake thorough investigation of the potential transferable solution options to the key impacts of tidal lagoons from other relevant coastal, marine and river industries. In addition, the Ecosystem Service Approach is combined with Cost Benefit Analysis (CBA) to determine the changes in ‘optimisation’ of lagoon solution implementation as a result of inclusion or exclusion of the wider environmental and societal positives and negatives. This demonstrates use of known procedures in a novel way.

1.5 Thesis Overview

The thesis is structured as seven chapters within three main parts, as shown in Figure 1. Part 1 (Chapters 1 and 2) consists of introductory and background chapters. This introductory chapter aims to set the scene for the research, providing a research context and problem to be addressed. It includes the aims and objectives of the research and the research significance. Chapter 2 provides essential background for the research, providing a "stepping off point" of knowledge that the research hopes to build upon.

Part 2 is the core of the research and therefore this thesis (Chapters 3, 4 and 5). The three core chapters are directly aligned with the three research objectives, and ultimately make up the three years of research. Chapter 3 walks through the process of identifying the key impacts of tidal lagoons through the development of a risk register and industry engagement. Chapter 4 focuses on the investigation into solution options to the key impacts of tidal lagoons, through systematic literature review and development of a solution options look-up database. Chapter 5 considers the final objective relating to the selection, assessment and valuation of different solution options to address the key impacts of tidal lagoons. The chapters in Part 2 are the core contribution of the research to the sector. These three chapters combined address all three objectives of the research to achieve the overarching research aim.

Part 3 (Chapters 6 and 7) includes a summary of the key research findings and a discussion on the industry context of these. This considers the recent significant developments in the lagoon sector and how that reflects against this research. The final Chapter in Part 3 and of this research provides a set of conclusions.

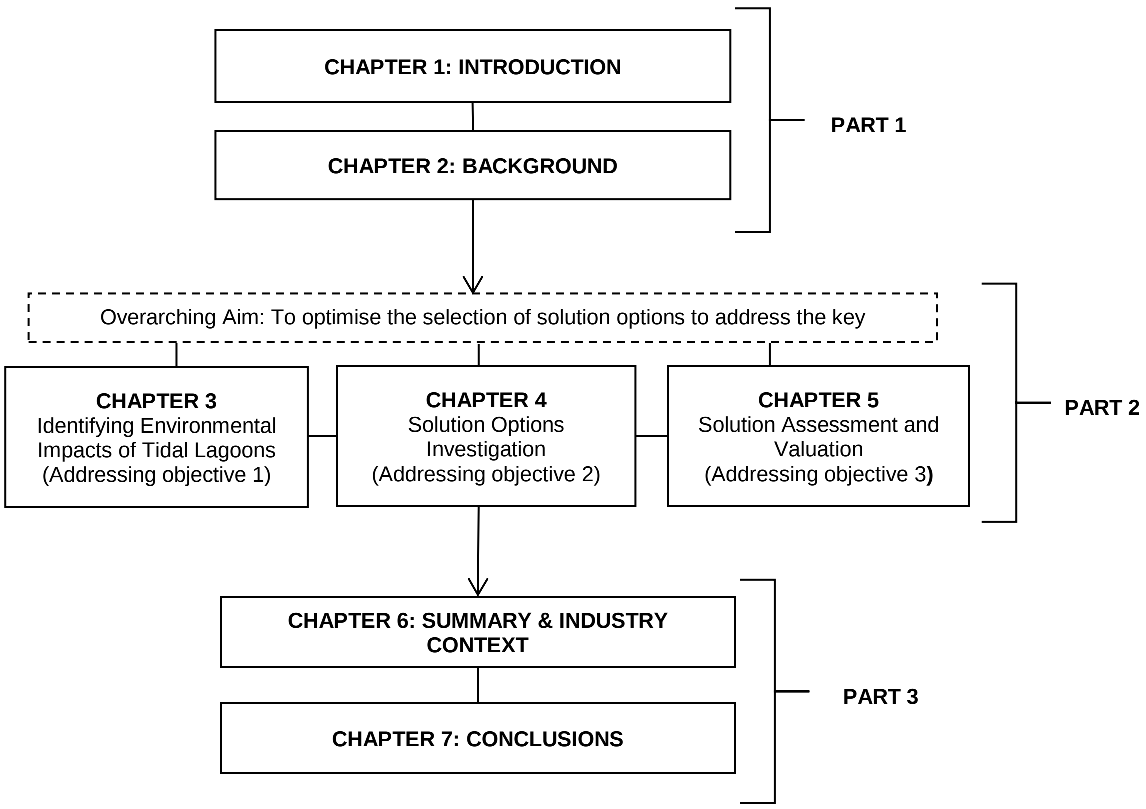


Figure 1 Thesis overview: seven chapters within three parts

2 Background

2.1 Introduction

This Chapter includes all the background theory necessary to understand the research. No new research or opinions are included in this section; the chapter contains only existing information collected from other literature resources. This includes an explanation of tidal theory, energy extraction from tides, a brief history of tidal range energy and consideration of the current ‘state of the art’. The Chapter also considers the UK’s tidal range energy potential, the opportunities and challenges facing lagoon development, how lagoons might be constructed and operated and an indication of what current relevant research is being undertaken.

2.2 Tidal Theory

In 1687 Sir Isaac Newton demonstrated that the tides were caused by the gravitational pull of the Earth, Moon and Sun as part of his law on universal gravitation [19]. This initial description of tidal theory in terms of orbital mechanics was a fundamental breakthrough in humanity’s understanding of the physical universe surrounding us.

Newton’s Law of Universal Gravitation explains that the gravitational force of any two bodies is a function of their masses and the distance between them; the greater the mass and the closer the objects are to each other the greater the gravitational attraction [1, 2]. The Earth and the Moon are held in mutual orbit by gravitational attraction. Gravitational forces combine with centrifugal forces on Earth to create the overall residual ‘tide-raising’ forces, as illustrated in Figure 2.

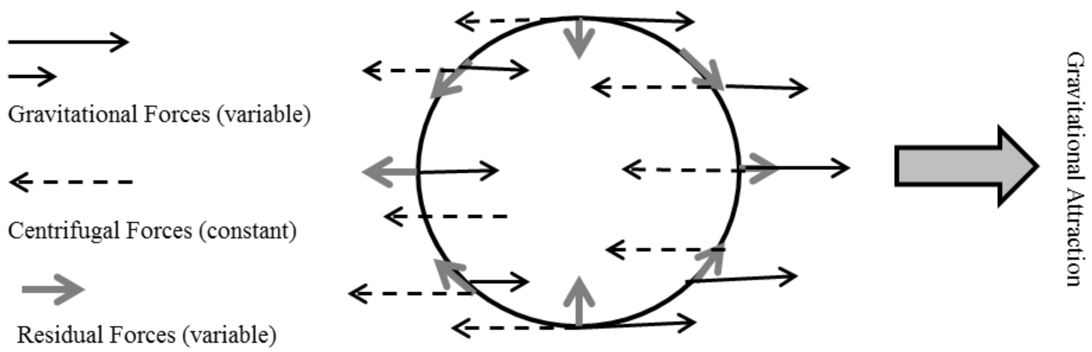


Figure 2 Gravitational, centrifugal and residual forces. Adapted from source: [2]

Assuming a completely round and smooth Earth's surface and an even layer of ocean we can imagine that two tidal 'bulges' would occur as a result of these residual forces, creating two high tides and two low tides around the Earth. The Earth-Sun system also generates similar gravitational forces but the Moon is closer to the Earth and so the strength of the lunar- related forces are greater, in accordance with Newton's law.

When the Moon and Sun are aligned with Earth their tidal effects reinforce each other to produce larger than average tides known as spring tides. Conversely, when the Sun and the Moon are at 90 degrees to each other they begin to cancel each other's effect and this configuration creates smaller tidal effects known as neap tides, as shown in Figure 3.

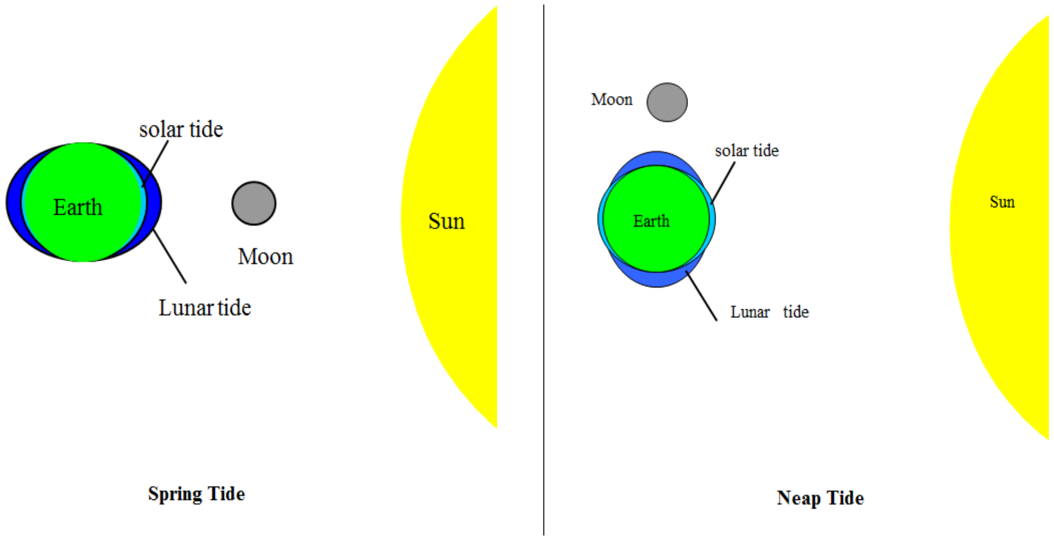


Figure 3 Demonstration of moon and sun configuration and resulting spring and neap tides

Figure 4 shows a typical example tidal cycle over a lunar month (approximately 30 days) [21]. The rotation of the Moon around the Earth, the alignment with the Sun and the Earth's own rotation typically creates two spring and two neap tides per lunar month.

The majority of the Earth's coastlines have two high tides and two low tides a day. When a coastline has two high and two low tides a day of approximately the same height this is known as semi-diurnal tide. If the two tides in a day differ significantly in height this is called a mixed semidiurnal tide. In some areas only one high tide and one low tide occurs each day, known as a diurnal tide, for example in the Gulf of Mexico. The differences in daily tidal profiles occur due to geographical location as a result of the Earth's axial tilt and continents blocking tidal bulges reaching a location as the earth rotates [22]. Figure 5 provides examples of differing tidal daily profiles [21]

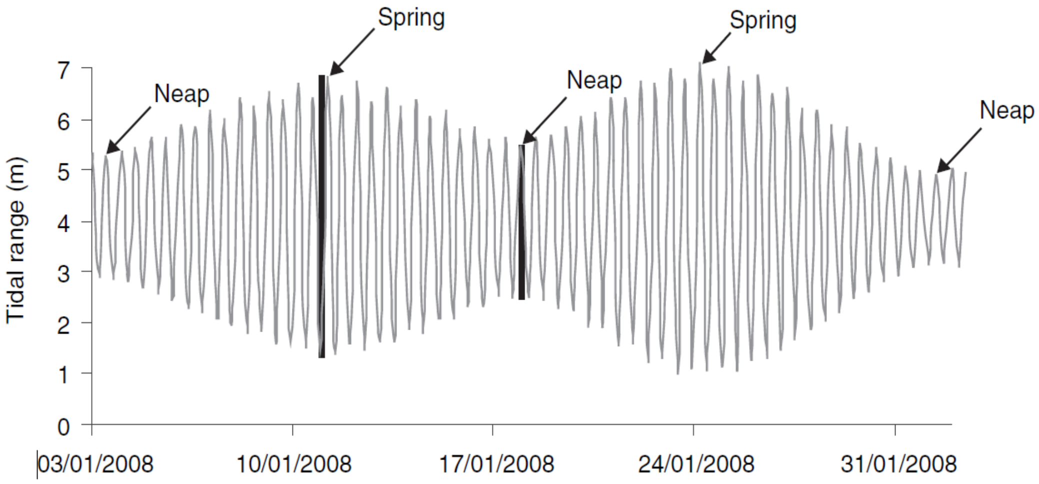


Figure 4 Example of typical 30-day tidal cycle. Source: [21]

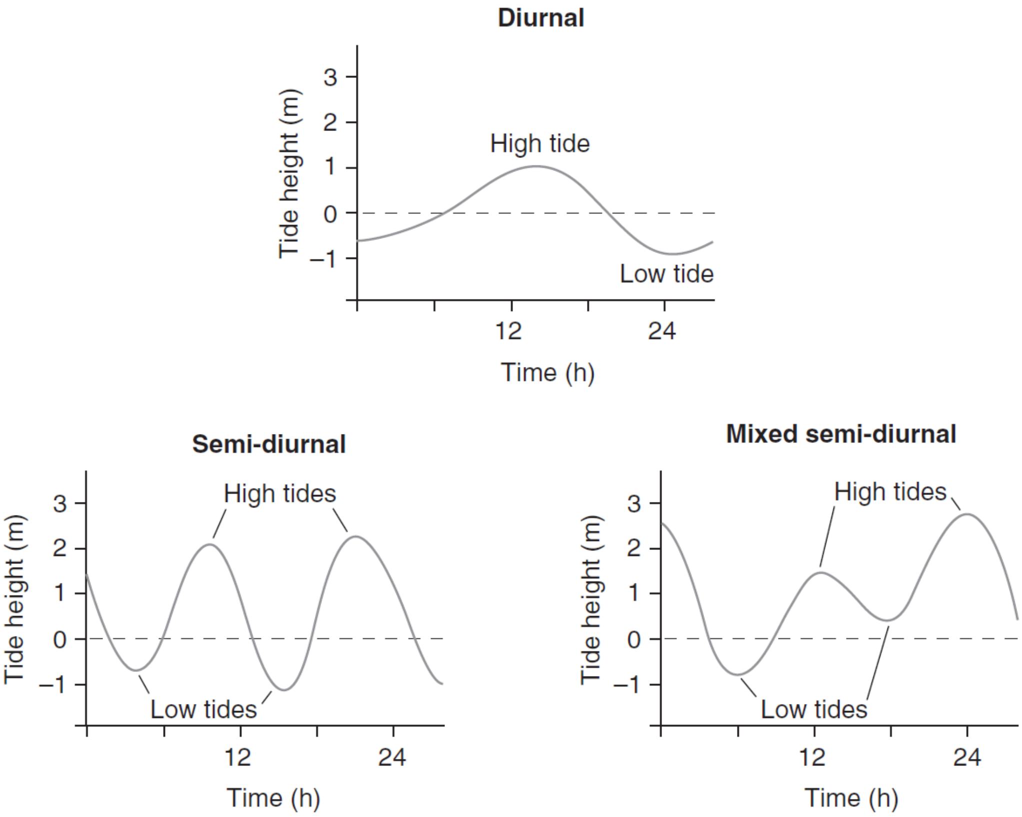


Figure 5 Example daily tidal profiles. Source: [21]

2.3 What is Tidal Range Energy?

An understanding of tidal theory allows us to consider the potential opportunity for extraction of energy from the tides. Energy from the tides is typically split into tidal stream energy and tidal range energy. Tidal range utilises the height difference between low and high tides at a given location, and converts the potential energy stored when a body of water is impounded. In contrast, tidal stream energy captures the movement of water horizontally with the ebb and flood of the tides. This research is concerned only with tidal range energy. Figure 6 shows a basic breakdown classification of marine energy and where tidal range sits within this.

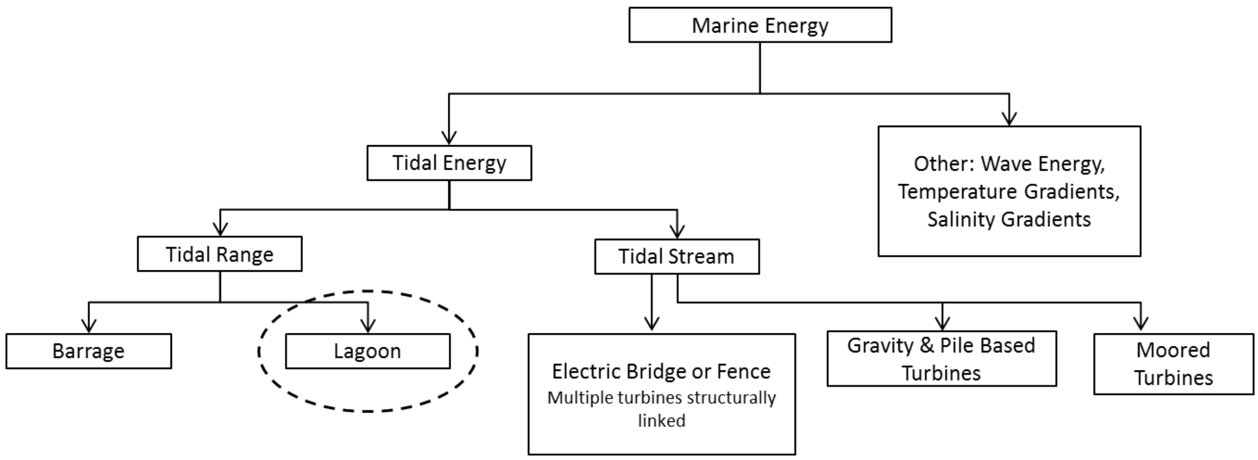


Figure 6 Basic classification of marine energy [110]

Tidal range technologies harness energy by impounding water behind walled structures. Tidal range energy traditionally refers to tidal barrages, but recent interest has focused on the potential development of tidal lagoons. A tidal barrage typically extends and blocks off the banks of a river or estuary, whilst a tidal lagoon forms either an enclosed area along one side of an estuary or can be a stand-alone structure completely offshore [23]. Figure 7 shows a basic sketch describing this difference.

Tidal range structures, such as barrages and lagoons, extract energy from the tides by creating an artificial height difference, or head. The kinetic energy from the flow of water down this height difference is then converted into electricity via turbines. This energy generation can be on an ebb tide, a flood tide or two-way, depending on how it is operated:

- **Ebb Generation**: Tidal power generated as water leaves the tidal basin on an ebb tide
- **Flood:** Tidal power generated as water enters, or floods, into the tidal basin on incoming tide
- **Two Way:** Tides generated on both ebb and flood tides

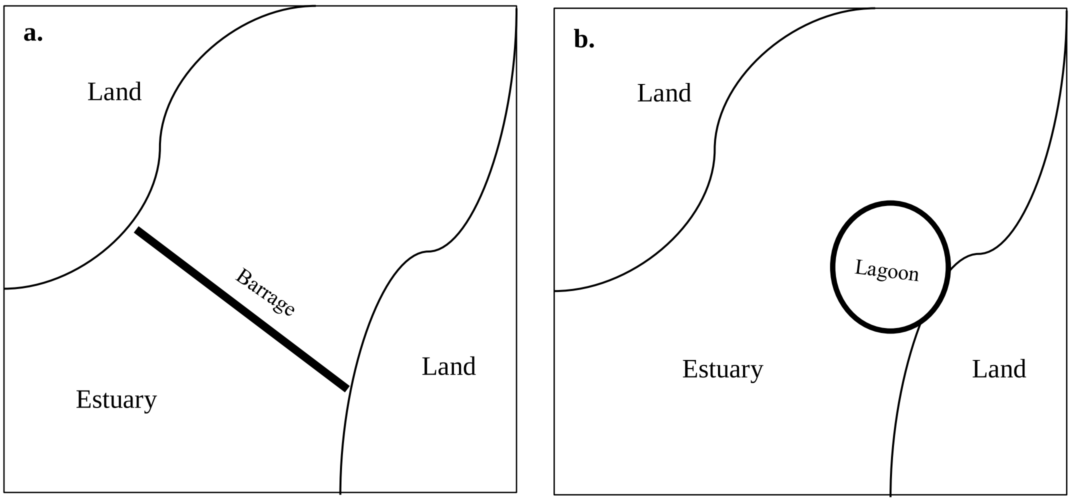


Figure 7 Basic birds eye view sketch of a barrage (a) and a lagoon (b) [126]

Figure 8 provides annotated diagrams of energy generation at ebb and flood tides [24]. Figure 9 provides a schematic graph of energy generation from an ebb tide [24]. A basic cross-sectional structural layout for an example lagoon wall and example turbine housing can be seen in Figure 10 and Figure 11 respectively.

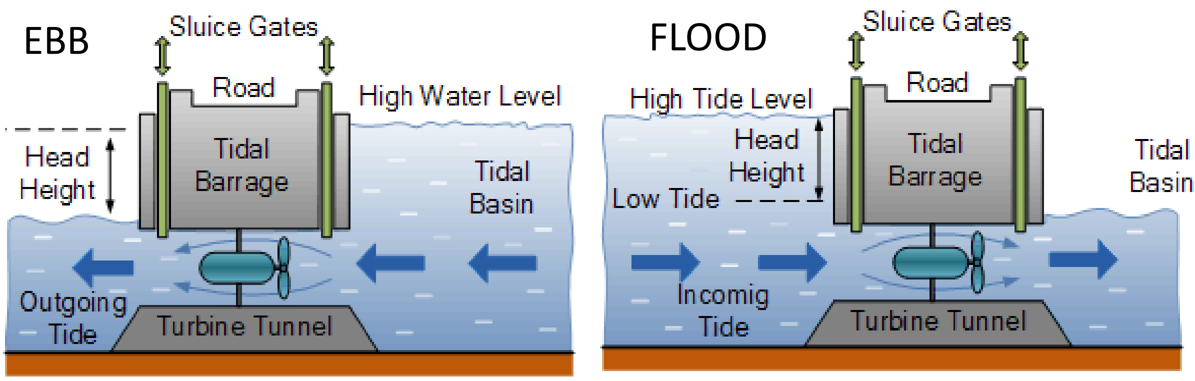
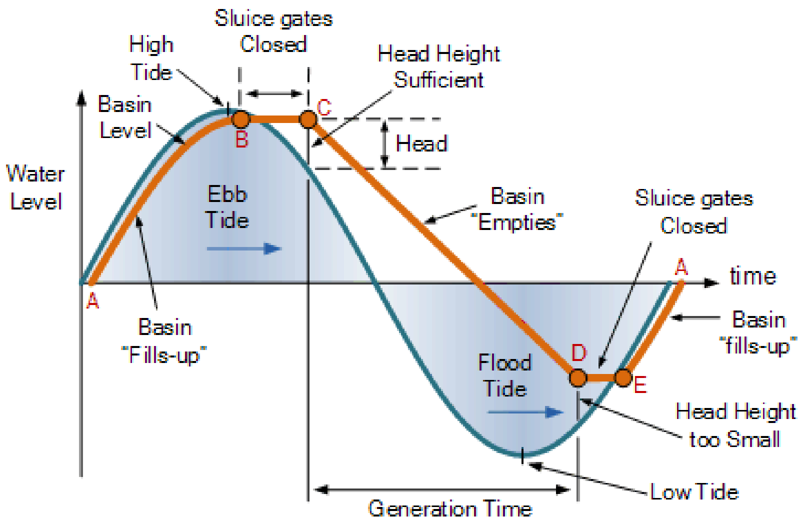


Figure 8 Ebb and flood tidal energy generation. Source: [23]

The potential power from tidal range structures is proportional to the height difference between the upper and lower water bodies (H) and the surface area of the contained water in the basin (A). With this in mind, the potential energy (E) can be calculated as in Equation 1, to include water density (ρ) and the acceleration due to gravity (g).

$$E = \frac{1}{2} A\rho g H^2 \qquad (1)$$



Between E, A and B: Basin fills on incoming tide
B: High tide is reached
B to C: Sluice gates close to trap water in the basin
C to D: As tide goes out (Ebb) a height difference occurs (Head), the gates open and energy is generated
D to E: No longer a head height difference available.

Figure 9 Ebb tide energy generation schematic graph. Source: [23]

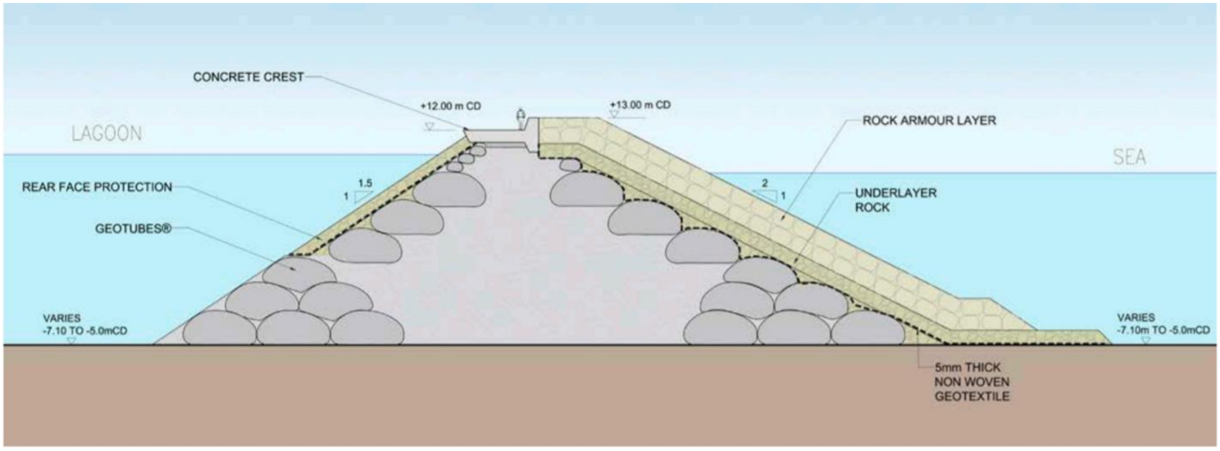


Figure 10 Cross section of example lagoon sea wall [6]

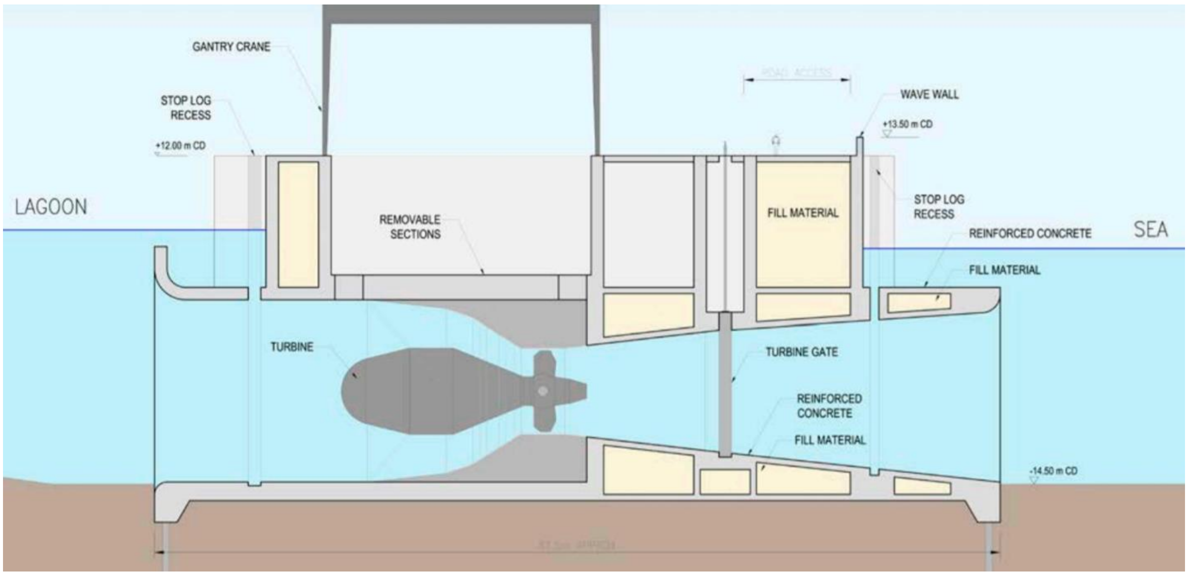


Figure 11 Cross section of example turbine housing for a tidal lagoon [6]

2.4 History of Tidal Range Energy

2.4.1 Flour to Electricity

Figure 12 shows a timeline of historical events in the tidal range energy industry. Harnessing power from the tides is not a new concept. The earliest evidence of using tidal power dates back to 600 AD [25]. The first strategies for harnessing tidal power included the impounding of rising tides by building basic dams or barrage structures, then releasing the water through a waterwheel, typically for grinding flour [25]. There is evidence of 'tide mills' that date back to the Middle Ages; the oldest known reference dates back to 619 AD (Nendrum Monastery, Northern Ireland) [26]. In the 18th Century it was estimated that 200 tidal mills were still operational in the UK [26]. One of the last working tide mills in the UK is Woodbridge, which is now a living museum [27,28]. Proposals for barrages for use as large shipping harbours, transport links and flood protection schemes began in the 19th Century [26]. Despite early proposals serious investigation into large scale projects only began in the early 20th century with the first considerations of tidal barrages for electricity production being put forward around 1925 [26] [29].

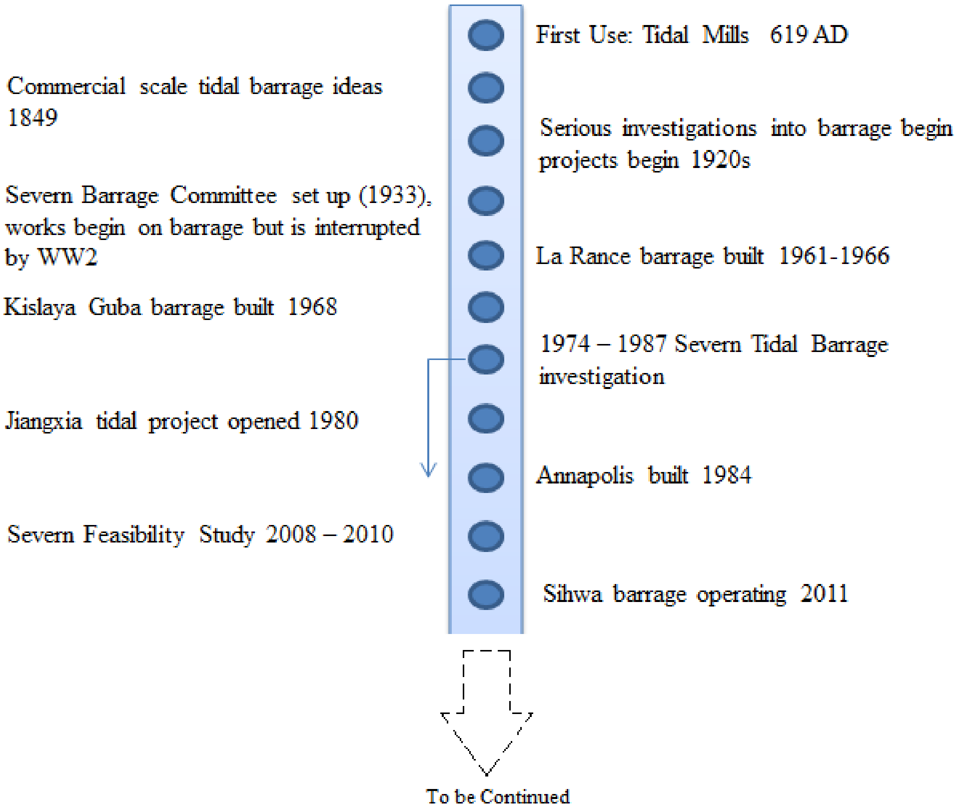


Figure 12 Tidal energy historical timeline

2.4.2 Existing Projects

2.4.2.1 La Rance

La Rance tidal power barrage, completed in 1966 near St Malo, France (240 MW), was the first commercial scale tidal electricity project to be completed (Table 1). This large modern-era project replaced the waterwheel and used bulb-type hydroelectric turbines [25,26]. Stretching 750m across the Rance River in Brittany it completely blocks the channel [30]. Since its construction and operation, the key environmental impacts have been changes to the sediment regime, with around 30,000m^3 of silt added to the marine basin each year [31]. This is thought to be caused by an increase in slack water times and therefore reduced current [31]. As a result La Rance, still operational today, has an intensive mechanical dredging strategy for sediment removal particularly in areas of the channel still used for navigation [32].

2.4.2.2 Annapolis

The first tidal range project in North America was built in 1984 in the form of the 20 MW Annapolis project in Nova Scotia, Canada (Table 1). The project is located in the Bay of Fundy and Annapolis River [33]. The key environmental concerns associated with this project include the increase in erosion upstream and downstream due to significant changes to the water flow. In addition the project is known as a potential 'marine life trap' with two notable cases of humpback whales being trapped in the upper river section behind the barrage walled structure [33].

2.4.2.3 Sihwa

The Sihwa barrage in South Korea was converted to tidal range operation in 2011/12 making it the world's largest tidal power station to date at 254 MW (Table 1). Sihwa was originally built as dam in 1984 [34]. The dam blocked the natural flow of the river and altered the sediment regime. The changes in sediment regime resulted in significant deterioration of the water quality, including excess plankton growth (aka eutrophication) [35]. In 2011, retrofitted tidal turbines were installed into the dam once again allowing the passage of water through the structure. This reinstated the flow of water, improving the sediment regime and water quality whilst generating renewable electrical energy, changing its status from a dam to a tidal barrage [36].

2.4.2.4 Small Scale Examples

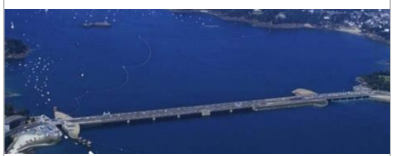
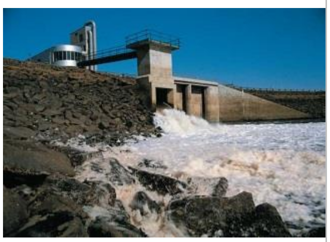
There has been several smaller projects such as the Kislaya Guba 1.7 MW plant in Russia opening in 1968 and the Jiangxia 3.2 MW tidal range project opening in 1980 in China, which was the first tidal range project in Asia.

2.4.2.5 Severn Estuary

The earliest large scale proposals in the UK are linked to those for the Severn Estuary [18]. The Severn Estuary, located in South West UK, is a key focus site for tidal range energy due to its significant tidal range resource (see Section 2.5 Potential for UK Tidal Lagoons for more details). Thomas Fulijames initially proposed a Severn Barrage in 1849 for use as a large shipping harbour, transport link and flood protection scheme [26]. A Severn Barrage committee was set up in 1933 chaired by Lord Brabazon and as a result work on determining barrage feasibility began. However this work was interrupted by WW2 and that particular project never re-started [26]. The Severn Tidal Barrage proposal for a 8.6 GW barrage from Wales to England was then investigated for 13 years between 1974 and 1987 but was eventually shelved again, this time due to economic and environmental concerns.

In 2008 a cross-government group led by, what was then known as, the Department of Energy And Climate Change (DECC) initiated another feasibility study into Severn Tidal Power within the Severn Estuary [37,38]. In 2010, the government concluded that they did not see a strategic case for tidal power in the Severn in the immediate term due to significant cost risks to the tax payer [37]. This feasibility study also produced a Strategic Environmental Assessment (SEA) of tidal power in the Severn Estuary which concluded that a key barrier to tidal range development would be regulatory concerns and the uncertainty surrounding environmental impacts and the associated costs of mitigation [39].

Table 1 Overview of the largest commercial scale tidal energy projects in the world

Project	La Rance	Annapolis	Sihwa
Built	1961-1966	1980-1984	2003-2012
Opened	29th November 1966	1984	2011
Location	Brittany, France	Annapolis, Nova Scotia	Ansan city, Korea
Capacity	240 MW (10 turbines)	20 MW	254 MW (10 turbines)
Length	750m	46.5m	12.7km
Operation	50 years (unbroken)	34 years	7 years
Tourism	70,000 visitors/year	40,000 visitors/year	-
Electricity	540 GWh/year	50 GWh/year	552.7 GWh/year
References	[18,26,30]	[33,40–42]	[43]
Image (see references above for source)			

2.5 Potential for UK Tidal Lagoons

Since the Severn Estuary Tidal Barrage investigations, there has been a reduced focus on tidal barrages for UK development. This has been largely down to the increasing awareness of the environmental impacts related to the existing tidal barrages around the world. The environmental impacts such as sediment regime changes and damage to wetland habitats have been a noticeable concern and are often directly linked to a barrage blocking the flow of a river or estuary. Whilst research still continues on tidal barrages, key literature has suggested that tidal lagoons could be a potential alternative tidal range energy option for the UK [17]. Recent developments in the UK tidal range energy industry have shown a shift in focus from tidal barrages to tidal lagoons [18].

In 2012 the Crown Estate and Black & Veatch published a study reviewing the UK's wave and tidal energy sources [44]. This study identified significant potential for tidal lagoons in the waters around the UK. Figure 13 shows the overall tidal resource range around the UK [18], with **Error! Reference source not found.** showing identified possible lagoon locations based on mean tidal range of around 4m and suitable water depths below mean sea level (25m) [44].

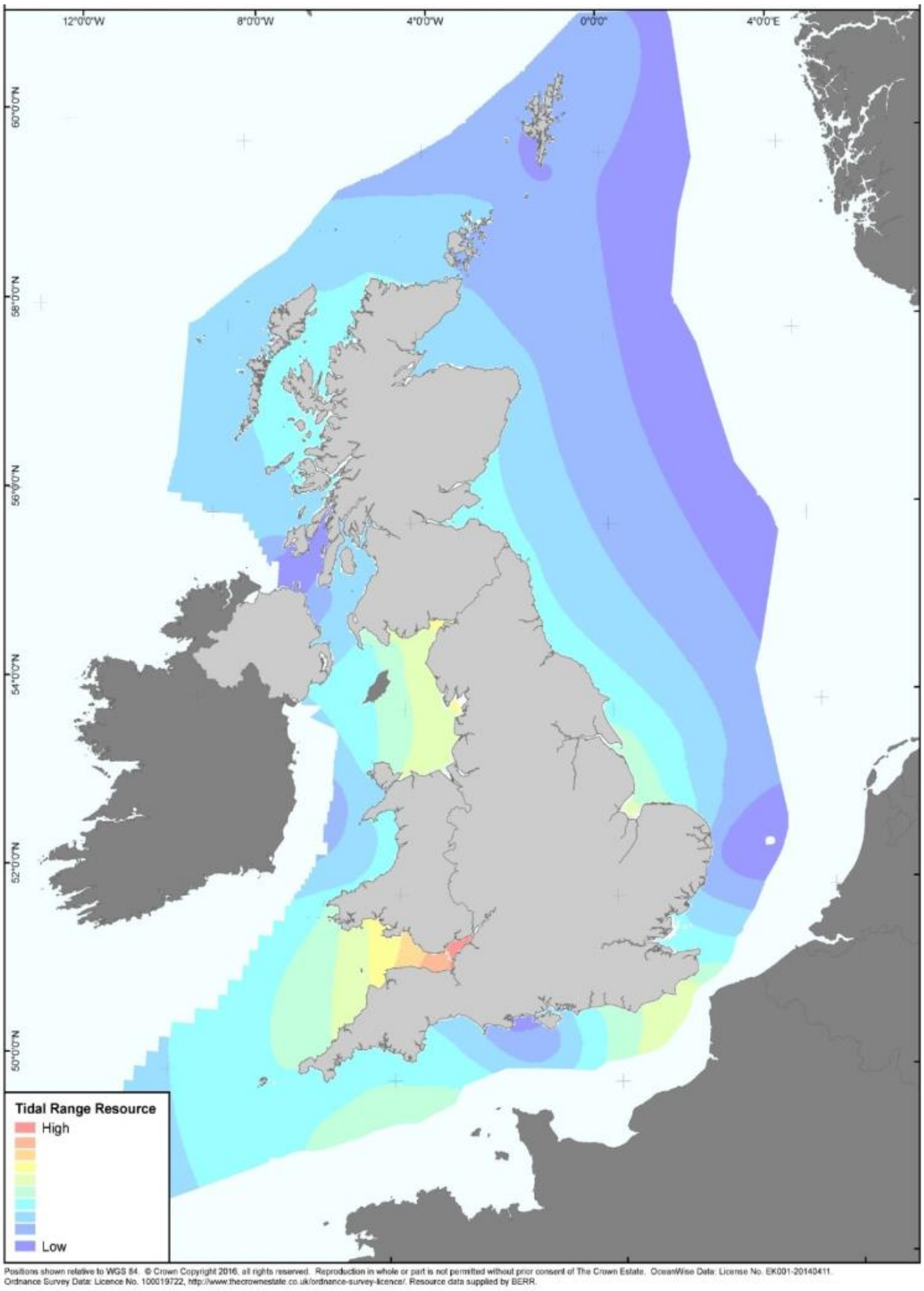


Figure 13 Tidal range resource UK [44]

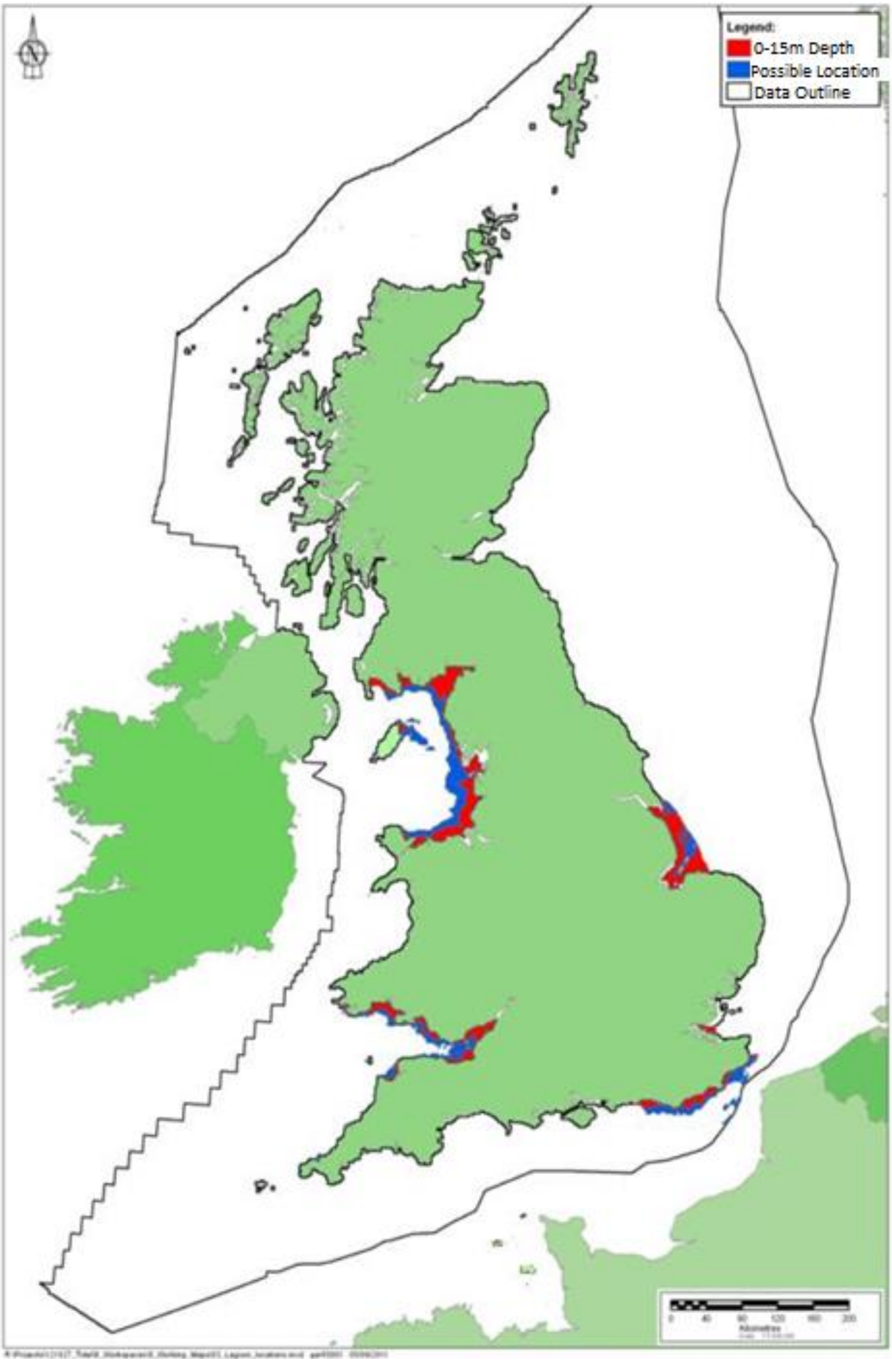


Figure 14 Potential identified tidal lagoon locations [44]

Table 2 provides a summary of known potential barrage or lagoon locations in the UK, including nine estuary locations. Table 2 includes estuaries that have the potential for installed capacity greater than 100 MW and a mean tidal range around 4m. More information on previous barrage plans in the UK can be found in a review undertaken by Baker in 1991 [45].

Table 2 Potential sites for tidal range projects in the UK. Sites in order of tidal range potential and include nine estuaries (in bold). Information sourced: [44]

Location	Mean tidal range (m)
Severn Cardiff - Weston	7.8
Severn Outer	7.2
Solway Firth	5.6
Morecambe Bay	6.3
Wash	4.7
Humber	4.1
Thames	4.2
Dee	6
Mersey	6.5
Duddon	5.8
Stangford Lough	3.1
Milford Haven	4.5
Ribble	6.1
Wyre	6.6
Cromarty Firth	2.8
Conwy	5.2
Loch Broom	3.2
Padstow	4.8
Loch Etive	2
Langstone Harbour	3.1
Hamford Water	3
Dovey	2.9
Loughor	3.9

These studies suggest that the majority of the UK's practical tidal range energy resource is in the Severn Estuary; it is no surprise then that the focus of tidal energy project studies in the past has been around the Severn (Section: 2.4 History of Tidal Energy). The Severn estuary is bordered by South West Wales and South West England. It is surrounded by a number of large cities, many of which host major port facilities including Swansea, Cardiff, Newport, Bristol and Bridgewater (Figure 15) [39].

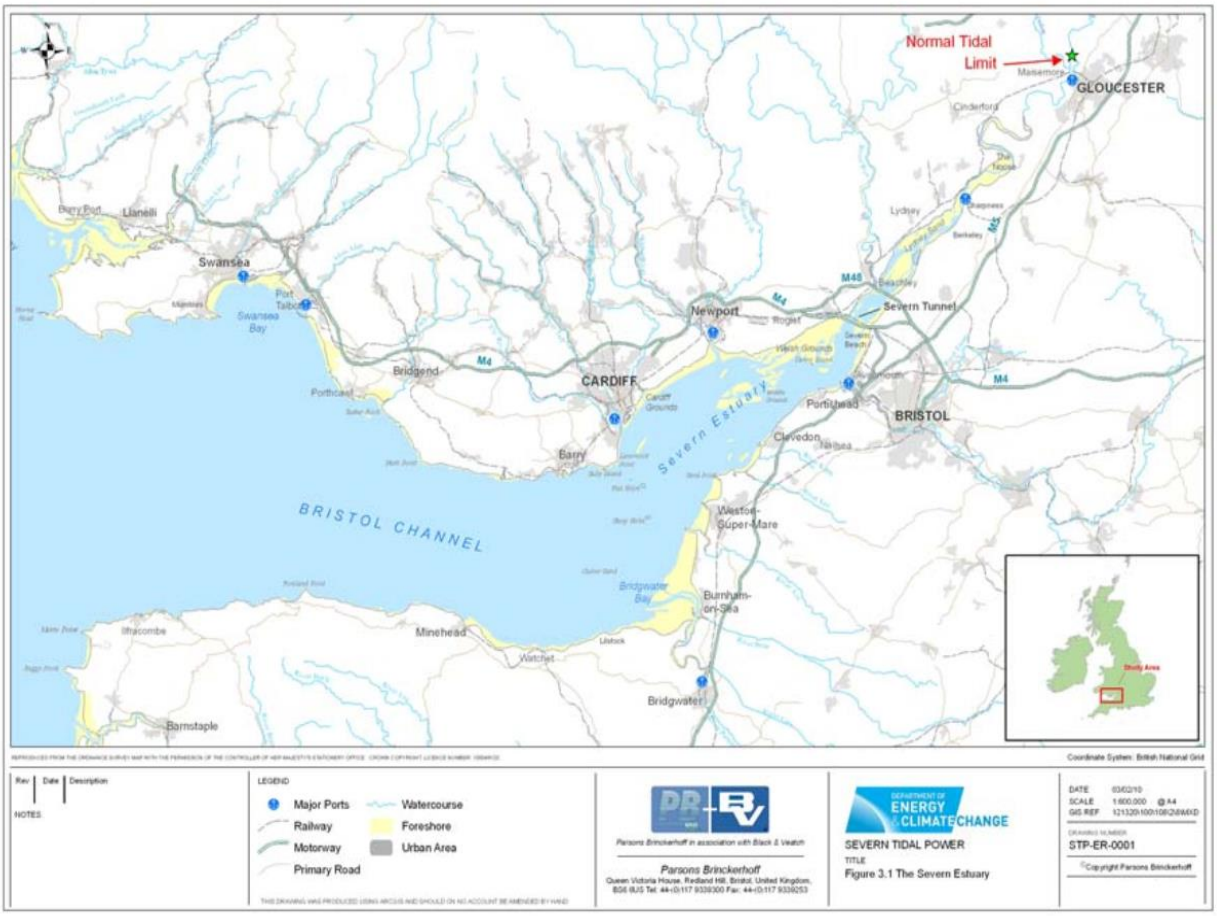


Figure 15 Severn Estuary map [39]

Tidal lagoons have the potential to contribute significantly to the UK energy mix. Tidal range schemes, including both barrages and lagoons, have a theoretical resource potential of 121 TWh/year in the UK [44]. To put this into perspective, in 2015 the UK produced 339 TWh of electricity [46]. In theory, although not necessarily in practice, tidal range schemes could contribute up to 36% of the UK's electricity production, with lagoons contributing 7.4%, of that figure. An industrial estimate for a fleet of UK lagoons is a contribution of up to 8% of the UK's electricity supply [9].

In addition to significant resource potential for energy generation lagoons also have many other key advantages over other renewable energy technologies which justify the further investigation into their feasibility. The key advantages include:

- A long expected life span (120 years) [8,18,47]

- Potential large scale energy extraction [5,6,18,45]

- Predictable supply of energy (predictably intermittent) [5,6,47,48]

- Potential to phase shift energy with lagoons located at different phases of the tide to allow for continual baseload supply [5,8]

- Use of already developed technology (sea walls, turbines) in a new application – reduced uncertainty surrounding technology readiness etc [18]

- Strong scope for enhancing existing UK supply chains [7,18,49].

2.6 Tidal Lagoon State of the Art

There is currently no man-made, energy generating tidal lagoons in the world. The first serious talks surrounding tidal lagoon projects have arisen in the last decade and this industry has been forming primarily in the UK to date. TLP's proposal for a pilot scale tidal lagoon at Swansea Bay in Wales was the first to gain traction in the industry after a formal application for planning was submitted by TLP in 2012. This has recently been rejected by the government based on cost concerns. See Section 2.6.1 for more information on Swansea Bay Lagoon (SBL).

In the last 4 years there have been major developments in the tidal lagoon industry in the UK, as shown in a summary of recent developments in Figure 16. The first strong positive signal for the industry was the accepting of the DCO for SBL. Following TLP's initial proposal for SBL they then announced plans for a fleet of lagoons around the UK, pushing forward with this concept by submitting another planning application, this time for a larger full-scale lagoon at Cardiff Bay, the Cardiff Bay Lagoon (CBL).

Following a backlash of concerns on the lack of investigation into tidal lagoons following TLP's lagoon fleet proposals the government announced a review on the feasibility of tidal lagoons for the UK energy market in 2016. Charles Hendry was appointed to lead this review and reported the results in 2017 in the 'Hendry Review' [18]. The results reflected favourably on the UK tidal lagoon industry and recommended a pilot lagoon project progress with careful environmental monitoring. See section 2.6.2 for a summary of the relevant findings from the Hendry Review. The long government delay of response to the Hendry Review and subsequent rejection of SBL puts pressure on existing lagoon companies like TLP to continue a programme of works, without confirmed government backing for any of the lagoon projects. Whilst there are indications of deals being made with the UK and Welsh governments [50], the general expectation is now of UK government rejection of funding for lagoons with the Welsh Government working towards securing alternative sources of funding for the SBL [51].

In September 2017, the CBL secured a grid connection, kick starting the progression for the full-scale lagoon. Whilst TLP with Swansea Bay and Cardiff Bay lagoons is at the forefront of minds when considering the tidal lagoon industry in the UK, there are a number of other developers with lagoon plans and relevant tidal range technologies. Table 3 shows the developers currently active in the UK tidal range industry and their key project plans or technology if applicable.

2.6.1 Swansea Bay Lagoon

TLP's pilot project SBL was expected to be 320MW capacity, generating 530GWh of energy per year [47]. This was expected to power 155,000 homes for the lifetime of the lagoon (120 years) [47]. The lagoon was designed with 16 turbines and a 9.5km breakwater wall, forming a U-shape, connected to shore at Swansea Bay, allowing for a lagoon surface area of 11.5km^2 [47].

The construction and manufacturing of the lagoon was expected to create 2232 jobs and equate to carbon savings of 236,000 tonnes carbon equivalents per year [47]. The expected benefits and opportunities that TLP are proposed for SBL include area regeneration, tourism and recreation (100,000 visitors a year), and Integrated Multi-Trophic Aquaculture (IMTA) [47]. This proposal was awarded a development consent order in 2015 [6], was investigated as part of the Hendry review [18] and has recently been rejected by the UK government based on cost concerns [52]. TLP have submitted a rebuttal to government statements [15] and the Welsh government is considering alternative funding for the lagoon. This is discussed further in the industry context and summary Chapter 6.

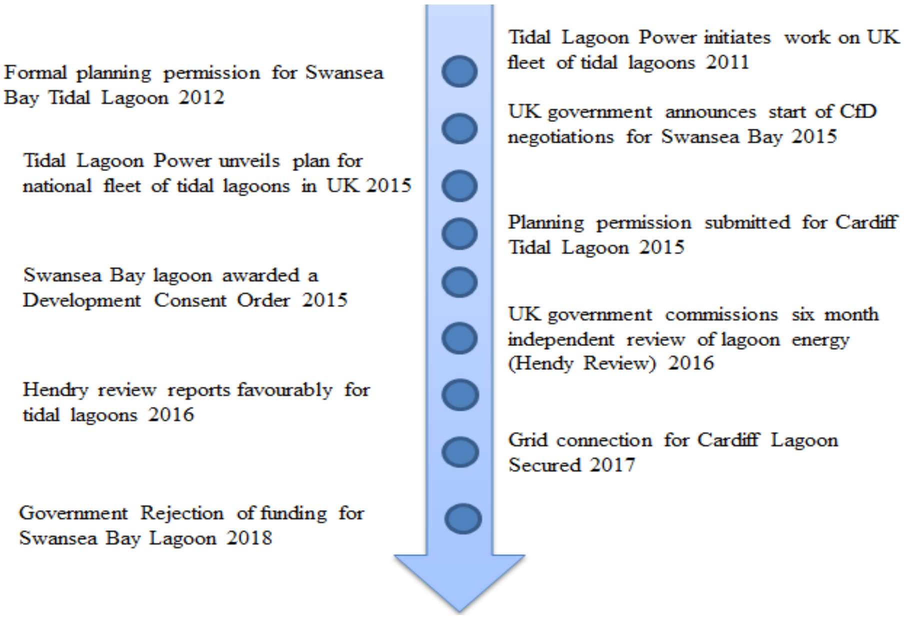


Figure 16 Summary timeline of recent developments in the lagoon sector (continued from Historical Timeline Figure 12)

Table 3 Table showing the developers currently active in the UK tidal range industry

Developer	Projects Name/Location	Type	Project Stage	Capacity	References
Tidal Lagoon Power (TLP)	Swansea	Lagoon	UK Government rejection of project funding	320 MW	[47]
	Cardiff	Lagoon	Grid connection obtained. Planning application submitted	3 GW	[49]
	Newport	Lagoon	Planned	1.4 to 1.8 GW	[53]
	Colwyn	Lagoon	Planned	n/a	[54]
	West Cumbria	Lagoon	Planned	n/a	[55]
	Bridgewater Bay	Lagoon	Planned	n/a	[56]
North Wales Tidal Energy (NWTE)	North Wales	Lagoon	Planned	n/a	[57]
North West Energy Squared (NWE^2)	Morecambe bay	Barrages	Planned	5 GW	[58,59]
Solway Energy Gateway	Solway Electric Bridge	Electric bridge	Planned	100 MW	[60]
Natural Energy Wyre (NEW) (Previously: Wyre Tidal Energy)	Wyre, Fleetwood	Barrage	Planned	120 MW	[61]
Ecotricity	Various n/a	Lagoon	Planned	Range 0.36 to 0.9 GW	[62]
LongBay SeaPower	West Somerset	Lagoon	Planned	1.5 to 4.5 GW	[63]
Tidal Electric Ltd	Scotland	Offshore lagoon	Planned	0.2 GW	[64]
VerdErg (turbines)	VETT turbines for lagoon application	Mixed	Pilot scale applications (rivers)	n/a	[65]

2.6.2 Summary of Hendry Review

The final independent review of tidal lagoon feasibility for the UK, led by Charles Hendry, was published on 12th January 2017 and is also known as the "Hendry Review". Its main aim was to assess the strategic case for tidal lagoons and the role they could potentially play in the UK's energy mix. The full report [18] along with a summary [66] was published. This section provides a further summary of the main points from the review which are relevant to this research. The key outcomes were:

- Tidal lagoons would deliver security of supply, assist in decarbonisation commitments, provide opportunities for the UK supply chain and allow the UK to become a global leader in the industry

- Tidal lagoon impact on consumer bills is attractive when compared to nuclear projects over a long period of time. Tidal lagoons can play a competitive role in the UK's energy mix in terms of CfD cost per MWh

- There is a strong case for a pathfinder project (<500MW) as soon as reasonably practicable

- Lagoons will require a high level of on-going monitoring of environmental impacts to ensure appropriate mitigation can be put in place

- Developers should be required to demonstrate that they have taken into account the potential for sediment deposition rates in the planning and consenting process

- Tidal lagoons would certainly bring wider benefits beyond those of power generation, but these are very site specific, hard to quantify and unlikely to make significant contribution to capital expenditure (CAPEX)

- An analysis on purely economic aspects inevitably overlooks the wider benefits of a tidal lagoon programme and ultimately the decision for tidal lagoons in the UK is a strategic decision, every bit as much as an economic decision

- Recommended that allocation of development of lagoons for specific sites will be by competitive tender; this will allow these large and complex projects greater flexibility to reflect other desirable aspects of a project such as flood protection, regeneration and tourism.

Overall the review was positive for the industry, stating that lagoons will be cost effective for the UK tax payer, will provide a number of additional wider benefits and are in line with the government's energy and climate commitments. The review recognised the importance of the wider implications of tidal lagoons and the need for these to be taken into account in the selection of future developments.

The review included a recommendation for competitive tender in the future to allow flexibility for the wider benefits to be accounted for when comparing new development options for a site. The review also stated the need for ongoing environmental monitoring and research with a particular focus highlighted on sediment deposition rates and wider environmental benefits. The review stated that lagoons could not be a purely economic decision but a strategic decision that considered the wider implications. This recommendation was based on the large and complex nature of lagoon developments and their potential for far reaching economic and environmental risks and opportunities.

2.6.3 Industry Challenges

It is now clear how lagoons have become a focus in the tidal range industry in the UK. They have a number of benefits over other low carbon technologies, could significantly contribute towards renewable electricity and low carbon energy targets both nationally and internationally and are a natural next-step-on from historical tidal barrage developments. Despite these advantages there are still a number of concerns. The main barriers to the development of the tidal lagoon industry have previously been: a) Lack of serious proposals, b) High capital costs and, c) Regulatory environmental concerns. Recent developments in the industry have seen serious proposals put forward in the form of TLP's Swansea Bay and Cardiff Bay lagoons (addressing point a). Whilst there are still political issues surrounding a UK government deal for tidal lagoons, high capital costs and costs to the tax payer, these are being well researched as part of the Hendry review and ongoing battle with TLP and the UK government (point b). The remaining, relatively unexplored challenge for the industry is now to overcome the uncertainty surrounding tidal lagoon environmental impacts and regulatory concerns (point c).

Lagoons, like other renewables, have an overarching environmental benefit in displacing fossil fuels and therefore combatting climate change. This is a globally important benefit and care needs to be taken in order not to overshadow this positive impact with damaging local and regional environmental negatives. These local and regional impacts are at the forefront of minds as a result of the environmental impacts seen in existing tidal barrage developments and the previous outcomes of feasibility studies for tidal range energy developments in the Severn Estuary. Tidal lagoons are seen as a more sustainable option compared to tidal barrages, but this does not mean their environmental impacts can be overlooked. Tidal lagoons are expected to be located in unique habitats that arise as a result of high tidal ranges such as estuaries. In the UK for example the Severn Estuary is a feasible site in terms of tidal energy resource, but is also known for its many environmental designations, see Figure 17 [67].

It is of particular importance that the first tidal lagoon in the world sets precedence in addressing its environmental impacts in order to allow for the sustainable development of a tidal lagoon industry in the future. Recent developments in the sector mean it is now vital to investigate the environmental impacts of tidal lagoons. Tidal lagoons will have environmental impacts; the challenge is to determine how negative impacts can be reduced and positive impacts enhanced to allow environmental net gain to be achieved over and above that which is required for environmental regulations. In order to achieve environmental net gain the environmental impacts of tidal lagoons need to be better understood. Potential solution options to address negative environmental impacts need to be sought and methods to assess the applicability of these solutions investigated. Managing the uncertainty in planning and implementing the world's first tidal lagoon is critical; any research into lagoon environmental impacts at this stage in the industry's development will help manage that uncertainty. Reduced uncertainty will reduce regulatory concern and increase investor confidence, further pushing the industry forward.

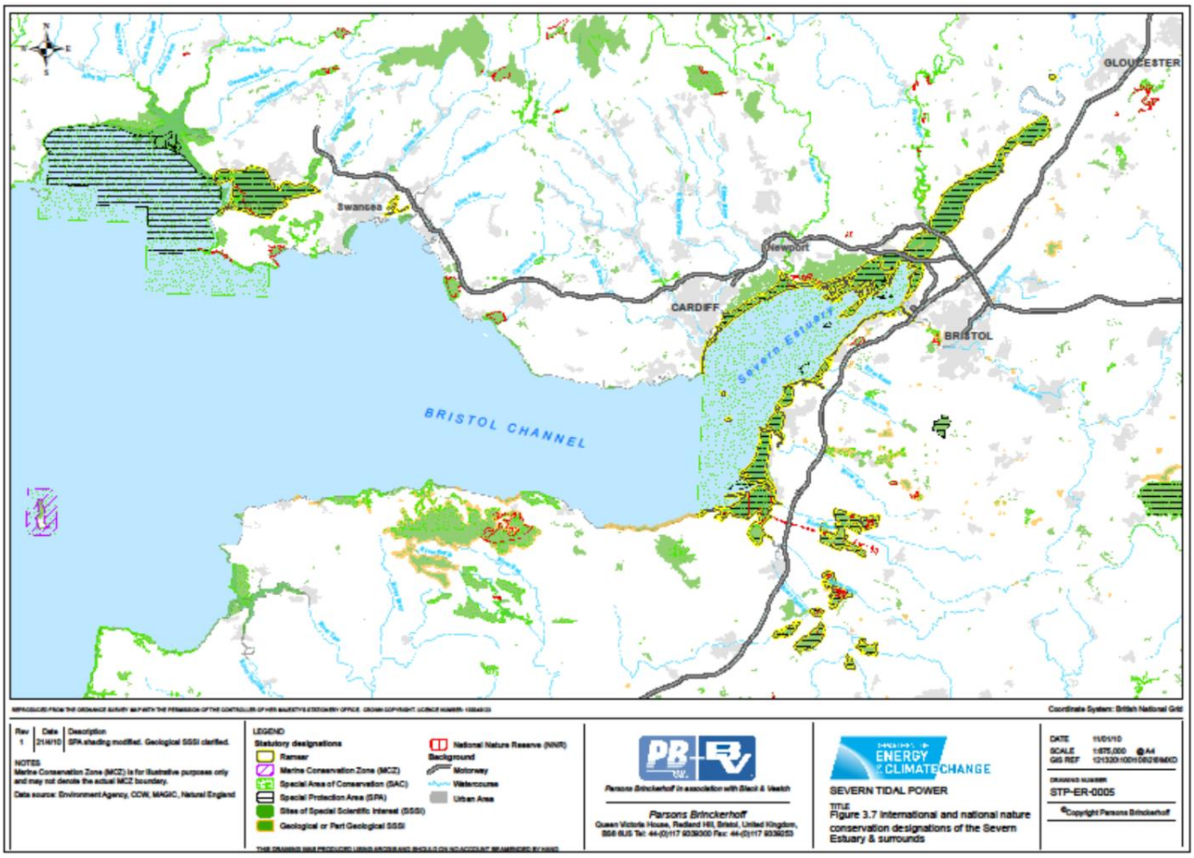


Figure 17 Environmental designations on the Severn Estuary [67]

2.6.4 A Place for this Research

The environmental impacts of tidal range schemes are well documented, including impacts such as hydrodynamics [68–73], morphodynamics [74,75], water quality [76,77], and ecological and social impacts [17]. Research focusing on tidal lagoons specifically is also recently well documented, in terms of either focus on individual environmental impacts e.g. hydrodynamic changes only, providing review of feasibility, technology or energy generation estimates, and developer site environmental investigation documents [78–85]. There is no existing research that holistically investigates the variety of environmental impacts associated specifically with tidal lagoons, considering both the positive and negative impacts, the wider indirect implications and the potential for environmental net gain. This presents an industry knowledge gap. The first key objective of this research is to: *Identify the key impacts of tidal lagoons.* This will be done through literature review and extensive industry engagement.

There are no tidal lagoons in the world, therefore there is no operational data on the environmental impacts to be addressed, let alone monitoring of different solution options to analyse mitigation efficiency and success. However, the technology and engineering concepts used in tidal lagoons are not new and have been applied in other industries with similar environmental impacts to those expected of tidal lagoons. There is a vast amount of transferable knowledge embedded within other sectors which is yet to be drawn out for application in the lagoon industry. The second objective of this research is to: *Determine solution options to the key impacts of tidal lagoons.* This will include a systematic literature review of transferrable solution options from other relevant industries to address the environmental impacts expected to arise as a result of tidal lagoons.

When considering selection of environmental solution options for application in marine projects, developers often use standard parameters such as cost of solution, likely success, development stage of the solution and uncertainty surrounding it. An approach that is currently being used in other industries for large projects is Ecosystem Service Assessments and Valuations as part of economic appraisals for projects. The final objective of this project is to: *Assess and value solution option combinations for addressing the key impacts of tidal lagoons.* This will include a comparison of a 'traditional' solution selection method (multi-criteria decision analysis MCDA) with a 'less-traditional' method using ecosystem service approach as part of a Cost Benefit Analysis (CBA).

2.6.5 Solution Assessment Research Tools: Brief Background

Multi criteria decision analysis (MCDA) is a tool often used in the sustainable development sector, it is popular due to its ability to consider multi-dimensional criteria in complex projects [86]. The tool helps guide a decision or preference in complex projects and is therefore popular in renewable energy developments where multi-discipline factors or stakeholders need to be considered. MCDA allows selection of a few criteria which are deemed vital contributing factors to a particular decision, these criteria are then assigned values based on individual judgement of the potential alterative options [87,88].

This process allows consideration of several criteria which would otherwise be incomparable, such as uncertainty, cost, likely success, development stage etc. It is often used to decide the most attractive options or scenarios for developments as it provides methodology which is repeatable and easily adapted to potential updates in criteria or weightings [89]. A relevant example use of an MCDA is as a tool for marine energy development planning recently developed for tidal stream arrays, in which the author considers location, cost, energy produced and social acceptance criteria [90]. MCDA can incorporate ecosystem services as part of the decision criteria or these can be considered separately through a dedicated ecosystem service approach.

Ecosystem services (EsS) are the 'goods and services provided to people by the environment' [91], the 'benefits provided by ecosystems that contribute to making human life possible and worth living' [92]. The Millennium Ecosystem Assessment defined ecosystem services into broad categories of provisioning services (i.e. fuel, food, timber), regulating services (i.e. carbon regulation, air quality regulation), supporting services (i.e. photosynthesis, nutrient cycling) and cultural services (i.e. recreation, inspiration for art) [93], this has been expended further into more detailed divisions by the European Environment Agency in the Common International Classification for Ecosystem Services (CICES) [94]. The concept of EsS is not only academic, there has been recent rise in the use of this term in the business world, linked with natural capital and the requirement for social responsibility.

The ecosystem service approach is a key element of planning and sustainable development and is a primary framework arising from the United Nations Convention of Biological Diversity [91]. The UK has a national level study which provides ecosystem services relating to different habitats and other related guidance, the UK National Ecosystem Assessment (UKNEA) [95,96]. It is increasingly becoming recognised that a wider ecosystem service approach to sustainable energy development is required [97–102], particularly in projects such as lagoons which are likely to be multi-disciplinary. The ecosystem service approach allows for the link to be made between environmental impacts and the translation of those impacts on the goods and services provided to society, or the impact on society. The approach can be the link between EIA's and socio-economic assessments [100]. It ensures that an assessment is inclusive of socio-economic impacts relating to the environment and is a methodology to allow a holistic, 'whole systems' approach. This is crucial in allowing outputs from environmental impact assessments to be communicated in societally relevant formats [100].

The ecosystem service approach documents the ecosystem services received from the marine environment and then investigates how these services change because of implementation of a particular development or technology, in this research that is lagoon solution options, an example of other application is the impact of offshore wind energy on ecosystem services [103]. The marginal change to ecosystem services is first described, then quantified if possible and monetised if proportionate and relevant to do so. The descriptive aspect is known as an ecosystem service assessment (ESA), the valuation or monetisation aspect known as an ecosystem service valuation (ESV). Aggregating these monetary values, both positive and negative over a discounted period of time is referred to in this research as a cost benefit analysis (CBA) and will be a CBA of the changes (+ and -) to the ecosystem services only.

2.7 Chapter Summary

This background chapter explains the relevant tidal theory, discusses the key differences between tidal range and tidal stream energy and how tidal lagoons fit within the marine energy industry classification. A history of tidal range energy is reviewed to include tidal barrages and the events leading up to the recent focus on tidal lagoons. The UK potential for tidal lagoons is also reviewed and current 'state of the art' for tidal lagoons is presented, including the key industry benefits and challenges. Finally, the chapter concludes with consideration of how this research might fit in with the existing body of knowledge and gives brief background into some of the research tools that will be used. The background chapter combined with the introduction chapter now makes up Part 1 of the thesis setting the scene for the research, providing a research context and problem to be addressed.

3 Identification of Impacts

3.1 Introduction

The main aim of this chapter is to address the first research objective, i.e:

- To identify the environmental impacts of tidal lagoons

There are currently no man-made, energy generating, tidal lagoons in the world. As such no lagoon specific operational data was available to contribute towards addressing this objective. The data for this section of the research was instead gathered through literature review and extensive industry engagement. The chapter begins with description of an initial scoping exercise then follows a traditional reporting structure, including methods, results and discussion.

The raw data and Excel files are referenced and published on the website 'Zenodo' for the reader to access directly, via author permissions [104–109]. Some of the research in this chapter has been peer reviewed and published in two separate papers, a practitioner publication for the Institute of Engineering and Technology (IET) [110] and a paper in the journal Renewable Energy [111]. The chapter repeats some of the content in these documents. The full document copy of these is included in Appendix 1 and 2 of the thesis. Some of the research from this chapter was also presented at the International Conference on Ocean Engineering (ICOE) 2016 and All Energy 2016, see Appendix 3 and 4 for copies of the conference presentation materials.

3.2 Scoping Exercise

The starting point of any research project is to determine what the existing knowledge baseline is and how new research can build upon it. This research started with a literature review on the environmental impacts of tidal lagoons, to provide that baseline of understanding and act as a scoping exercise to determine the research objectives.

While a traditional literature review consists of a large written document. With an industry focused EngD it was deemed more beneficial to the sponsoring company to create a searchable and filterable Excel file on the negative and positive impacts of tidal lagoons. This document was labelled 'Risk and Opportunities Register' [104] and included a review of journal publications, industry updates, reports and feasibility studies in the tidal lagoon and barrage industries along with the tidal stream sector where appropriate and relevant to do so.

It was immediately apparent during the development of the register (July 2015) that there was a general lack of independent published research specifically on the environmental impacts (positive and negative) of tidal lagoons. This was understandable given that there were no tidal lagoons in the world. However, at the time there were significant developments in the lagoon industry sector which made an understanding of their impacts vital to allow further progress to be made. The scoping exercise therefore highlighted this as a significant research gap.

In addition, it was clear when documenting both the negative and positive environmental impacts in the literature that the potential environmental benefits of lagoons were particularly under-represented. The imbalance of documented negative and positive environmental impacts meant that the idea of environmental net gain in lagoons, including the wider environmental implications, was relatively unexplored.

It was clear that the scoping register documenting existing literature was providing only a small insight into what was actually happening in the industry at the time. This informed the decision to conduct extensive industry engagement to extract the information available from key people working on tidal lagoons that was not yet available in print. The main aim of the industry engagement was the same as that of the literature review, i.e. to identify the key environmental impacts of tidal lagoons (both positive and negative), but it also attempted to make a start on the second objective of identifying potential solution options by exploring solution ideas with participants to gain a baseline understanding of what solutions industry was currently working with. The register has not been updated since its initial use as a scoping exercise in July 2015 and therefore serves as an indicative snapshot of the literature that was available at the start of the research. The full register can be seen on Zenodo [104].

3.3 Methodology

Under normal circumstances industry engagement aims to take a representative sample of an industry's population in order to consider a working hypothesis. Due to the relative infancy of tidal lagoons in the UK and therefore a relatively small pool of potential industry participants, the focus of the engagement was instead on including as many of the most relevant participants in influential roles within key organisations as possible, rather than obtaining a large sample size of non-relevant participants.

The pool of participants was split into those working on tidal range projects (herein referred to as 'developers') and those in government, conservation, regulatory, practitioner or other influential organisations (herein referred to as 'influencers'). The participants were categorised in this way as it was expected that developers would have an in depth, detailed understanding of a specific project/s and would be a relatively small number of people. In comparison, influencers were expected to be a larger pool of participants from a range of non-lagoon specific backgrounds having only general non-project specific views on tidal lagoons. The differences in the two categories warranted a different approach to data collection and analysis and the methodologies of each are explained in separate sub-sections in this document. The scale of the impacts discussed with participants included regional and local impacts. The global benefits/negatives of lagoons was not considered at this stage of the research e.g. the contribution to climate change mitigation as it was felt this overarching benefit might overshadow the participation, reducing the opportunity for detailed investigation into regional impacts.

All participants of the industry engagement were asked to answer questions in their professional opinion and not on behalf of the organisations they were employed within. Due to the infancy of the lagoon sector at the time, many organisations did not yet have a standard stance or practice for lagoons. Therefore, the engagement provided a snapshot of what the current industry perspectives were of the people working, or likely to be working, on the development of future tidal lagoons.

3.3.1 Questionnaires for Influencers

3.3.1.1 Data Collection

The online survey tool 'Typeform' was used to send questionnaires to influencers. This tool allowed a simple link to be sent to participants, their responses were then automatically logged on a downloadable excel file. The full questionnaire tracking and responses can be found on Zenodo 'Questionnaire tracking and responses' [105]. The questionnaire is still live, contains all of the questions asked and can be accessed by the reader here:

- https://lagoonresearch.typeform.com/to/HQ1szq. Note: to move on from each section you will have to enter responses, please feel free to do so.

The full list of questions can also be found in the 'Questionnaire tracking and responses file' [105] or in summary form in Table 6 at the end of this methodology section. At the start of the questionnaire, after permissions were obtained, the participants were asked to provide some background information on their current role to allow an understanding of what potential angle they would be approaching the questionnaire from. The questionnaire then focused around the following topics on tidal lagoons:

- Future lagoon outcomes
- Key environmental impacts (-)
- Benefits and opportunities (+)
- Solutions to environmental impacts

- Key industry challenges

The topics and questions were developed around collecting information to address not only the first research objective to *Identify the key environmental impacts of tidal lagoons* but also to provide a starting point for the second objective to *Determine solution options to the key impacts of tidal lagoons*. Alongside this the engagement also allowed consideration of how developers and influencers are approaching the challengers in the industry and what future outcomes they are working towards achieving.

The questionnaires included a mix of closed and open questions and targeted individuals in decision-making roles. The questionnaire included some multiple choice questions; the options for these were developed based on the initial scoping literature register findings [104]. A focus was placed on providing enough information to allow the participants to make an informed decision, without the questions being biased or leading. Participants were selected based on academic and industrial reputation, industry literature review and conference contacts. Along with the initial email with the questionnaire link, participants were also sent an information sheet explaining the research objectives (see Appendix 5). Where possible this email was accompanied with a follow up call. An email reminder or 'nudge' was also sent following initial contact to remind participants of the research if they had not yet participated. All of the emails were written to individuals and not sent as automatic group emails.

A total of 47 emails were sent out to participants. The questionnaire received a 51% response rate, with 24 individuals from 21 different organisations participating. Table 4 shows the list of participant roles, with Figure 18 showing the variety of organisations involved in pictorial form. The identifying information of those participants is not presented in this publicly available document in the interests of privacy and requested anonymity. Examiners and supervisors of this research can assess the full list of participants with author permission in the 'Questionnaire tracking and responses' file on Zenodo [105]. The response to the online questionnaires was deemed sufficient to allow for descriptive analysis and conclusions to be drawn.

Table 4 List of the roles of influencer's participating in the questionnaire

Participant Roles or Department
Marine Advisor
Energy and Marine Manager
Head of Policy (Land use)
Policy Department
Policy Advisor
Fisheries and Marine Project Lead
Marine Planning Officer
Principal Renewable Specialist
Innovation Associate
Research and Development
Offshore Developer Engagement
Policy Department
Policy Advisor - Marine
Technology Manager
Senior Specialist - Tidal Range, Estuaries
Water Resource Specialist
Renewable Energy Business Development
Marine Consents Advisor
Marine Renewables Research and Guidance
Wave & Tidal Sector Specialist
Head of Energy industries and Innovation
Marine Licensing Case Manager
Director of Environmental Policy
Marine Scientific Advisor

Figure 18 Organisations associated with the participants of the questionnaire (influencers)

3.3.1.2 Questionnaire Data Analysis

Software QSR NVivo 10 was used to code the open ended questionnaire responses [112], and the full coding NVivo analysis file can be found on Zenodo [106]. Coding is a method of qualitative data analysis, where passages of text are assigned a code-label relating to a particular theme or topic, and passages with the same label are judged to be of the same topic. This method allows patterns to be identified within qualitative data [113]. Some code-labels were pre-determined based on the questionnaire topics (aka a priori codes) [114], others were developed based on new findings arising within the data itself (aka grounded theory) [114].

The raw coded data was then analysed further in an Excel file 'Industry Engagement Analysis' on Zenodo [108]. Descriptive statistics such as percentage distributions were used to analyse the closed question data and subsequently the coded qualitative data from open ended questions. It was not deemed appropriate to use more rigorous statistical analysis given the exploratory nature of the research and the lack of an empirical hypothesis to validate [115]. Reflecting the analysis, the results are presented as percentages, either as percentage mention, percentage selecting, or percentage participants to mention. Table 6 in the methodology summary presents a brief overview of the questions asked, the type of question and how the results have been analysed and presented.

3.3.2 Interviews with Developers

In order to gain deeper insight into industry perspectives, semi-structured interviews were conducted with developers. Participants were identified through literature review, and internet research. Individuals were sent an initial interview information sheet (Appendix 6) and invited to contribute to the research through interviews. The semi structured interview included a select few questions to guide the participants towards particular topics (see Appendix 6), but no other direction was given. The broad topics were the same as those identified for the questionnaires for influencers (future outcomes, environmental impacts, environmental benefits, potential solution options, main challenges).

Interviews were conducted face to face or via Skype video call. Participants were sought from the tidal lagoon industry, in addition to related sectors such as tidal barrages, tidal fences, tidal bridges and hydroelectric projects. Each interview was recorded [107] and later transcribed for analysis [109], the full recordings and transcripts can be accessed by examiners and supervisors on Zenodo. A total of 8 developers from key organisations participated in the interviews, see Table 5 for a list of organisations, the identifying details of the participants is not shown in this document in the interests of participant anonymity. All the interview transcripts were then coded using software QSR NVivo to provide key response results and these results are presented as either percentage mention or percentage participants to mention. The Excel file 'Industry Engagement Analysis' on Zenodo [108] shows all of the industry engagement raw results analysis including a list of participants and is accessible with author permission for research examiners and supervisors only. See Table 6 for a summary of the questions asked, the type of question, how they were analysed and in what unit they are presented.

Table 5 Developers interviewed and associated organisations

Developer Participant Organisations
Tidal Lagoon Power Ltd
North Wales Tidal Energy
North West Energy Squared
Electric Mountain
Solway Energy Gateway
Wyre Tidal Energy
VerdErg
Cardiff University – Associated with Severn Barrage

3.3.3 Methods Summary

Table 6 below shows a summary of the methodology used in data collection, analysis and presentation. There is some information in Table 6 and in the code label information in various related Excel files on Zenodo that are very broad terms requiring further explanation. Table 7 provides definitions for terms where the meanings are not immediately obvious.

Table 6: Summary of the chapter methods, including interview and questionnaire data collection, analysis and presentation

		Collection, Analysis and Presentation of Data							
		Question Asked		Question Type		Data Analysis		Data Presentation	
		Interview (developers)	Questionnaire (influencers)	Interview	Questionnaire	Interview	Questionnaire	Interview	Questionnaire
Engagement Topic	**Outcome**	If you had to say the project had one goal, mission or priority outcome, what would you say that was?	Of the outcomes below, please select one which you believe to be the most important for future tidal lagoon developments. [1]	Structured	Multiple choice[1]	Coded response to question	Number of options selected	% mention	% to select
	Impact	What do you consider to be the top three environmental impacts?	What do you consider to be the top three most significant direct environmental impacts of tidal lagoons?[2]	Structured	Multiple Choice[2]	Coded response to question	Number of options selected	% mention	% to select
	Benefits	Participants spoke freely about the benefits	Other than low carbon electricity and the direct economic benefits, what would you consider priority opportunities that a tidal lagoon could offer?	Non-structured	Open ended	Coded benefits section of transcripts	Coded question responses	% mention	% mention
	Solutions	Participants spoke freely about solution options	Please select ways in which environmental impacts could be addressed through technological or environmental solutions.	Non-structured	Open ended	Coded solutions section of transcripts	Coded question responses	% participants to mention	% Participants to mention
	Challenges & Developer Focus	Participants spoke freely about industry challenges. They were also asked: “suggest how the regulatory process could be improved”	In your professional opinion, where should developers be focusing to reduce the environmental impacts posed by tidal lagoon developments?	Non-structured	Open ended	Coded challenges and improvement sections	Coded question responses	% Participants to mention	% Participants to mention
	Participant Background or Role	Participants spoke freely about themselves	What broad category would you place your current role into?[3]	Non-structured	Multiple choice[3]	Coded introductions	Number of options selected	% local connection	% to select

[1]High public acceptance, good environmental status, speedy deployment, maximising public goods and services, reliable supply of electricity, cost competitiveness of produced electricity, providing resilience to climate change, reliable technology.
[2]Sediment regime alteration, changing hydrodynamics, restricted passage and migration, blade interaction with marine life, noise and vibration, introduction of invasive species, benthic habitat loss, other.
[3]Engineering, environmental, technological, policy, financial, socio-economics, other.

Table 7: Definitions and examples of phrases used that require further explanation

Topic	Option Choice	Definition/Examples
Outcome	Good Environmental Status	Reducing environmental impacts and enhancing benefits as far as possible to achieve the best environmental status
Outcome	Maximizing Public Goods & Services	Providing services or goods through the development of the lagoon in which the general public would benefit from e.g. leisure and recreation, area regeneration, positive aesthetics
Impact	Restricted Passage and Migration	Restricting any migratory route or passage of any species of fish or marine mammal
Impact	Introduction of invasive species	The accidental introduction of a non-native species through development of a lagoon or the 'natural corridor' effect that the lagoon might have, connecting different habitats to each other and allowing the movement of species into habitats that they would not normally reside in
Solution	Engineering Design & Technology	Any solution mentioned that is related to changing the initial engineering design or the choice or design of the technology itself with the view to avoiding environmental impacts. E.g. Turbine blade number, shape of the lagoon wall, material used for the wall, built in additional habitats etc.
Solution	Operation & Maintenance	Any activity undertaken after the construction phase which attempts to reduce or restore environmental impacts e.g. Zonation activities based on breeding seasons, temporarily pausing generation to allow species migration, manipulation of the water levels within the basin for environmental benefits such as flood control rather than purely for energy generation.
Solution	Compensation & Catchment Measures	Any activity based on compensation or offsetting of impacts through the use of offsite areas. E.g. habitat creation or restoration, Payment for Ecosystem Services (PES) schemes, catchment management measures.

3.4 Results

The results provide an insight into what was at the forefront of the influencers' and developers' minds, regarding the environmental impacts of tidal lagoons. Results are presented here on participant backgrounds, desired future lagoon outcomes, environmental impacts and benefits and finally solution options and further industry development. The Excel file 'Industry Engagement Analysis' [108] shows how the figures in this section were created.

3.4.1 Participant Background

Background information on the participants was obtained to allow further understanding of how the results on the key environmental impacts of lagoons might be biased towards particular roles. Figure 19 shows how influencers categorised their current role. Of the influencers who participated, 67% are from either environmental or policy roles, with the remainder residing in technological or socio-economic categories.

The interviews with developers have shown a pattern of strong local connections between developers and the local area of their proposed project or development. Over half of the developers mentioned their local connection when introducing themselves at the start of the interview. It was often the case that the developer organisations were formed from locals, local business people or local forums, as opposed to large multi-national organisations which is often the case in other energy sectors. An example here is Wyre Tidal Energy which was formed by three local businessmen passionate about the local area of Fleetwood and its regeneration [116].

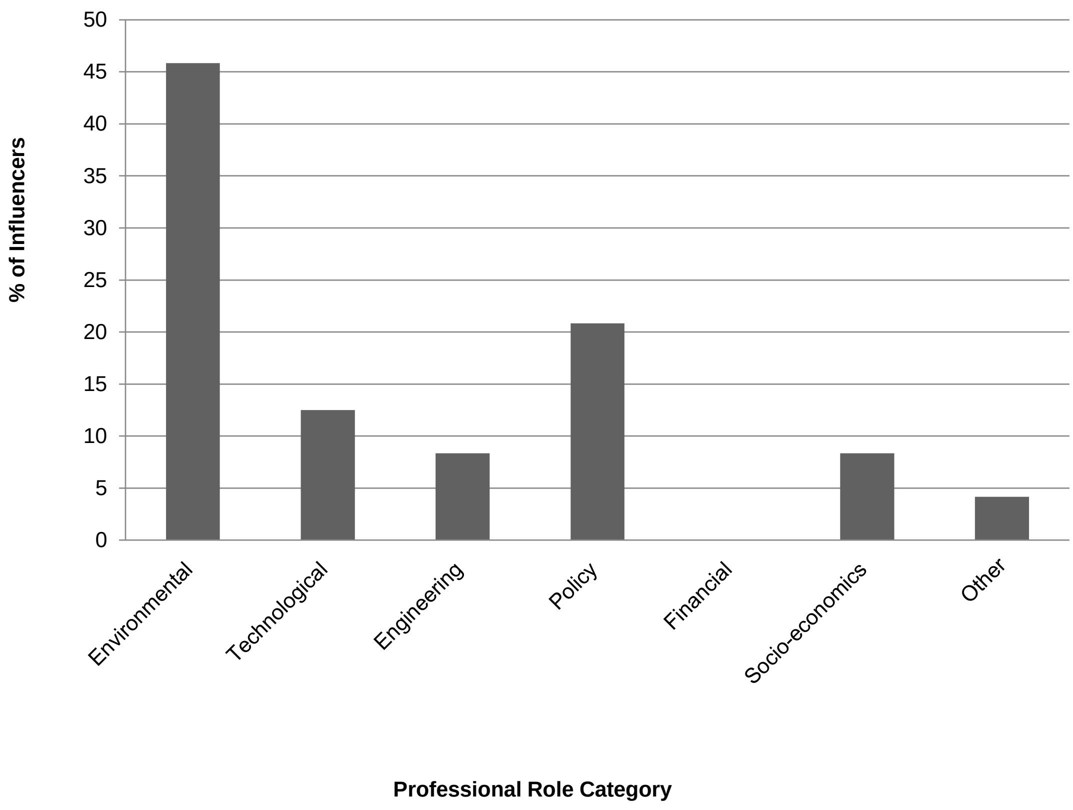


Figure 19 Influencers' professional backgrounds displayed as percentage number of influencers

3.4.2 Priority Lagoon Outcomes

Participants were asked about which outcomes they believed to be a priority for a future tidal lagoon development (Figure 20). Influencers selected 'Good Environmental Status' and 'Cost Competitiveness' as the key priority outcomes. 'Good Environmental Status' here is defined as reducing the environmental impacts and enhancing environmental benefits where possible.

For developers, 'Area Regeneration & Wealth' received the highest percentage mentions with 'Reliable Electricity Supply' and 'Good Environmental Status' in joint second. Neither influencers nor developers considered 'Speedy Deployment' as an important outcome at the time of engagement. There are other differences seen here, for example, with 'Cost Competitiveness' and 'Reliable Technology' showing different levels of priority between the two groups.

Figure 20 shows what influencers believe to be the key outcomes based on their respective professional backgrounds (stacked bars). We can see from this that the majority of participants selecting a 'good environmental status' are from an environmental background and those participants with technology, policy or socio-economic backgrounds found cost competitiveness a key priority outcome.

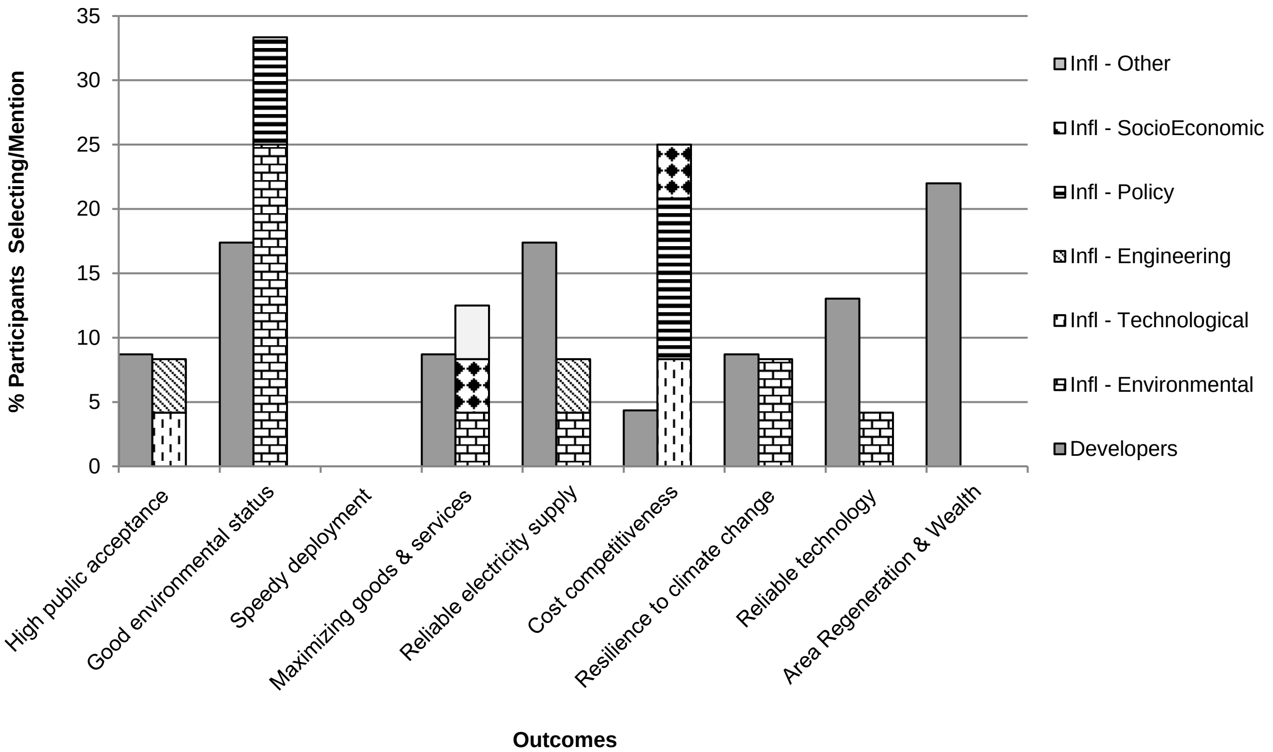


Figure 20: Participants desired outcomes for future tidal lagoons. Developers and Influencers shown, with influencers shown as stacked bar representing the different professional background categories

3.4.3 Key Environmental Impacts & Benefits

Whilst both influencers and developers agree that a ‘Good Environmental Status’ is a priority outcome for tidal lagoons, it is important to further understand which specific environmental impacts and benefits are underlining this outcome and how the influencer and developer views compare on these specifics.

Figure 21 shows what participants believe to be the top three environmental impacts of tidal lagoon developments. The top two most significant impacts in the view of both the influencers and the developers are ‘Sediment Regime Alterations’ and ‘Changing Hydrodynamics’.

Developers and influencers selected different options for their third most important impact. Developers believe that ‘Water Quality’ is the third most significant impact of lagoon developments, whilst influencers selected ‘Restricted Passage & Migration’ for that position. ‘Water Quality’ was not mentioned at all by influencers (a box for ‘Other’ impacts was provided in the questionnaire), despite it being in the top three environmental impacts for developers. Whilst influencers placed more weight on ‘Restricted Passage & Migration’, developers still had this impact in mind, with it lying in fourth position in terms of its significance as an impact.

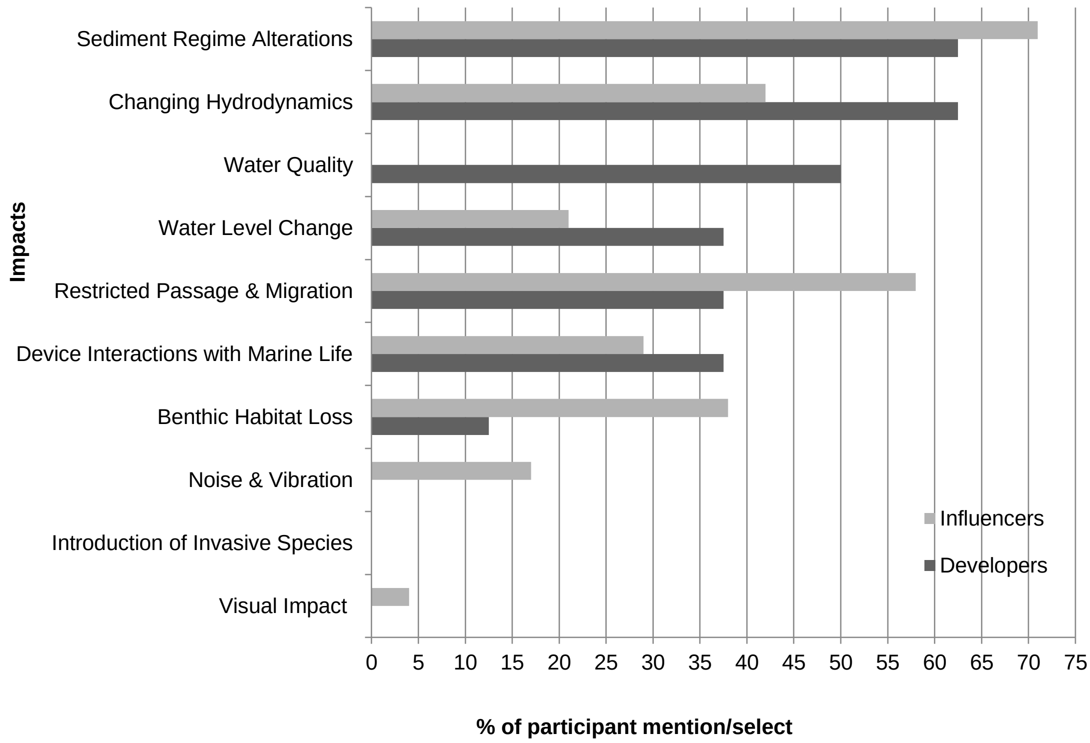


Figure 21 Participants key environmental impacts of tidal lagoon developments

Participants were asked what they deemed to be the priority opportunities a tidal lagoon could offer aside from low carbon electricity and any direct economic benefits (Table 8). Influencers' most mentioned benefits include 'Flood Defence & Control', 'Habitats & Biodiversity' and 'Leisure & Recreation'. In contrast, developers most mentioned benefits were 'Area Regeneration & Socio-economics', 'Local Employment' and a 'Local Economy Boost'. These benefits were also areas of high percentage difference in mention between influencers and developers (green cells Table 8). This further suggests that influencers and developers have different priorities when considering the benefits of tidal lagoons. Benefits which had little to no difference in the percentage mention (red cells Table 8), suggesting an overall consensus in the priority given to them by influencers and developers include 'Base load potential', 'Multiple use opportunities', 'Tourism' and 'UK image'.

Table 8: The benefits of tidal lagoons as % mention by developers and influencers. Colour is assigned to the highest % mention for each benefit between influencers and developers, i.e if the colour is on developer side then developers mentioned this benefit the most. The actual colour depends on the scale of this % difference, (Green = ≥5% difference in % mention, Amber = ≥2 % ≤4 %, Red = <2%).

Benefits	% mention	% mention
	Influencers	Developers
Area Regeneration & Socio-Economic Benefits	6	14
Coastal Erosion Protection	8	4
Community Share	2	4
Education & Research	5	7
Energy Base Load	3	4
Export Opportunities	3	4
Flood Defense & Control	16	9
Habitat Biodiversity	14	6
Leisure & Recreation	13	4
Local Economy Boost	3	9
Local Employment	3	11
Multiple Use	6	6
Renewable Energy Acceptance	6	0
Supply Chain	3	5
Tourism	6	7
Transport & Connectivity	0	5
UK Image	3	2

3.4.4 Environmental Impact Solutions

Environmental impact solutions are grouped into three broad categories: 'Engineering Design & Technology', 'Operation & Maintenance' and 'Compensation & Catchment Measures' (see Table 7 in the methodology section for further definitions). Both developers and influencers were asked about what the potential solutions could be to address environmental impacts, and the responses are summarised in Figure 22. Due to the infancy of the lagoon sector the solution options identified by participants (both developers and influencers) were often around transferable solutions from other industries. For example under engineering design there are multiple strategies, one example of which is using ecological criteria in the building design, such as the rock pools built into Sydney Harbour wall [117]. Numerous operation and maintenance strategies arose throughout the engagement with both influencers and developers; these were largely based around the pausing and restarting of generation depending on important ecological seasons, temporal or spatial zonation of activities and control of in-basin water levels for environmental gains. Measures based around habitats and biodiversity creation and restoration were mentioned by both influencers and developers for the compensation and catchment based measures solution option. Overall developers had a broader view of the potential solution options than influencers, demonstrated by the larger triangle spread of representation in Figure 22. All of the developers interviewed mentioned some form of solution under the 'Engineering & Technology' category, with 75% also mentioning a 'Compensation & Catchment Measures' solution. These two categories were also identified by influencers, 67% of them mentioning a solution in both 'Engineering design & Technology' and 'Compensation & Catchment Measures'. 'Operation & Maintenance' was mentioned the least by both influencers and developers, with 50% and 22% mentioning them respectively.

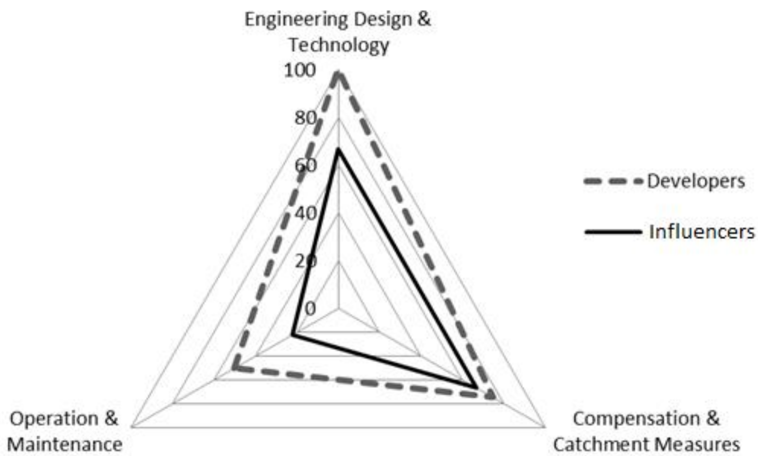


Figure 22: Developer and regulator suggested solution options for environmental impacts grouped into three broad categories and presented as % participant mention.

3.4.5 Further Industry Development

Influencers were asked to suggest areas in which developers should be focusing their efforts to reduce environmental impacts of tidal lagoons. A variety of suggestions arose; however, a clear theme relating to location developed with 29% of influencers suggesting a focus on site selection to avoid impacts in the first instance. Of equal focus (29%), influencers wanted to see developers focusing on the issues of intertidal habitat loss.

When developers were asked what they believe to be the key challenges in the industry 33% mentioned finding a suitable site. Whilst influencers wanted to see a focus on site selection, developers believe this to be one of their key challenges. Other key challenges for developers were found to be lack of information and experience in the lagoon sector, maintaining interest in lagoons as a form of energy generation and securing funding.

When developers were asked specifically where improvements could be made in the regulatory process, 50% stated that clearer more accessible lagoon-specific policy or guidance was required, with 63% suggesting a reduced process time for consents.

3.5 Discussion

The initial scoping exercise register on the environmental impacts and opportunities of tidal lagoons in July 2015 highlighted that the published literature was not representative of the progress being made in the lagoon industry at the time. This presented a number of opportunities to address key knowledge gaps. In particular the benefits were found to be under-represented in the literature, with a holistic approach to environmental impacts of tidal lagoons rarely found.

The imbalance of the environmental negatives and positives found during the scoping exercise along with the general lack of lagoon specific published information prompted consideration of how environmental net gain could be achieved in lagoons, without a full available knowledge base on the likely impacts being available. This formed the basis justification for extensive industry engagement to build and document this knowledge base in order to allow further research to be undertaken.

The main aim of this chapter was to achieve the first research objective: ‘To identify the environmental impacts of tidal lagoons’. Alongside this aim a number of other key findings were discovered and have also been presented in the results and discussion sections of this chapter and published in two papers [110,111]. Solution options were also discussed in the industry engagement and this provided a springboard for the next chapter of the research which investigates solution options to the key environmental impacts of tidal lagoons.

3.5.1 Desired Outcomes

The industry engagement indicated that the industry is collectively considering achieving a 'good environmental status' as the lagoon sector begins its development. Whilst both the influencers and developers are working towards this outcome, previous research has yet to explore whether their views on the details of the environmental impacts of lagoons are aligned. Aligning their views on these details such as the key impacts, benefits, solutions and key challenges would allow for a smoother transition from lagoon planning to development and towards achieving a good environmental status in future lagoons. Through industry engagement this research has provided a first step towards achieving this industry aim, by identifying the views of the influencers and developers, considering the areas of contrast and consensus and later providing recommendations on how to move the industry forward in light of this information.

The priority outcomes selected by influencers and developers reflect their likely key objectives. For example, the nature of an environmental influencer's role in the industry is to protect the environment, whereas a developer is most concerned with generating a reliable and predictable supply of electricity and to obtain the associated revenue. Many developers also have strong local connections to the area of a development and as such their priorities with local area regeneration and wealth are also not surprising.

'Speedy Deployment' was not a priority for influencers or developers at the time of engagement. It is clear that other outcomes are a priority for tidal lagoons at this stage. This is surprising given the current urgency towards transitioning to a low carbon economy. There is also a risk that ocean energy will not be sufficiently mature before that capacity is taken up by other forms of renewable energy, hence the need for a speedy deployment should not be overlooked. The relative infancy of the lagoon sector and the fact that there has yet to be a single tidal lagoon development in the world could provide the reasoning behind the lack of priority on speedy deployments. The consensus suggests that it is better to go slow with the first development and ensure that other higher priority outcomes are achieved first and foremost to bolster investor certainty and set a sustainable precedent for future tidal lagoon sector development. If the questionnaire were to be undertaken again in the present day (2018), this outcome might be different, especially given the financial difficulties TLP have faced as a direct result of the delays in government decisions on SBL for example.

The environment is at the forefront of both influencers' and developers' minds in terms of a priority outcome for lagoon developments. However, there are also a number of other outcomes seen as priorities by the industry. It is vital that whilst the industry strives towards a positive interaction with the environment it does not lose sight of a lagoon's primary purpose: to generate low carbon electricity at a cost competitive rate. In addition, whilst there will be a number of local environmental impacts, there is an overarching environmental benefit which should not be forgotten, i.e. that tidal lagoons are contributing towards tackling global climate change.

The wider literature now shows that whilst many still believe that lagoons have the potential to be environmentally friendly alternatives to barrages [118] and are working towards this outcome [63,85,119], others still consider the uncertainty surrounding the identification of impacts a key barrier to lagoon development [4,18,66,120]. Environmental impacts of barrages and the misalignment of views of different stakeholders have been historical issues in the tidal range sector [75,118,121,122], with the top two key challenges of lagoons being recently identified as cost and environmental effects [5]. One of the key objectives of the industry engagement was to determine the key environmental impacts of tidal lagoons, in order to investigate solution options for them. The next section discusses this in more detail.

3.5.2 Impacts & Benefits

An ecosystem is a complex web of interactions amongst the living (biotic) and non-living (abiotic) environment. Any environmental impacts of a tidal lagoon will therefore have a complex impact on inter-tidal, marine and terrestrial ecosystems. It will also have knock-on implications for the wider environment, people, society and economics. In this sense, determining the top three environmental impacts allows us only to scrape the surface of this vast web of interactions. However, there is use in asking influencers and developers to consider the top three, as this shows us what impacts are currently being focused on in the industry, and therefore in practice. The wider literature serves as an indication of the types of environmental impact of lagoons currently being focused on including impacts such as hydrodynamics [68–73], morphodynamics [74,75], water quality [76,77], and ecological and social impacts [17]. Research focusing on tidal lagoons specifically is also recently well documented, in terms of either focus on individual environmental impacts e.g. hydrodynamic changes only, providing review of feasibility, technology or energy generation estimates, and developer site environmental investigation documents [78–85]. With certain papers placing a focus on fish safety and the consequences of flood plain damage to migrating birds [5,83].

Sediment regime and hydrodynamics are seen as key abiotic drivers of an ecosystem; this may suggest why they have been selected as key impacts by both developers and influencers. These impacts also interact with each other, with changing hydrodynamics influencing the sediment regime and a change in the seabed morphology as a result of sediment regime change influencing the local hydrodynamics. These impacts are also well studied [68–75], which could explain why they are at the forefront of the industry's mind. Conversely, perhaps the reason why the impacts are well studied is because the industry has been placing a focus on them. Never-the-less, this does represent an area of consensus between influencers and developers.

The impact of 'Water Quality' represents an area of differing prioritisation amongst developers and influencers. This was a key impact raised by developers and was not mentioned directly by influencers. This question to influencers was a multiple-choice question in which 'Water Quality' was not an option. Although an 'other' box was provided for influencers to raise the issue, this style of questioning may have resulted in the differences seen. The water quality impact here is related to the entrapment of water in a basin, which may also entrap pollutants, similar to the eutrophication issue previously seen at Sihwa Barrage [35]. This impact could potentially be worsened by run-off from surrounding land. It could be that the influencers who were questioned are not aware of this issue, or, that they do not consider this issue to be of higher concern than the other impacts. Influencers did consider 'Restricted passage and migration' as a key issue, which can be linked to issues of water quality; this may also explain the difference seen in prioritising key impacts.

Environmental impacts can be categorised into knowns, known unknowns and unknown unknowns [110]. All of the impacts in this engagement have to be knowns or known unknowns, and the uncertainty surrounding impacts may have been one of the factors influencing participants' choices. The engagement work cannot take into account the unknown unknowns and these will only become apparent if a tidal lagoon is given the go-ahead, in which case careful monitoring will be required.

Often overlooked, tidal lagoons will also have a number of positive environmental impacts or benefits, and therefore beneficiaries such as people, society and the wider environment. The key benefits mentioned by influencers and developers were different and as such would have different beneficiaries. Developers mentioned key benefits where the beneficiaries will mostly be the local area, the local economy and the local people. In contrast, the influencers' priority benefits provided a spread of beneficiaries across society, the local ecosystem and individuals.

This result can partly be explained by the participants' backgrounds. Over half of the developers had local connections to the area of the project or development they were associated with; it is not surprising then that they chose benefits that would ultimately provide opportunities for the local area and its community. In addition, local benefits are likely to increase local support for a project, reducing public opposition. As influencers are not necessarily linked to an individual project's locality, they are more likely to take a more holistic view and consider the wider potential benefits of a project.

If the positive environmental impacts can outweigh the negative for a particular development then an overall net gain can be achieved for society in terms of the overall impact a lagoon might have on the environment. For this to be achieved a holistic approach needs to be taken with consideration of the wider environment and identification of potential solution options that span a variety of disciplines. Where possible environmental impacts can be described, quantified and valued [123]. They can then be incorporated into economic appraisals to allow developers to find a financially and environmentally effective means of providing solution options that achieve environmental net gain that goes over and above regulatory requirements. This idea of environmental net gain for tidal lagoons is relatively unexplored; this was highlighted in the scoping exercise where there was a significant lack of published material, particularly on the potential environmental benefits of tidal lagoons.

3.5.3 Solution & industry Development

Environmental impact solution options are often applied working down the mitigation hierarchy (Figure 23). Within this, avoidance of an impact is addressed first, then reduce, restore and finally looking to offset as a last resort. Arguably, what is missing from this list is to enhance potential environmental benefits, and therefore the ability of a project to leave a lasting 'net gain' legacy. There are a number of solution options within these hierarchy steps (Figure 23) and for simplicity they were grouped for the study into the three broad categories: 'Engineering Design & Technology', 'Operation & Maintenance' and 'Compensation & Catchment Measures'.

Both influencers and developers are considering solutions at the top end of the mitigation hierarchy in terms of the avoidance of impacts through engineering design and technology choice. There is yet to be a lagoon developed and so it is understandable that the industry is looking to avoid as many impacts as possible in the first instance through these solutions. Given the relative infancy of the industry, the majority of work to date has been on the engineering design and technology planning and so this might explain the large percentage of industry participants mentioning these solution options, in particular the developers.

Alongside this, site selection as another avoidance strategy is also being taken into consideration by all of the participants. Influencers believe developers should place more focus on this, whilst developers consider choosing a suitable site to be one of their biggest challenges. An issue arises here in that the areas with the best tidal range often provide a unique habitat to be protected e.g. the Severn Estuary [124], therefore selecting a site that has the best resource for energy generation and that also avoids sensitive habitat is a challenging endeavour. Conundrums like this allow for other solutions further down the mitigation hierarchy to come into play.

The results suggest that the industry is considering either avoiding impacts or compensating them via strategies such as changing lagoon wall design, turbine technology or habitat creation. The middle section of the hierarchy to 'reduce' and 'restore', for example through operation and maintenance strategies, is not being highlighted as a focus in the industry's minds at the time of engagement. This represents an area where further research is required to fill the gaps in the solution options being considered by the industry. Further attention on the reducing and restoring strategies such as 'Operation & Maintenance' would allow a full mitigation hierarchy of solutions to be provided to the industry, thereby reducing the environmental impacts of tidal lagoons as much as possible. An example of potential operation and maintenance strategies that could address the key environmental impacts of hydrodynamic and sediment regime changes are managing ebb and flood generation times and considerate dredging techniques.

The scope within solution option 'Compensation & Catchment Measures' is wider than the suggestions arising from participants or by this study thus far. There is an opportunity here to consider innovative wider environmental solutions such as Payment for Ecosystem Services (PES) for example. Incorporating the benefits these solution options might have in terms of enhancement over and above that of regulatory requirements for the environment, society and the economy would allow for a stronger case for tidal lagoons in the future. A vital avenue for further research is therefore the consideration of the overall environmental and economic benefit of differing solution options that will allow for the largest positive net gain in future tidal lagoons to be realised.

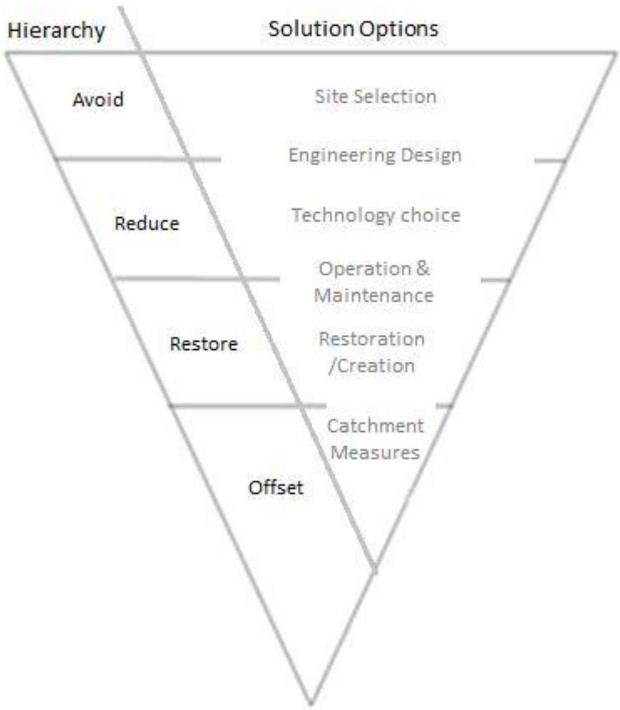


Figure 23 : Mitigation hierarchy for environmental impacts. Hierarchy adapted from source: [39]

One of the key requirements for the industry's development is that influencers and developers work together to move forward through the planning and regulatory process ensuring that lagoons are developed efficiently and sustainably. The key challenges in the industry include a lack of clear and accessible guidance available for developers, in addition to lengthy regulator processing times. More recently it has become clear that the political aspects surrounding the lagoon industry also present significant challenges. This political aspect in terms of government funding has not been explored in this research, but is discussed in Chapter 6.

The infancy of the industry means that to date there is no specific lagoon guidance and instead the industry relies on adapting guidance from other sectors. If lagoon-specific guidance were to be developed this would provide certainty of information to developers and indeed the influencers themselves, in addition to reducing regulatory process times. Clarity and consistency of specific guidance may also reduce the costs often associated with the requirements of a precautionary approach to development as suggested in the Ocean Energy Forum's Strategic Roadmap [125]. It is essential that any lagoon-specific guidance is set up prior to the first lagoon project; this ensures that the process is in place to support the industry through the development process and takes away some of the risks and costs associated with being the 'first mover' in a new industry.

Lack of industry experience and information is an issue, for developers and for influencers. Developers have no blueprint of plans to work with in development and influencers lack the evidence they need to ensure compliance with legislative regimes and environmental directives. This issue will improve with time and thorough monitoring will allow for updated and enhanced regulatory guidance and smoother developer deployments. It will also provide opportunities in terms of exportable skills, experience and information as the world's first movers in the tidal lagoon industry. Chapter 4 of this research includes a systematic literature review which discusses the available wider literature on solution options.

3.5.4 Uncertainty and Limitations

This was not an in depth social science study, however the research was grounded in basic social science theory on industry engagement and qualitative data analysis through coding. Whilst the industry engagement attempted to include every participant in influential roles within key organisations the response rate was not 100%. Therefore, the results were in the end a sample of the lagoon industry and not a complete set. The research did not include a study on how best to get a representative sample of people from the lagoon sector and in hindsight this would have enhanced the robustness and confidence in the research outputs if it had been undertaken. For example, this may have included aiming for a representative split of participant backgrounds or representative split in organisation types. This was not considered at the time because the tidal lagoon sector was in its infancy and as such the number of known people working in it was limited. The plan was to speak to them all and avoid the need to choose a representative sample.

The participants were split into two pools ‘developers’ and ‘influencers’ and this allowed us to make comparisons on their perspectives. Due to the different tidal lagoon knowledge level and participant number between the two pools of participant, two different strategies were used to collect data (questionnaires and interviews). This difference in strategy raises uncertainty in the ability for the outputs to then be compared directly. Whilst the different methods may pose slight differences in the results, the general perspectives of both the influencers and developers on the same broad topics were obtained and these general perspectives are what is being considered and compared in the research. The different methodologies are not thought to undermine the key outputs, but they do represent a level of error surrounding them that should be noted as a limitation.

3.6 Conclusions & Recommendations

This section of the research presents a first identification and analysis of the influencer and developer views on the environmental impacts of tidal lagoons. The industry perspectives on the key impacts and benefits will be used moving forward to the next chapter to determine potential solution options to address the key environmental impacts.

Aligning the views of the influencers and developers on this topic is vital to allow for a smooth transition of tidal lagoons from current planning to future development. Whilst this study considers and compares the influencers and developer perspectives it is not the main focus of the research and provides only a starting point to realising this collaborative sector aim.

Both influencers and developers are ultimately working towards ‘Good Environmental Status’ as one of the priority outcomes for tidal lagoons, and so this provides a foundation of a common goal to strive for. It is important to keep in mind that other outcomes are also of high priority and that the primary goals of a lagoon are ultimately to produce low carbon electricity at a cost competitive rate. In addition, whilst lagoons will have a number of local environmental impacts, it is essential not to forget the overarching global benefit of their potential contribution towards tackling climate change through the displacement of fossil fuels.

Environmental impacts of a lagoon will have complex implications for the intertidal, marine and terrestrial ecosystem in which it is developed [32,35]. The impacts identified in this section of the research look at the known and known unknown impacts, since the unknown unknowns will only be apparent once a tidal lagoon is operational. ‘Sediment Regime Alterations’ and ‘Changing Hydrodynamics’ are at the forefront of influencers’ and developers’ minds as the key impacts of tidal lagoons. Whilst there is some differences in the priorities given to ‘Water Quality’ and ‘Restricted Passage and Migration’ by influencers and developers, both impacts are considered to be of high priority by the industry as a whole. These key impacts will be taken forward into the next section of the research where potential solution options are considered for addressing the key environmental impacts of tidal lagoons.

A number of key benefits of tidal lagoons were highlighted by influencers and developers. Influencers’ key benefits provided beneficiaries spanning the ecosystem, society and individuals whilst developers focused mainly on the benefits to the local area and its people. It is expected that this result is due to the strong local connections the developers have with the local project areas. Effective management of environmental benefits and impacts of a lagoon could result in an overall positive impact on the environment (net gain), that goes over and above regulatory requirements. There needs to be consideration of both positives and negatives along with solution options that consider the wider environment if this is to be achieved.

The industry is focusing largely on avoiding or compensating impacts through engineering design, technology and compensation measures. There is a short-fall in the focus being placed on restoring and reducing environmental impacts through operation and maintenance strategies and an underestimation of the potential scope of contribution that compensation and catchment based solution measures could provide. In addition, one of the biggest hurdles currently being presented to the industry is the lack of clear and accessible regulator guidance providing a focused connection point between influencers and developers. The three key industry recommendations from this section of the research are as follows:

- Lagoon-specific regulatory guidance or policy should be developed providing clear and accessible information to both influencers and developers to ensure a smooth development of the sector and reduction in regulatory process times.
- Further research should be undertaken into reducing and restoring environmental impacts through the use of operation and maintenance strategies.
- There needs to be further acknowledgement in the lagoon industry of solution options that go over and above regulatory requirements to provide environmental and economic enhancement to achieve overall project net gain. In particular this should be further investigated within the compensation and catchment based solution options.

These recommendations are carried forward into the next section of this research. They also provide a starting point for other external research that works towards marrying the views of the influencers and developers on the environmental interactions of tidal lagoons.

3.7 Summary

The scoping exercise literature register highlighted the need for industry engagement due to the lack of literature on tidal lagoon specific environmental impacts which was not deemed to be representative of the developments occurring in the industry at the time. Questionnaires with influencers and interviews with developers allowed the first objective of the research to be achieved, i.e. *Identify the key impacts of tidal lagoons*. Alongside this objective the research resulted in a number of other secondary outputs, some of these are presented alongside the key results in this chapter (e.g. key industry challenges and desired future outcomes), and also documented in publication (environmental impact frameworks, comparison of industry perspectives) [110,111]. This chapter also provided a brief consideration of the industry's view on the potential solution options to the key impacts of lagoons. The next chapter builds on this further by addressing the next research objective: to *Determine solution options to the key impacts of tidal lagoons*.

4 Solution Options Investigation

Chapter 3 included extensive industry engagement to determine the likely key environmental impacts of tidal lagoons. It also provided a snapshot of what solutions are being discussed within the lagoon industry. This chapter builds on this research and aims to address the second identified research objective, i.e.:

- Determine solution options to the key impacts of tidal lagoons

Tidal lagoons are a new idea, but the key concepts making up this idea are not new. Other industries have applied similar technology and engineering concepts and as such have had to manage similar environmental impacts. These other applications include use of walls to impound water in the coastal defence, dam, barrage and hydropower industries, and use of turbines to generate energy in river run, pumped storage and tidal stream applications. In addition, environmental impact such as water and sediment pollution, fish and marine mammal impacts, marine spatial planning conflicts and loss of marine biodiversity are commonly addressed in the maritime and river industries. It is expected then that the nascent lagoon industry can draw from the experiences seen in these industries that have already successfully (or not) managed similar environmental impacts. This chapter uses a systematic literature review to quantify the available literature covering relevant solution options from other industries that could be applied to future lagoon developments to address their expected key environmental impacts. This chapter is presented in traditional format: methodology, results, discussion and conclusions. The chapter includes quantitative analysis of what resources are available to the lagoon industry, how this compares to the current industry understanding presented in Chapter 3, where the expertise lies globally, what environmental impacts are being addressed and how applicable and transferable the solutions are for lagoon application. The research in this section of the thesis has been written and published in the journal Marine Policy [126], see Appendix 12.

The main Excel file including the whole screening process, database of solution options and subsequent analysis of that data can be found on Zenodo, referenced as follows:

- K. Elliott, Systematic Review Screening Record & Analysis, (2018). doi:10.5281/ZENODO.1297037. URL: https://zenodo.org/record/1297037

4.1 Methodology

4.1.1 Literature Search

The review uses the PRISMA statement as a reporting style guide [127] alongside guidance from Collaboration on Environmental Evidence [128] on systematic literature review methodology. This method was chosen based on its existing use and recent recommendation in the marine environmental sector [129–131]. Whilst the PRISMA methodology was used and followed in full, Sections 5 and 6 of the CEE were used as secondary supporting guidance to inform key parts of the methodology, such as conducting a literature search and screening documents for eligibility.

The literature search was performed on three databases: Google Scholar (https://scholar.google.co.uk/), SciVerse Scopus (https://www.scopus.com/home.uri) and Science Direct (http://www.sciencedirect.com/). Google scholar is not typically used in systematic reviews due to the way it filters results differently to other search engines, it was included in this research as it was deemed an important search engine to allow the capture of industry related literature. Together, these form a comprehensive database of peer-reviewed research. The collected papers were between 1987 and the cut-off date of 04/04/2017. The following search terms in the title, abstract or keywords allowed the papers to be included in the initial literature search: 'Marine' or 'Ocean', 'Environmental impact' or 'Environmental risk' and 'Solution' or 'Mitigation'.

The search engine results were first filtered by relevance (rather than date) to the search terms; this was expected to give the most accurate papers first. The initial literature search brought up 1114 papers, 688 papers after duplicates were removed. Figure 24 shows a flow chart of paper selection, which is a standard PRISMA reporting guideline. Grey literature, such as websites or documents outside traditional commercial or academic publishing and non-English publications, were excluded from the review at this point if found.

4.1.2 Selection Criteria

The 688 papers from the initial search were screened in terms of their abstract contents. A total of 559 papers were excluded at this stage (Figure 24), with the exclusion criteria and the number excluded for each reason shown in Table 9. The remaining 129 paper abstracts included information on solutions which could be applied to the impacts likely to be presented by tidal lagoons in the future. As a general rule, if the abstract was unclear or any uncertainty surrounded its inclusion it was included for the next stage of screening.

The next stage was full text screening of the 129 papers selected from the abstract screening. The exclusion criteria here were the same as the abstract screening stage, with the additional exclusion factor of books and any further grey literature found, Table 9. Books and grey literature were excluded as any new, credible and innovative solutions were expected to be represented in the up-to-date, peer reviewed research papers. A total of 52 papers were excluded at the full text screening stage of the review.

Following this final screening stage, a total of 77 papers were included in the final data collection and quantitative analysis (Figure 24). The full list of included papers can be seen in Appendix 7. All the papers included had viable solution options presented in their full text that could be applied in the future to the environmental impacts that may arise as a result of the implementation of tidal lagoons in the UK.

Table 9 Paper exclusion criteria at abstract and full text screening stages with number excluded for each reason shown

Exclusion Criteria	Abstract Screening	Full Text Screening
Impacts presented could not be related to lagoons	146	16
Impacts identified but no solution options given	143	11
Focus of the paper is not on environmental impacts	96	16
Focus of the paper on carbon emissions or climate change	67	1
Impacts are purely terrestrial	49	1
Paper is for global scale impacts	44	0
Impacts are of the environment on engineering	13	1
Not available/ Not Found	1	1
Books or grey literature publications	0	5

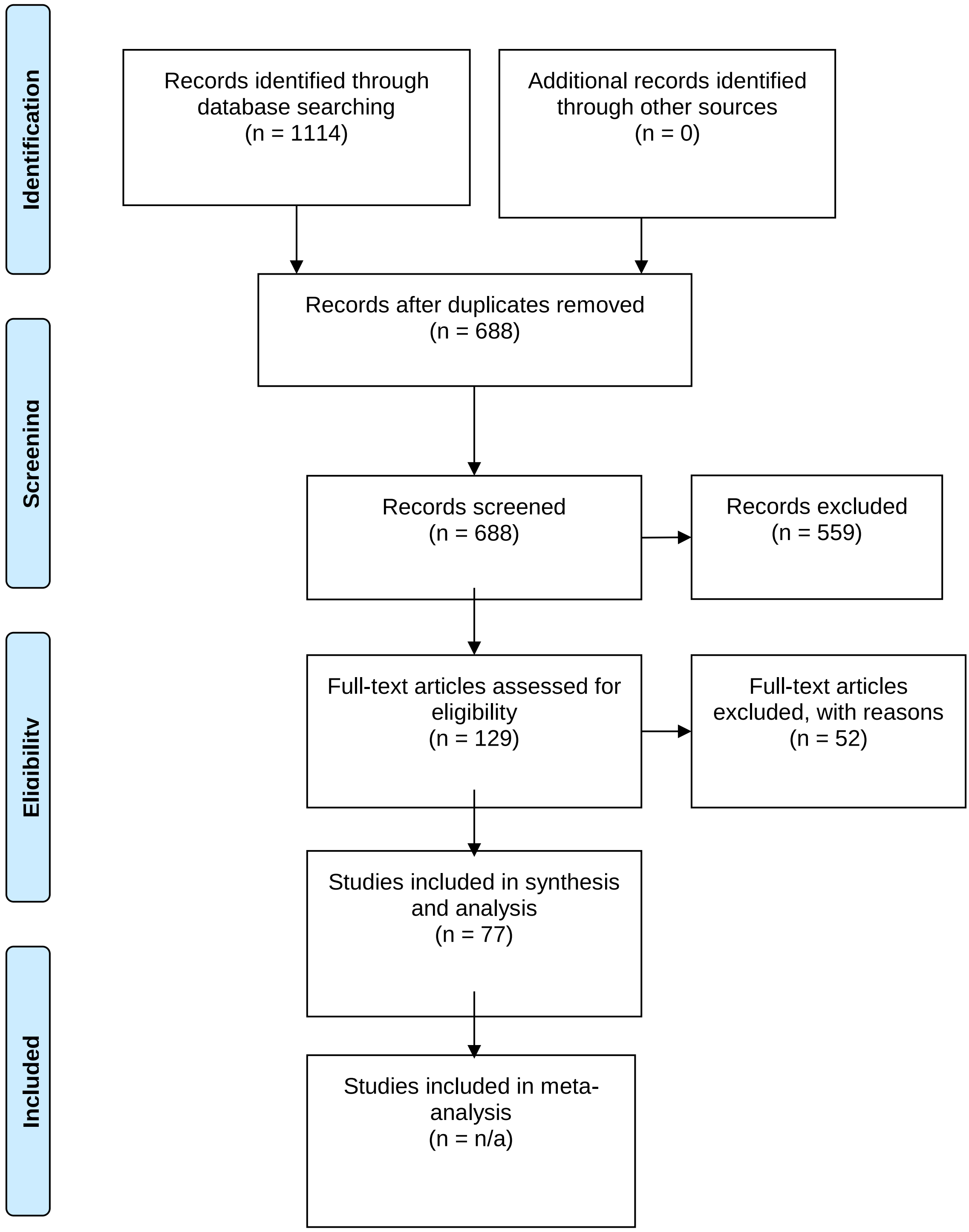


Figure 24 Flow chart of the review paper selection process and the number of papers excluded at each stage. This follows the PRISMA statement guidelines on reporting review process [127]

4.1.3 Data Extraction

From the final 77 papers that remained after the screening process, information for analysis was extracted. The data extracted from the papers centred around two main themes: 1) characteristics of the paper; and 2) solution options presented for environmental impacts. The data extracted from the papers along with information on the purpose for extraction is detailed in Table 10.

Table 10 Data extracted from the final 77 papers, further details and the reason or purpose for extraction

Data Extracted	Details	Purpose
Publication year	Year first published	Provides timeframe information
Author location	Based on first author affiliation	Provides idea of global expertise
Study location	If applicable (not all focus on a location)	Indication of application areas and expertise
Type of paper data	Review, model or analysis of existing data, direct observation, expert opinion	Provides indication of the quality and type of data available is it real world or theoretical
Paper Discipline	Environmental, engineering, social, economic, legal	Indication of from which disciplines solutions are arising
Study area type	Marine, coastal, river, other	Indication of relevance to coastal lagoon applications
Environmental Impact being addressed	e.g. fish and marine mammals, pollution (sediment/water), hydrodynamics, habitats and biodiversity, sediment regime	Indication of which impacts are well researched in terms of solution options
Description of solution option	Qualitative description	Provides understanding of the solution options available
Solution Type	Engineering, site of technology design, operation and maintenance, compensation or catchment based measures.	Provides information on which stage solutions are most well researched and where any gaps lie.
Mitigation hierarchy of solutions	Avoid, reduce, compensate/catchment based	Provides information on which stage solutions are most well researched and where any gaps lie.
1-5 Scale of solution development application	1 = Theoretical, 2= Simulated or modelled, 3= Tested, 4 = Applied at pilot scale, 5= Applied at large scale	Gives indication of how developed the solutions are
1-5 Scale of solution applicability to lagoons	1 = Other Industry, 2= Other industry, easily adapted to lagoons, 3= Marine Industry, not easily adapted, 4= Marine industry, easily adapted, 5=Lagoon or barrage specific	Gives an indication as to how applicable the solutions are to application in the lagoon industry

*Scores assigned on author judgement and literature source information

The information extracted allowed a quantitative analysis of patterns, identification of knowledge gaps and further interpretation of the potential solution options that could be applied to the environmental impacts likely to arise in the future tidal lagoon industry. This builds a picture of the extent and relevance of the literature available and if the solution options presented from other industries could be valuable in the future lagoon industry.

4.2 Results

4.2.1 Analysis of included literature

The number of papers on solution options for environmental impacts increases significantly after 2012, with 70% of the included papers from 2012 onwards (Figure 25). From the first paper in 1987 to 2011 there was an average of only 1 paper published per year. In comparison from 2012 to 2017 the average number of papers per year was 11. This suggests that this research field of beginning to address environmental impacts is relatively new and momentum is building on the subject of solution options.

The majority of papers are review papers (39%), followed by modelling or analysis of existing data (25%) with the remainder being direct observation studies (19%) and expert opinion (17%). The high number of review papers has allowed a greater net to be cast in terms of studies covered in this review (directly or via another review). Review papers are not normally included in systematic reviews but they have been included in this research, normally practice would be to seek out the source references. They are included here if they are reviews of environmental impacts to which solutions were presented, the solutions are what the research is interested in and not the impacts being reviewed. Although it is a concern that the review papers will only provide theoretical ideas rather than concrete data, this is mitigated by the fact that a fifth of the papers included are direct observation papers, indicating that papers that have implemented and directly observed solution options to environmental impacts are also represented in the study.

A large majority of papers on solution options (75%) are from an environmental discipline with the remaining third from either social (12%), engineering (9%), economic (3%) or legal (1%) disciplines. This is not surprising given the strong grounding in environmental disciplines required when considering solution options to environmental impacts. 87% of the papers included in the research are from either coastal or marine view points, this is not surprising given the aim of the study to find solutions for tidal lagoons using search terms ‘ocean’ and ‘marine’. However, the remaining 13% of papers that met the criteria for inclusion were from river or other areas such as inland aquaculture farms or wetlands, showing that a wide variety of other industries could contribute transferable solutions to the lagoon industry.

Assuming that paper author affiliation and study area represents geographical areas of expertise, the main clusters of expertise on solution options to environmental impacts relevant to tidal lagoons lie within North America (30%), Western Europe (14%) and Southern Europe (14%) (Figure 26). The author affiliations and number of papers mapped in Figure 26 show a truly global perspective on the solution options to environmental impacts. It is foreseeable that industry focused studies may be in local languages to reach specific target audiences, these will have been excluded from the study but may still contain valuable solutions.

A large proportion of papers (40%) had no specific area of study. The study area clusters align partly with the main author affiliation locations, with key clusters in Europe, North America and Australasia. Figure 26 represents the review papers' global information gathering on solution options to the environmental impacts that tidal lagoons may present in the future. Despite the most progress on lagoon deployment being made in the UK to date, Figure 26 suggests that there are lessons to be learnt globally from other industries, in particular from the key clusters in North America, Europe and Australasia.

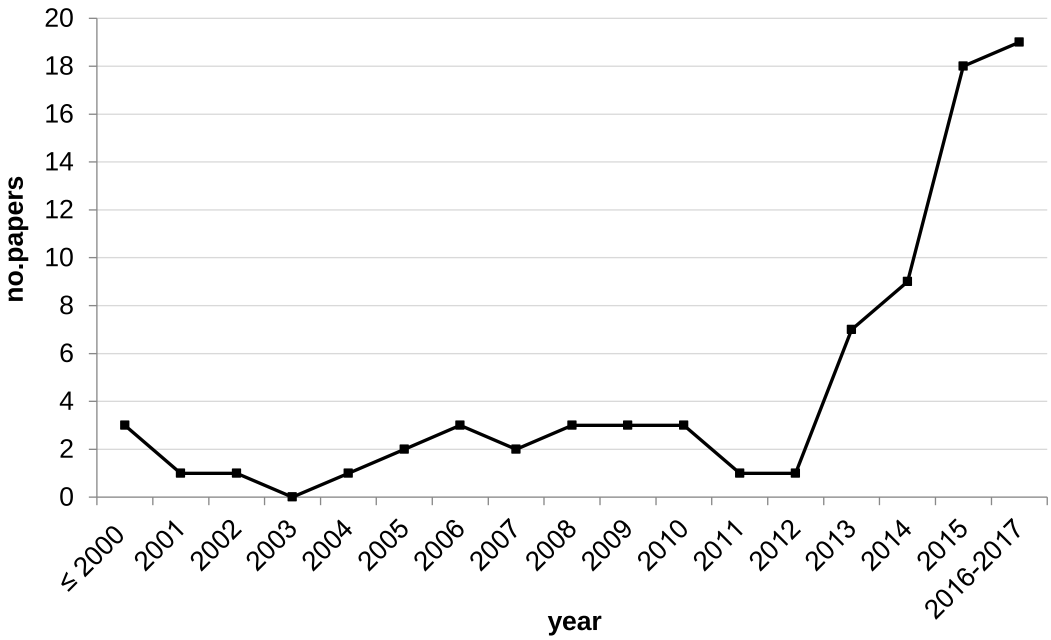


Figure 25 Number of papers per year

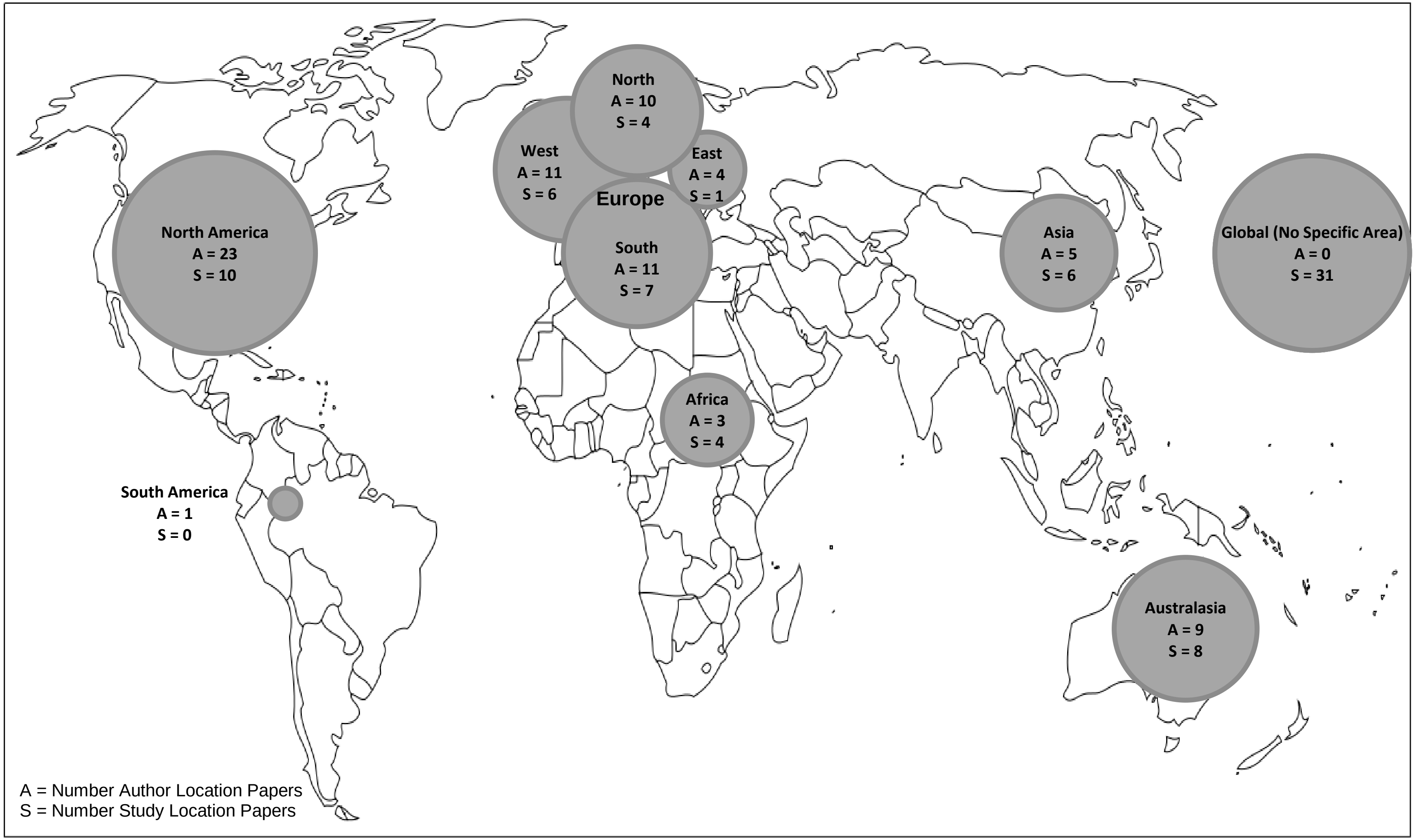


Figure 26 Number of papers per author affiliation location (A) and study area location (S). 31 papers of 77 (40%) had no specific area of study. (Base Map Source: [262])

4.2.2 Environmental Impacts Addressed

Whilst the key environmental impacts from industry perspectives have been discussed in Chapter 3 the environmental impacts addressed in the included papers in this literature review on solution options are varied and numerous. In order to provide an analysis these have been broadly categorised into impacted groups as follows: sediment regime, hydrodynamics, habitats and biodiversity, fish and marine mammals, pollution (water or sediment) and general impacts (more than 5 impacts considered in one paper). Figure 27 shows the percentage number of papers against the impacted group which the papers addressed. These environmental impact groups have been selected based on the impacts addressed in the literature, not on the findings in Chapter 3.

Almost a quarter (22%) of the papers consider solution options for the impact of either water pollution or pollution in the sediment [132–148]. These impacts included marine water quality pollution from oil spills, increased vessel activity and associated pollution, pollution within entrapped or enclosed water bodies and marine litter due to increased tourism. They also included sedimentation pollution due to increased dredging activities and disturbance of contaminated sediments, entrapment of outflows and the pollution of sediment and benthic communities. The relatively high number of papers on these impacts could suggest that they have been common impacts in other marine, coastal and river industries and therefore may also be an issue for lagoons. The papers discussed also present solution options for these impacts, so on the other hand the high number of papers could suggest that these impacts are well researched and therefore more easily addressed.

18% of the papers considered the impacts on fish and marine mammals, including noise pollution due to the construction of marine infrastructure, increased seismic marine surveys and vessel activity, blade interaction, barriers to migration and disruption to breeding grounds [149–157]. A further 16% of papers considered changing hydrodynamics as the key environmental impact [158–169], 13% covered the impact on habitat or biodiversity loss [170–179], with 12% focusing on sediment regime changes including morphodynamics, bathymetry alterations, coastal sedimentation and/or erosion [180–188].

All the impacts considered in the included papers are thought to be applicable to tidal lagoons in the future (part of the inclusion/exclusion criteria). Therefore, the solutions presented in the included papers could also potentially provide the foundation for solution options for the environmental impacts of tidal lagoons.

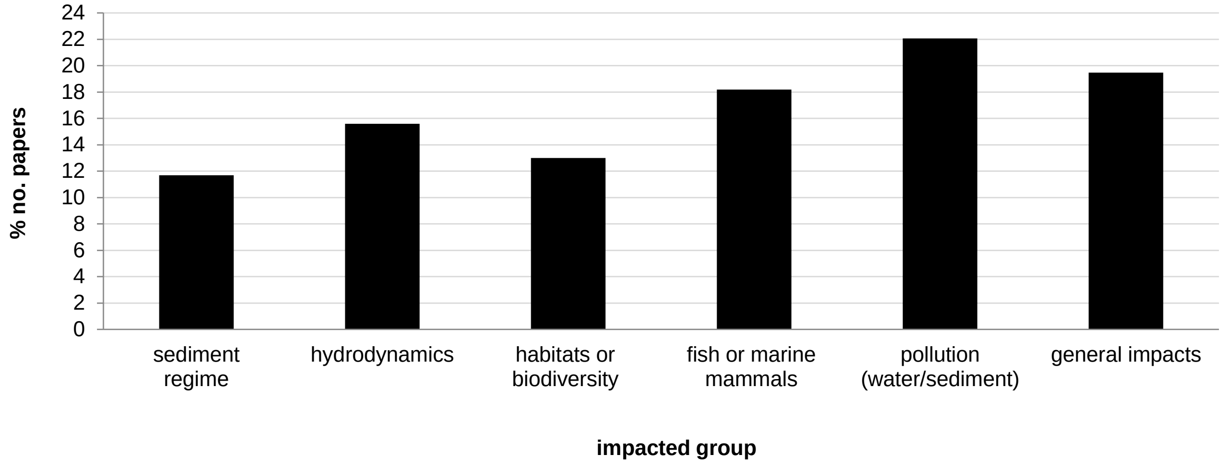


Figure 27 Percentage number of papers addressing different environmental impacts

4.2.3 Solution Options and Lagoon Application

Every one of the 77 included papers addressed a tidal lagoon-relevant environmental impact with a solution. Some of these solution options were the same, but nevertheless a database of literature on potential solution options to address the environmental impacts of tidal lagoons has been created [189].

For analysis the solution options have been grouped into: 'Engineering, site or technology design', 'Operation and maintenance' and 'Compensation and catchment based measures'. Whilst it is impractical to list all of the solution options Table -11 provides examples of solutions within each of these categories and Case Studies 1 to 3 provide further example and detail. Figure 28 shows the spread of papers within these solution option categories.

Within the literature, 44% of the solution options fall under the 'Operation and maintenance' category. This includes, but is not limited to, temporal and spatial zonation of activities, sustainable dredging options and management of dredging material, advances in environmental monitoring, planning vessel activity and safety and operational timing and structure of energy generation. 30% of the solutions were within the 'engineering, site or technology design' category. This category refers to environmental awareness within site location, site design around sensitive locations, novel data or models to aid in site selection, integration of green infrastructure such as coral reefs, careful selection of building materials to promote target habitats, selection of technology to reduce impacts, wall design to reduce impacts and enhance potential environmental benefits. The solution category reported the least in the literature is that of compensation or catchment based measures (25%). Within those solutions examples include habitat creation or restoration papers, payment for ecosystem services (PES) schemes or other catchment based activities. Table -11 provides a more detailed list of solution examples.

Chapter 3 found through industry engagement that the solution options mentioned the most were within categories based on engineering, site or technology design, or compensation and catchment based measures [126]. Neither developers nor influencing organisations mention operation and maintenance strategies most frequently. In comparison this chapter and this literature review found that the majority of papers are on operation and maintenance type solutions. Figure 28 compares the industry's view on solutions from Chapter 3 [126] to the solution categories uncovered as part of this chapter and systematic literature review. The results suggests that the gap in operation and maintenance understanding found in the industry engagement presented in Chapter 3 [126] could be filled with the operation and maintenance solution options found within this literature review.

Traditionally solution options for environmental impacts follow the mitigation hierarchy [190,191]. This includes first avoiding environmental impacts, then reducing and finally compensating where necessary. Although the effectiveness of the mitigation strategy is occasionally questioned [192] it is still an established framework for addressing environmental impacts [193] . The solution options found in the literature review were categorised according to this basic mitigation hierarchy and compared to the text book version (Figure 29). In reality the number of solution options found within this paper do not follow the theoretical hierarchy in that 'avoiding' solutions do not appear in the majority of papers, with 'reducing' solutions next and 'compensation' least. The majority of solutions presented are to reduce environmental impacts, then to avoid and finally to compensate.

Table -11 Selection of example solutions within each solution category

Solution Category	Selection of Examples
Engineering, Site, Technology Design	Sensitive site selection, 'safe' exposure levels and distances from protected or otherwise sensitive areas [194]
	Site selection in terms of best potential for habitat creation within the structures themselves, site selection to promote habitat creation on the structure over that lost during installation [172]
	Using artificial reefs or installing marine structures with appropriate materials that will allow for an enhanced reef effect providing habitat [173]
	Building and designing of green infrastructure within the design plans such as providing green (or in lagoon case blue) corridors or hubs or targeting particular keystone or umbrella species in the design of structures [174]
	Use of multi-purpose offshore installations to reduce impacts and increase viability of blue growth projects [195]
	Advancements in turbine design to reduce collision risk, careful selection of turbines to suit not only energy generation but sensitive species in the area [17]
	Incorporation of bubble curtains, flashing lights, passive acoustic monitoring, fish ladders, spill gates, fish lifts, surface collector or guidance nets, hydro sound dampeners in the initial engineering design for the impacts on fish and marine mammals[149,153,196]
	Use of nearby land sloping characteristics in the initial design of a structure to predict and prevent the amount of run-off related water contamination or in the lagoon case pollution entrapment [148]

	Incorporation of engineering flooding options in the initial engineering plans such as use of beach nourishment or artificial sand dunes to avoid coastal erosion [160].
	Better use of modelling, monitoring, incorporation of historic knowledge and advancements in new techniques, transfer of knowledge between industries, holistic view coupling of models to better understand and select sites, technology and engineering design [135,155,163,181,187,197–200].
Operation & Maintenance	Use of coastal geo-indicators and ecological indicators to provide rapid response to operation and maintenance plans [180][186]
	Integration of ecosystem functioning and ecosystem based management into coastal management practices to reduce environmental impacts, using an ecosystem based approach [201][202]
	Use of dredge and fill beach nourishment techniques to reduce erosion [182]. Could be dredged material from the lagoon.
	Control of sedimentation through sediment retention before entrance, sediment bypassing, control of hydrodynamic flow to reduce sediment accumulation, flushing or sluicing and managing existing deposits through sensitive dredging. Optimal dredging times and frequency. Potential end use of dredged sediments in civil engineering such as road subgrade layers. [179,183–185]
	Use of linkage framework to manage cumulative and overlapping ocean activities resulting in cumulative environmental impacts [203]
	Use of flora to filter pollutants or effluents [146]
	Spatial and temporal zonation and exclusion zones of activities to reduce environmental impacts [156,157,178,204]

	Energy generation operation to reduce hydrodynamic impacts [82]. Careful operations management of vessel activity, relocation of vessel movement to lower risk areas, careful monitoring of vessel speed limits, optimal vessel use in terms of time at sea and frequency of trips to reduce noise and water pollution and chance of collisions or oil/fuel spill [147,156].
	In situ sediment pollution remediation techniques, including thin capping, solidification, sediment flushing, nanocompite reactive capping and bio reactive capping, Stabilisation of sediments using hydraulic binders [137,185]
	Visitor education on environmentally friendly practices in and around tourist attractions to reduce marine litter and pollution [139,205]
Compensation or Catchment Based Measures	Use of habitat creation through wetlands and vegetated ditches to reduce flooding or storm damage or to mitigate water pollution, improve water quality and compensate for loss elsewhere [132,134,142,158,164]
	Use of satellite remote sensing data to find and repair/compensate damage to ecology or habitat loss, mainly used for oil spills currently but could be applied to habitat loss [133]
	Use of geoengineering such as urea fertilisation to increase fish populations or using natural sediment transport systems to deposit sediment along the coastline to compensate for loss [206]
	Use of natural resources to increase flood defence level, such as mangrove restoration or afforestation [165]
	Use of Payment for Ecosystem Services (PES) schemes to conserve threatened ecosystems or to compensate over and above the value of ecosystem lost [207]
	Soft engineering approaches to provide compensation such as mangrove afforestation, coral reef transplants or introductions, marine reserves, planting of water filtering plants [161]

	Use of bioremediation methods like those seen in water pollution incidents [136]
	Incorporating net gain bargaining in development of marine energy, integrating ecosystem service impacts into decision making [176]

Note: These solutions are just to provide examples within each category. They are not a comprehensive list of solution options. To see the full list go to the database on Zenodo (see link in Chapter Introduction)

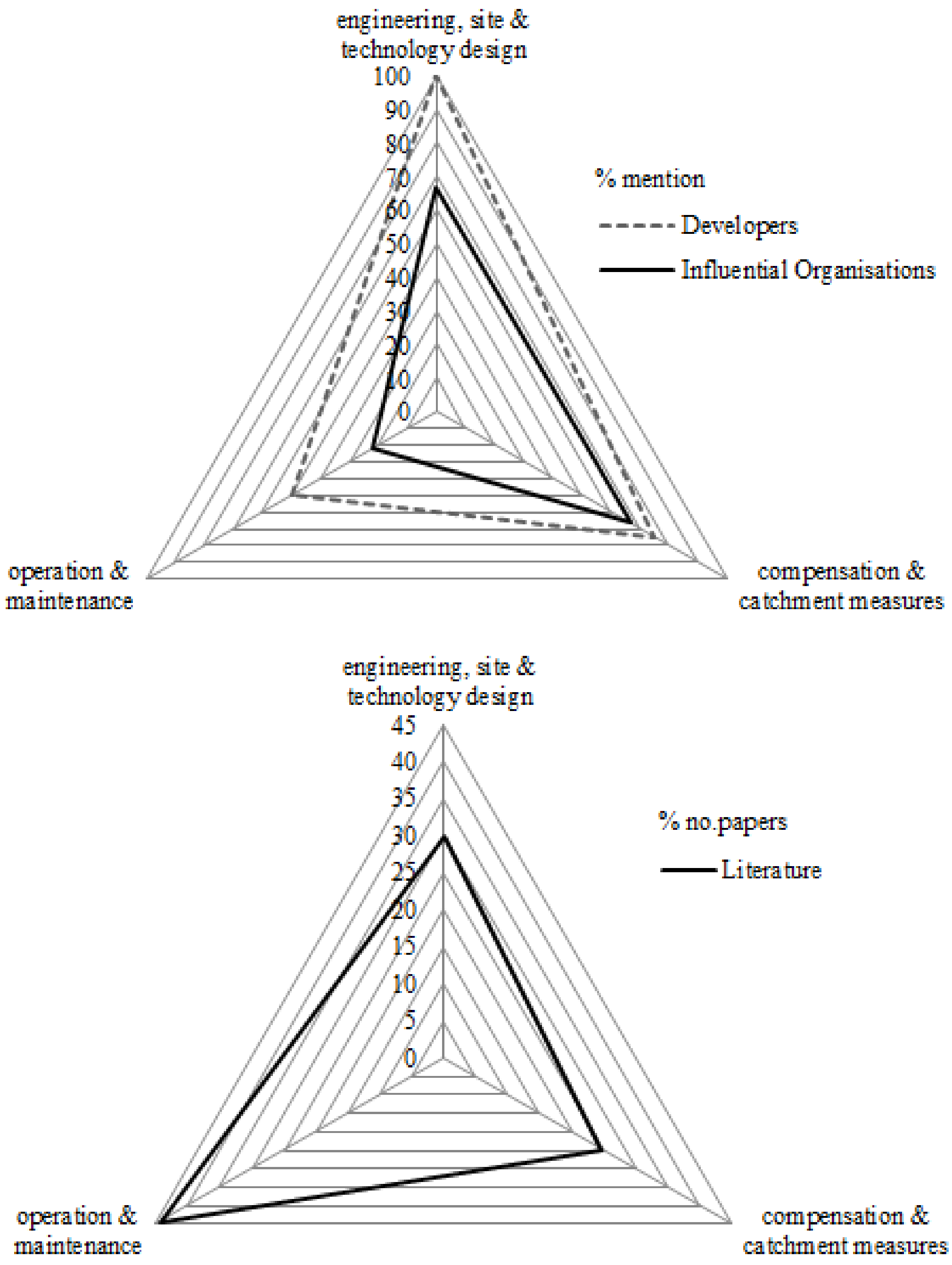


Figure 28 Spread of solution options mentioned in industry engagement (Chapter 3 Figure 22) (top) [126] **and within this Chapter literature review (bottom) over three basic solution option categories**

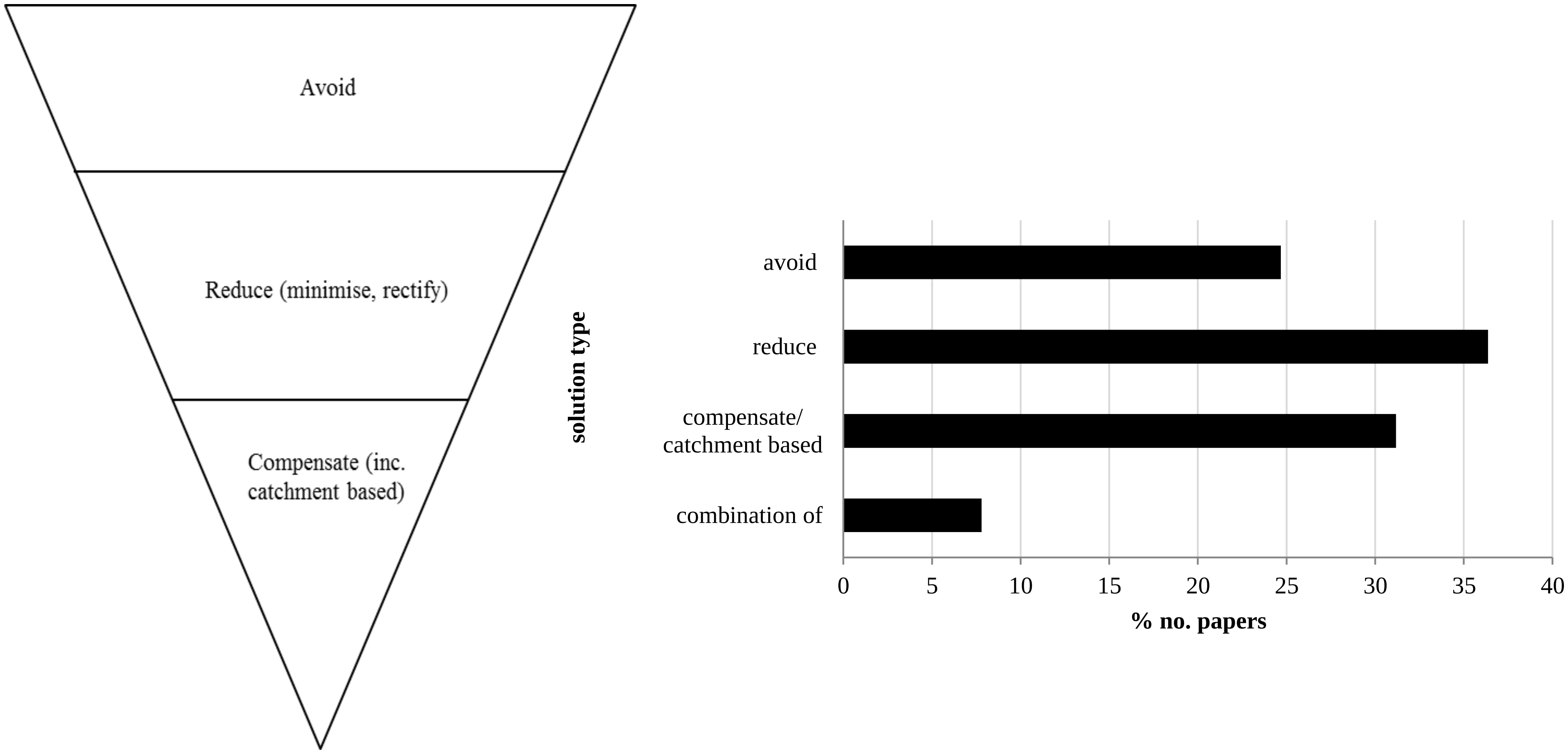


Figure 29 Traditional mitigation hierarchy (left) compared to the solution options found within this systematic literature review (right)

4.2.3.1 Solution Case Study 1: VETT Turbines and Impact Avoidance

A key concern with tidal energy schemes is the impact of fish mortality. The first stage of the mitigation hierarchy is to avoid impacts, with one strategy being through careful technology choice. The Venturi-Enhanced Turbine Technology (VETT) being developed by VerdErg is based on the Bernoulli principle and exposes no moving parts to the water channel [208]. VerdErg have achieved excellent results in recent tests, showing no impact on fish mortality with passage through the VETT's primary flow path [209]. This is therefore an example of a potential technology choice which could reduce the impact of a tidal energy development on fish mortality.

4.2.3.2 Solution Case Study 2: River Fowey PES Scheme

An example of a catchment-led approach to addressing environmental problems is that of the River Fowey PES auction. The River Fowey had issues with water pollution as a result of cumulative agricultural run-offs [210]. The West Country Rivers Trust, as part of the 'Upstream Thinking' initiative, distributed funding to farmers via a competitive bidding auction to deliver land-based measures which in turn improved the river's water quality [210]. Similarly, PES has the potential to help reduce nutrient levels in coastal waters e.g. nitrogen levels in Poole Harbour as per the Defra PES pilot project [211]. This type of approach could be applied to not only offset any negative environmental impacts which may arise due to tidal lagoon development, but to help to deliver an overall net gain in the methods used to address the environmental impacts of a lagoon development.

4.2.3.3 Solution Case Study 3: Built-In Enhancements, Sydney Harbour

Adding new infrastructure in the sea will be a driver for change in the marine environment [212]. Building in enhancements early on in the engineering design can increase the positive environmental impacts of a development, contributing towards achieving environmental net gain. An example here is the intertidal habitats created in seawalls in Sydney Harbour. The designs do not compromise the engineering requirements or cost but do increase the diversity of species able to live on the sea walls [212]. Figure 30 shows a photograph of their construction.

Figure 30 Built in rock pools in Sydney Harbour walls. Source: [212]

4.2.4 Relevance to Lagoons

The 77 papers included in this review present a wide variety of solutions, some theoretical, others already applied in large-scale industries. Some of the solution application industries are similar to tidal lagoons, for example tidal barrages, others from less similar industries, like the natural hazard management sector. Each solution was ranked based on two scales, the first on level of development (theoretical or applied), and the second on relevance to lagoons (lagoon specific or other industry) this was based on information from the literature sources and author judgement (Figure 31). This was a highly subjective process. In this research only the authors judgement was used and was based purely on the information provided in the resource in which the solution was obtained, from personal or colleague experience/knowledge of the sector. This included any examples or case studies of its use (at utility, commercial, prototype or theoretical model scale), and information on where and what application it was used for e.g. river industry, marine industry, hydroelectric industry or other. The uncertainty around these scores is therefore high. This uncertainty could be reduced if used in practice by conducting rigorous expert engagement to gain expert advice on each solution and/or using implementation/operational data sets on solution use to demonstrate and support evidence of its implementation, application and relevance to lagoons. The purpose of this was to determine how developed and relevant the solutions presented in the gathered literature might be to the future lagoon industry and therefore if this collection of literature could be a useful resource justifying further investigation in the future. Hence why no further rigorous expert guidance was sought or comprehensive data sets used. It aims to provide a first look at what is available currently to the industry.

The majority of solutions fall in the middle of being not quite lagoon-specific, but perhaps related to marine renewable energy and not fully applied, for example, applied at pilot scale or in testing. The bold black box in Figure 31 outlines over half of the solution options that require only minor shifts in either their development to applied scale or to be adapted to be lagoon-specific before they could potentially be implemented in the lagoon industry in the future.

Solutions Matrix		**Theoretical** →				**Applied**
		1	**2**	**3**	**4**	**5**
Other Industry	**1**	0	2	0	1	0
↓	**2**	1	4	7	6	3
	3	2	2	7	8	5
	4	2	6	5	5	6
Lagoon Specific	**5**	0	0	2	2	1
					Total	77

Figure 31 Matrix of solution options in terms of their development to applied scale (1 to 5, 5= fully applied, 1=Theoretical) and adaption to be lagoon specific (1=Other Industry, 5=Lagoon or Barrage specific). Graded Colour Scale: No.Papers ≤2 Light Greens, 3-5 Medium Green, ≥5, Bright Greens.

4.3 Discussion

The field of solution options for the environmental impacts likely to arise as a result of tidal lagoons is relatively new. The large growth in the number of papers over the last 5 years shows that the environmental industry is gaining momentum. This momentum is supported by the growth of the regulatory and legislative environmental sector and the increasing pressure for corporate environmental awareness and responsibility.

The lagoon industry is nascent, and environmental impacts are one of the key concerns for any future lagoon industry. With no operational man-made energy generating tidal lagoons in the world, there is no operational data on the environmental impacts of lagoons and no solution option guidelines to work by. Whilst tidal lagoons are a new concept, the technology and engineering feat they present is not new, and the individual engineering applications have been applied in other industries e.g. tidal barrages, dams, hydroelectric power stations, tidal stream turbines, breakwaters and coastal defence mechanisms. As such, the environmental impacts likely to arise from tidal lagoons are also likely to have already arisen and been addressed in other industries. This systematic review shows that there are wide-ranging solution options documented in the literature which have been either applied or suggested in other industries to address impacts similar to those which are likely to arise in the future lagoon industry. The review quantitatively analyses the literature to show the relevance and development stage of these solutions and if this resource warrants further investigation for the industry in the future.

The solution options have been analysed in terms of their potential to fill gaps, specifically the gaps in industry knowledge found in Chapter 3 during industry engagement [126], the cluster of expertise on solution options globally, the impacts which they seek to address and how well developed and adapted they are to a potential application in the lagoon industry.

The use of systematic literature review in the marine environmental sector is not a new idea [129–131]. O'Leary et al (2015) identifies eighteen systematic reviews published on marine topics between 2008 and 2015, with 25% of those using the same PRISMA method used in this research [213]. O'Leary recommends the use of PRISMA alongside the guidance published by Collaboration for Environmental Evidence, The paper identifies the risks of using only the stand alone PRISMA methodology without additional guidance and states that using only PRISMA methodology can give the impression of having undertaken a more rigorous review. This research uses both the PRISMA method and the Collaboration for Environmental Evidence guidance as recommended by O'Leary et al (2015) [213].

Liquete et al (2013) recognise that environmental assessment has grown rapidly over the last decade in their systematic literature review on the future prospects and current status for the assessment of marine and coastal ecosystem services [129]. The paper identifies that the majority of current papers focus purely on terrestrial information and move on to highlight the knowledge gaps in the marine and coastal sectors. Liquete et al (2013) use systematic literature review to classify and map marine and coastal ecosystem services and doing so, extract 476 indicators. Their review summarises the state of the available information related to ecosystem services in marine and coastal environments and is a key example of how systematic reviews can be used in the marine environmental sector to further quantify the knowledge base available within existing literature.

Sierra-Correa et al (2015) provide a further example of how systematic review can be used to obtain new knowledge from existing literature in the coastal or marine environment. The paper conducts a systematic review using PRISMA methodology with a focus on human-environmental interactions and ecosystem-based adaption for improving coastal planning on mangrove coastlines.

4.3.1 Addressed Environmental Impacts

All the papers included in the review consider environmental impacts relevant to tidal lagoons; this was part of the exclusion/inclusion criteria. One of the key impacts addressed in this literature review is that of water or sediment pollution. The high level of research on this impact suggests that it is a common impact in other coastal and marine industries globally and therefore should be further investigated in terms of the lagoon industry. Water or sediment pollution was not within the top three environmental impacts suggested by the lagoon industry in Chapter 3 [126].

The lagoon industry has indicated that one of the top three most significant impacts that tidal lagoons could present in the future is the impact on fish and marine mammals through restricted passage and migration, see Chapter 3 [126]. The systematic review in this Chapter provides evidence that there is a relatively high number of papers within the body of knowledge that provide solutions to address this impact, and therefore the lagoon industry should use this knowledge to address the key issue that was raised during the industry engagement. In fact both water or sediment pollution and fish and marine mammal impacts have a high number of papers and therefore solution options. Conversely, perhaps this provides an explanation as to why the industry perspective did not highlight water or sediment pollution as a key impact [126], if they are already aware of documented solutions options to address it uncovered in this review.

If we assume that the number of papers for an environmental impact relates to the level of research of solution options available for that impact, then the impacts with the lowest number of papers are the impacts with the least research on solution options available. These impacts may present a higher risk for the lagoon industry. The impacts with the lowest number of papers in the review, suggesting the lowest level of research on solution options, are sediment regime changes, hydrodynamic change and impacts on habitats and biodiversity. These impacts were also highlighted by industry as being the most significant environmental impacts that lagoons could present in the future [126]. It can be inferred then that these impacts are likely to be key barriers in the development of the lagoon industry unless suitable solution options can be found, adapted and applied at lagoon scale.

Although the number of papers for these key impacts is lower than for other impacts, there are still some solutions presented, and therefore solutions available to address these key impacts. In addition, the quantity of papers does not necessarily reflect on the quality or quantity of solution options presented. The solution options found in the literature should be used as a foundation or starting point for a drive and focus towards the development of applied, lagoon-specific solutions for these key environmental impacts.

4.3.2 Application of Solutions

The literature presents a vast global knowledge base, spanning a variety of marine, coastal and river industries that could be drawn upon to address the potential environmental impacts that might arise from tidal lagoons in the future. The tidal lagoon industry has the benefit of hindsight and learning from other industries with similar environmental impacts. It could and should utilise this.

The lagoon industry at present is very UK-orientated; the developers, regulators, policy makers, practitioners and consultants involved are largely based in the UK for now [126], however this review has shown there is relevant expertise from other industries worldwide. The first-mover country for tidal lagoons will have a significant opportunity to boost its indigenous socio-economics via its developed supply chains, increased employment and knock on economic gains. This has been planned by TLP in the UK, for example [119].

This systematic review into solution options shows a global knowledge base of options available to address environmental impacts from other industries. There are clusters of expertise on impact solutions all over the world. The nascent lagoon industry should draw upon this global expertise. Using, adapting and implementing global knowledge within tidal lagoons will help address and progress global goals, such as that of addressing climate change. The recent advancements in the UK tidal lagoon industry therefore have global relevance. This audience also has solution options and knowledge to provide. Wherever the first tidal lagoon is developed they will be able to capitalise not only on the developments made in the UK so far but also the existing global expertise. The first movers in this sector will also then be world leaders, with a global audience to export skills and knowledge back out to.

The review shows that the majority of solution options are arising from environmental disciplines. This is understandable given that a strong understanding of environmental impacts is essential to provide effective solution options. Environmental impacts are likely to have multidisciplinary implications, such as on the economic, social, engineering and legal sectors. As such, it would be beneficial for the lagoon industry if these sectors were also involved in the designing of solution options for environmental impacts, providing a multidisciplinary approach to a multidisciplinary issue.

It was found in Chapter 3 that the majority of industry stakeholders focused on solution options related to engineering, site or technology design or compensation and catchment based measures [126]. A gap in the industry solution options was presented in the form of those relating to operation and maintenance strategies [126] (Figure 28). In contrast, the literature presents the majority of solutions to be in the operation and maintenance category. The knowledge base within the literature could help fill gaps in the industry's understanding of solution options.

Combining both the industry understanding on solution options and the solution options found within the literature it seems that most bases are covered for addressing the environmental impacts of tidal lagoons. It is important for the lagoon industry to not only draw upon expert advice within the industry and from its stakeholders but also to refer and investigate further the available literature from other industries. In this way, the lagoon industry can find solution options from engineering, site and technology design, operation and maintenance and compensation and catchment based measures. This will reduce the number of gaps seen in the solution options available. Whilst most bases are covered in this way, the key question is now if those solution options are developed and specific enough for applications in the lagoon industry.

Whilst the majority of papers included in this review are reviews themselves, 19% are direct observation. This suggests that some of the solution options being presented in the literature have also been applied and observed and therefore are not just theoretical ideas. Figure 31 in the results gives a clearer picture of the number of solution options which are applied as opposed to theoretical and lagoon specific as opposed to from other industries. The majority of solution options presented in the literature are more advanced than purely theoretical but not quite applied yet on a large scale. Similarly, the majority of solutions are in the marine or coastal industries but not yet specific for use in the lagoon industry. Over half of the solution options in the literature are on the brink of being realistic options for lagoon scenarios in the future. Work is required to shift them towards being applied at larger scales and adapting them for lagoon specific applications, but they are ready and waiting to be advanced.

The key message is that even though the lagoon industry is nascent and there is uncertainty surrounding its potential environmental impacts, the solution options do not have to be completely new, novel or innovative. This chapter suggests that with a relatively small amount of development, previously successful solutions applied to similar environmental impacts in related industries can be adapted to successfully address any environmental impacts that may arise in the future lagoon industry. This review shows that there is a valuable global literature resource representing solutions from other industries which should be further investigated for tidal lagoons. It is assumed that because of this global resource there will also be global expertise potential and a global audience for the first movers to export skills and knowledge to.

4.4 Conclusion

There is pressure on the lagoon industry, and in particular whichever scheme becomes the first lagoon in the world, to ensure that any environmental impacts which may arise are addressed successfully. The world’s first lagoon needs to set the precedent on addressing its environmental impacts if the future lagoon industry is to flourish sustainably. With no operational tidal lagoon data available, there is no guidance on solution options for tidal lagoon environmental impacts. This review uses the PRISMA reporting guidelines methodology along with guidance from Collaboration on Environmental Evidence to consider a total of 1114 papers with a final 77 papers presenting solution options to the environmental impacts likely to arise as a result of tidal lagoon development.

The key environmental impacts according to the industry engagement discussed in Chapter 3 [126] are also shown in this review to have a reduced level of research available on solution options. These could present further concern for the industry and should be a focus for further research. Whilst this is a concern, the categories of solution options presented in the literature have also been shown to fill a gap in the current industry understanding.

The global spread of solution options gives the tidal lagoon sector a global audience and arena within which to both import and export knowledge and skills. The literature resource on solution options is vast and should be a valuable resource for the nascent lagoon industry. Other industries have applied similar engineering and technology concepts presenting and addressing the same environmental impacts which are expected of tidal lagoons. The lagoon industry can benefit from their hindsight and should capitalise on the opportunity to learn from this experience.

To conclude, this chapter quantitatively analyses environmental solution literature to identify the extent and relevance of this available research as a resource for the nascent lagoon industry. It opens the door on a vast and valuable research resource that the industry should be investigating. Over half of the solutions found in this review require only small shifts in their development for them to be realistic solution options for the lagoon industry in the future. This finding highlights and justifies the need for further investigation into transferable environmental management and policy options for application in the lagoon sector.

4.5 Chapter Summary

This chapter aimed to address the second research objective, i.e. to determine the solution options to the key impacts of tidal lagoons. This was achieved through systematic literature review of the transferable solution options from other industries that address similar impacts to those likely to arise as a result of tidal lagoons. This method was used as there are currently no tidal lagoons in the world with no known lagoon specific solution applications to monitor or draw expertise from. A large literature resource was uncovered and quantified, and it is recommended that this resource be investigated further and utilised within the nascent lagoon industry.

The solution options uncovered in this chapter are documented in a database on Zenodo [189]. Whilst an initial consideration of their applicability and relevance for lagoons has been undertaken this database does not provide a methodology to allow comparison and selection of the different solution options. The next section of the research presented in Chapter 5 considers how solutions can be selected, analysed and valued through a basic Multi-Criteria Decision Analysis (MCDA) for selection of solutions followed by a Cost Benefit Analysis (CBA) of solution option combinations. This CBA also includes consideration of the wider environmental implications of solution options and comprehensive ecosystem service assessment (ESA) and valuation (ESV).

5 Solution Assessment & Valuation

5.1 Introduction

Through industry engagement Chapter 3 identified the key impacts of tidal lagoons. Chapter 4 explored solution options to these impacts through systematic literature review of transferable options from other industries. The impacts have been identified, a database of solutions to address them created; the next stage of the research is to determine how to select and assess these solution options. This chapter builds on the previous research and aims to address the third and final objective to:

- Assess solution option combinations for addressing the key impacts of tidal lagoons

Traditional parameters considered in solution selection include: solution cost, development stage, applicability to the development (relevance), likely success and level of uncertainty. The first section of this Chapter applies a multi-criteria decision analysis (MCDA) to select two groups of solution options, considering these traditional parameters. The first group of solutions is deemed to be 'optimal' (Group A) in terms of the traditional parameters (low cost, well developed, relevant, successful and certain), the second group is deemed 'less-optimal' (Group B). The MCDA demonstrates a method of selecting a group of targeted solution options from a large database of solutions that addresses the key impacts of tidal lagoons. The database of solutions selected from is that which was created in Chapter 4. Groups of solutions have been selected rather than treating the solutions individually, this allows for consideration of the cumulative influence of solutions applied and to allow for solutions to address each of the key impacts to be considered simultaneously, it was also deemed an appropriate approach given the time constraints of the research.

Lagoons have the opportunity to be multi-use, multi-function, multi-disciplinary projects. The environmental impacts of lagoons and the solutions implemented to address them will have significant wider environmental, social and economic implications (both positive and negative). It is therefore worthwhile considering this wider 'value' in solution comparison, appraisal and selection.

In order to represent this wider value, the next stage of the research implements an ecosystem service assessment (ESA) and example valuation (ESV) which weights up the costs and benefits (CBA) of the marginal changes to ecosystem services as a result of solution implementation. Note this is not the costs and benefits of the financial cost of the solutions, it is the costs and benefits to the change in ecosystem services only. This wider assessment is undertaken on the two different solution groups selected during the MCDA ('optimal' Group A and ‘less optimal’ Group B). In this way, it can be determined if capturing the wider environmental, social and economic ‘value’ of solutions changes our understanding of what is ‘optimal’ and therefore the ‘optimisation’ of lagoons. This research demonstrates a methodology for selecting, assessing and comparing solution options to the environmental impacts of tidal lagoons and is to allow for further development of the knowledge in the sector and as a demonstration of how the wider value could begin to be captured in these developments. If it were to be applied in practice it would be set within the context of robust site-specific data and information. Given the values in this research are based on literature findings and assumptions the exact figures and values within should not be relied upon or any weight placed on them, the descriptive side of the ecosystem services is where the research is aiming to focus.

Part of this research was presented at the International Conference on Coastal Engineering (ICCE), see Appendix 8 and 9. The majority of this section of the research has been carried out in two main spreadsheets; both are made available to the reader with author permissions, should they require more information or further detail on the example values used, as follows:

- MCDA and solution selection of ‘optimal’ (Group A) and ‘less-optimal’ (Group B) [214]
- ESA, ESV and CBA of solution groups A and B: [215]

This Chapter follows a standard layout: introduction, methodology, results and discussion but also includes a brief background on the analysis tools implemented in the research. The Chapter is unavoidably table-heavy, the reader is encouraged to view the spreadsheets in which the work is presented as many of the tables are transferred from these.

5.2 Research Tools: Brief Background

MCDA is a popular tool which allows consideration of multidisciplinary and multi-unit criteria in decision making, it is often used in the sustainable development sector [86]. MCDA was chosen for the first selection of the solution groups for this reason, its ability to compare otherwise incomparable criteria such as: solution cost, development stage, applicability to the development, likely success and level of uncertainty for all the solution options for each environmental impact with one tool. MCDA can also be used to include environmental criteria such as ecosystem services, but this research has chosen to focus on this side of the research with a more specific, representative and detailed Ecosystem Service Assessment.

Other alternatives to MCDA, such as decision trees, only using cost parameters, or taking each solution individually for each of the criteria was deemed either not comprehensive enough or too time consuming for the purpose of this research, making the results not proportionate to the time needed to get to them. MCDA was deemed both time efficient and comprehensive enough for the scope of this research. One other advantage of MCDA (although not implemented in this research) is its ability to assign weightings to different criteria based on individual or project objectives. If this process were to be applied in practice, it is likely that weightings would be used, it is often difficult to provide strong justification, reasoning or references behind the different weightings when they are assigned and so this is often a major criticism of MCDA as a decision tool. Given that weightings can be based on personal preference and can have a strong influence on the final outcomes of the process there is a risk of introducing strong biases into the process and tweaking the final results to suit personal objectives. This is perhaps more sensitive in situations where developments are strongly linked to political influences or strong public opposition.

The next stage of the research uses the ecosystem service approach to incorporate the wider environmental aspect of solution implementation into the assessment and decision-making process. The Ecosystem Service Assessment (ESA) allows the impact solutions have on the environment and the knock-on impact of these on society to be described and quantified in terms of ecosystem services. Whilst MCDA can incorporate environmental and social aspects, it was deemed that an ESA would be a more thorough and detailed way to consider the true impact of the solutions on the marginal changes to the ecosystem services. However, as is recommended later in this research, results of an ESA can then be used to inform which targeted criteria could be input into the MCDA process to represent the environmental and social aspects, which in practice would stream line the process and allow for only one tool or method to be used e.g. MCDA. If one tool is used, this allows for easier direct comparison between different scenarios, different projects or different sites.

To provide a single unit for the information in an ESA, where relevant and proportionate to do so, it is possible to attach monetary values to the marginal changes in ecosystem services as a result of solution implementation. It is vital to note here that these monetary values obtained are only a very small part of the overall process and should not be focused on or taken as the final message. If this were to be applied in practice any monetary values which are obtained through an ESV should always be set back into the comprehensive and detailed setting of the descriptive ESA and would always be based on robust data sets and information which is site specific. This research presents the monetary values which were obtained based on the findings of an ESA as the final step in the process. The emphasis of this research is on the descriptive ESA and not the monetary values which are provided for **demonstration of the process only,** due to them being based on literature findings and a set of assumptions and not on robust site specific data. As such if more detail on the methodology of obtaining the exact monetary values is of interest to the reader, they should refer to the Appendix 11 or the Zenodo spreadsheet [215]. It is not included in the main body of the thesis, to avoid too much emphasis being placed on the monetary values by the reader.

The majority of this chapter and the main value of the research is obtained in description of the changes to ecosystem services as a result of solution implementation, these are then quantified in terms of likely significance and, where proportionate and relevant to do so and for demonstration only, they are valued (monetary values attached). This process should not end with the monetary values as the key message as is commonly understood [98,216,217] but that these should then be set back into the context of the descriptive and quantified assessment.

The main negatives of using the ecosystem service approach is the amount of uncertainty, error and potential subjectivity involved in the process, this can be particularly dangerous if monetary values are assigned and then set out of context of the descriptive ESA or too much weight is placed on the monetary values out of context of the background story. This research recognises this danger and attempts to place more emphasis on the descriptive ESA side of the research throughout the process and provides only a small example of how monetary values could be assigned as a demonstration. The output values are only as good as the input information.

5.3 Methodology

The research included an MCDA for solution selection, an ESA for assessment of solutions and an ESV and CBA for valuation, appraisal and comparison of solution options. The methodology is structured to allow a walkthrough of this process.

5.3.1 Solution Selection (MCDA)

Prior to the start of the MCDA, the database of solution options created in Chapter 4 was upgraded to make it more 'usable' to the industry. This included combining it with the key impacts database in Chapter 3, showing the solution options alongside each key environmental impact. The database is now searchable and is in use as a 'look-up' tool for solution options to key environmental impacts of lagoons. Additional features were added to this, including site parameters that could provide early indication of an environmental impact should a lagoon be developed there, and a list of indirect environmental impacts linked to each key impact. An example of this is for the key impact of 'sediment regime changes', where there are early site indications of 'high turbidity' and 'high sedimentation and transport rates' with indirect impacts such as 'benthic habitat loss', 'coastal erosion' etc. This updated look up tool is part-of and incorporated into the MCDA spreadsheet [214].

To select different solution options for the key environmental impacts to allow for later assessment, valuation and comparison a MCDA was undertaken on the solutions look-up database. The criteria used in the decision analysis were as follows: solution cost, solution stage of development, solution relevance, solution likely success, level of indirect impacts

Optimisation Score	Cost Range	Development Stage	Relevance to Lagoons	Likely Success	Addressed Impact Level
1	> £5m	Theoretical	Other Industry, not easily adapted to lagoons	Low	<10% of impacts addressed
2	£1m to £5m	Tested	Other industry, easily adapted	Low-Medium	10% - 25% impacts addressed
3	£100k to £1m	Applied at small scale	Marine industry, not easily adapted	Medium	25% - 50% impacts addressed
4	£1k to £100k	Applied at full scale <10 years	Marine industry, easily adapted	Medium - High	50% - 75% impacts addressed
5	≤ £1k	Applied at full scale >10 years	Barrage, lagoon or hydro specific	High	75%-100% impacts addressed

addressed and level of uncertainty.

Table 12 below shows the criteria used and the ranked ‘optimisation score’ assigned to them. The preferred way of assigning values would be based on lagoon specific data; however the lagoon industry is in its infancy and this data is not available. The next best approach was deemed to be to use the relevant chosen criteria and assign a rank based on author judgement and literature resources.

The bands for the criteria were set using working examples form the resource of literature obtained during the previous chapters on solution and environmental impact investigation alongside expert author and colleague judgement. The cost bands for example were provided based on an upper and lower limit from key confidential industry knowledge with reasonable bands then set within these. The addressed % impact level considered the list of indirect impacts against each environmental impact and how each solution might address these, for example if all of the indirect impacts would be addressed by a solution it was deemed that this would score 100% on the addressed impact level, if the solution addressed none of the indirect impacts on the list, this scored 0%. The list of indirect impacts can be found next to each environmental impact in the MCDA spreadsheet [214]. Figure 32 shows an example of indirect impacts list related to the environmental impact ‘sediment regime changes’. The development stage was based purely on the information provided about the solution from the resource it was obtained from, this usually provided information of if the solution had already been applied in practice, only the most up to date resources were used and google searches of each solution confirmed its development stage. The relevant to lagoon criteria was based on author judgement, any solution which had been applied to a barrage, lagoon or hydroelectric site was deemed highly relevant. Any solutions in the marine industry that could be easily adapted to lagoons the next relevant, not easily adapted after that, from another industry and easily adapted following and finally the least relevant solutions were those that were from another

Optimisation Score	Cost Range	Development Stage	Relevance to Lagoons	Likely Success	Addressed Impact Level
1	> £5m	Theoretical	Other Industry, not easily adapted to lagoons	Low	<10% of impacts addressed
2	£1m to £5m	Tested	Other industry, easily adapted	Low-Medium	10% - 25% impacts addressed
3	£100k to £1m	Applied at small scale	Marine industry, not easily adapted	Medium	25% - 50% impacts addressed
4	£1k to £100k	Applied at full scale <10 years	Marine industry, easily adapted	Medium - High	50% - 75% impacts addressed
5	≤ £1k	Applied at full scale >10 years	Barrage, lagoon or hydro specific	High	75%-100% impacts addressed

industry completely and would not be easily adapted to a lagoon scenario. Likely success was based on development stage and lagoon relevance, author judgement was used here, a solution that is only theoretical and is not relevant to lagoons and not expected to be easily adapted is likely to have a low likely success.

Table 12 MCDA optimisation parameters and scoring scale

It is possible to assign weights to the criteria, but for this analysis the weights are equal. Arguably the lagoon industry is still in its infancy and so it is impossible to sensibly assign weights at this stage, in addition it is a decision makers preference based on project specific goals as to what weights are assigned. This research is a demonstration of methodology to consider solutions on a high level, as such weights have not been assigned.

Every environmental impact has several solution options that can address it. Each solution option for each key environmental impact was scored 1-5 across all of the criteria in

Table 12, see Figure 32 for an example run through of this methodology. These scores were assigned based on judgement/ opinion with guidance from the literature which the solutions were sourced from. The average of these scores was taken and this provided the overall optimisation score for that solution. A high optimisation score meant a solution of low cost, high development stage, relevant lagoon application, successfully implemented previously and ability to address the majority of the indirect impacts, and vice versa for an overall low optimisation score.

Given that this process is highly subjective, uncertainty was considered throughout the process. Uncertainty surrounding the solution, the key environmental impact and the cost of the solution was taken into consideration again using a simple 1-5 scoring system (5=high uncertainty, 4=medium- high, 3=medium, 2= medium-low, 1=low). This uncertainty score acted as ‘error bands’ around the overall optimisation scoring. Figure 32 shows an example run through of this method and results for one key impact. This process was undertaken for all the key impacts of tidal lagoons. Whilst there are other, arguably more robust ways of monitoring uncertainty, such as the Monte Carlo approach as an example, this approach was deemed appropriate given the lack of accurate mathematical data available on the solution options (such as probabilities) and the timescales available for the research/proportionate amount of value it would add to the research findings.

The most optimal solutions were selected based on the highest optimisation score for each impact; if two scores were the same, then the one with the lowest uncertainty was chosen. The less-optimal solutions were selected based on the lowest optimisation score for each impact; if two scores were the same, the one with the highest uncertainty was chosen. In this way a most ‘optimal’ and a ‘less optimal’ solution was chosen for each key environmental impact. The optimal solutions for each impact were grouped together (Group A) and the less optimal solutions also grouped (Group B).

Key Impact
Sediment Regime Changes

Related Site Paramters Indicating Issue
High turbidity
High sedimentation
High transport rates

Related Indirect impacts	
Benthic habitat impacts	Asethetics and recreational value
Coastal erosion	Potential impact on fisheries
Changing local hydodynamics	Worst Solutions
Water quality and visitbility	Eco-tousim impact
Contaminated sediment	Sediment build up
Biodiversity implications	Damage to underwater heritage
	Changes to water depth

Key Impact Analysis

Solution Analysis						
Key impact Solution Options/Reccomendations	Cost (1= High, 5 = low)	Development stage	lagoon relevance	Likely Success (1 to 5 = Successful) Average of Development stage and lagoon relevance	Addressed indirect impacts level (1 to 5)	Overall Solution Score (Average)
Dredging and dumping	4	5	5	5.0	1	4
Dredging and utilising	4	5	5	5.0	2	4.2
Sensitive dredging (confined disposal, seasonal and temporal awareness, silt screens, dredging type etc)	3	5	5	5.0	3	4.2
Flushing or sluicing	5	5	5	5.0	2	4.4
Lagoon Shape design	3	3	4	3.5	4	3.5
Temporal actvivity zonation	4	5	4	4.5	3	4.1
Geoengineering e.g creating beach, sand dunes etc	2	5	3	4.0	3	3.4
Use of flora to stabilise sediment	3	5	3	4.0	4	3.8
Use of coral reefs to protect coastlines	3	4	4	4.0	3	3.6
Compensation habitat creation for lost habitat	1	5	4	4.5	4	3.7
Restoration of habitat for lost habitat	1	5	4	4.5	4	3.7
Use of geoindicators, environmental indicators of composite indicators for rapid change response	4	4	3	3.5	1	3.1
Control sediment generation through water shed management	3	4	5	4.5	5	4.3
In situ stabilisation of sediments	4	4	3	3.5	4	3.7
Site selection close to existing habitats with qualities for protecting coastline from changes in sediment regime	5	3	4	3.5	3	3.7
Use of turbidity and sedimentation measurements to best select suitable seabed disturbance points reducing seidment regime changes	3	5	4	4.5	3	3.9
Sediment bypassing or silt curtains	2	5	5	5.0	2	3.8
Modelling of habitat tolerance levels to sedimentation	5	3	4	3.5	1	3.3

Solution Analysis (MCDA)

Uncertainty Analysis (1 low, 5 high)					Optimisation Results 1= not optimal 5 = optimal. Uncertinaty shown with number of cells outlined						
Unc. Env Impact	Unc. Solution	Unc. Cost	Overall Uncertainty Error RSS	Overall Uncertainty Error (Avrg)	1	2	3	4	5	Optimal/Less	Solution Selected
1	1	1	2	1				4			
1	2	2	3	2				4.2			
1	1	2	2	1				4.2			
1	1	1	2	1				4.4		Optimal (Group A)	Flushing or sluicing
1	2	3	4	2				3.5			
1	1	1	2	1				4.1			
1	4	3	5	3			3.4				
1	3	3	4	2				3.8			
1	2	2	3	2				3.6			
1	3	3	4	2				3.7			
1	2	2	3	2				3.7			
1	2	2	3	2			3.1			Less- Optimal (Group B)	Use of geoindicators for rapid change response
1	3	3	4	2				4.3			
1	3	2	4	2				3.7			
1	4	3	5	3				3.7			
1	3	4	5	3				3.9			
1	5	5	7	4				3.8			
1	2	1	2	1			3.3				

Uncertainty Analysis, Optimisation Results & Solution Group Selection

Figure 32 Example run-through of MCDA solution analysis for selection of optimal (Group A) and less optimal (Group B) solutions: Example for one impact (Sediment Regime Changes)

5.3.2 Solution Assessment (ESA)

The MCDA produced two groups of solutions. The next stage of the research begins to describe and quantify the wider environmental, socio-economic 'value' of the solution options in terms of their impact on the marginal changes to the provision of ecosystem services. This section of the research applies the ecosystem service approach through a proportionate and relevant ecosystem service assessment (ESA) of the solution option groups (A and B) that address the environmental impacts of tidal lagoons.

The ESA first considers both the positive and negative EsS provided by a lagoon with no solution options (baseline) and then considers the marginal change of these services as a result of the implementation of solution groups A and B. The marginal change is assessed, not the absolute change as is recommended practice [216]. This assessment is based around the EsS provided at the operational stage of a lagoon only; the construction and decommissioning stages are not taken into consideration as they are thought to be temporary in terms of the implications for EsS.

The first stage of the ESA is to define a baseline by identifying the key ecosystem services that a tidal lagoon will provide if no solution options are implemented. We can then compare this baseline to a lagoon with solution from group A and from group B. Whilst the assessment is intentionally high level and not specific to any one lagoon project, where guidance or parameters were required Swansea Bay lagoon was used as a reference. See section 2.6.1 for more information on Swansea Bay lagoon. The EsS were identified using standard lists from literature sources as follows:

- UKNEA guidance [96]
- Natural Resource Wales ecosystem approach guidance [218,219]
- Green Book Principles [220]
- Environment Agency's Benefits Inventory [221]

The final list used is based largely on the EsS from the Green Book [220], with only the EsS relevant to lagoons selected for the research, this was based on author judgement. The level of detail in the Green Book [220] was deemed sufficient for this study, it was thought that the expanded divisions in the CICES [94] were not required. This is made up of regulating, provisioning and cultural EsS, supporting EsS are not included in the assessment as they underpin the other services and so are excluded to avoid duplication.

Once a baseline list of EsS that a lagoon could influence was created it was determined if these were likely to be positive or negative. For example, a lagoon provides energy which is a positive EsS provision (benefit), but it could also result in reduced water quality within the lagoon, which is a negative EsS (cost). These are the costs and benefits which are weighed against each other later on in the ESV. A standard scoring system proposed by Defra [222] was used to assess the EsS provided by the baseline (Table 13). This method allows both benefits and costs to be labelled (+ or -), in addition to providing a rough indication on the expected significance of those (+ Vs ++). This is comparing the costs and benefits to changes to ecosystem services, not the actual financial 'costs' of a lagoon. However, the ESA and ESV document does contain consideration of solution capital and operational cost (CAPEX and OPEX) in the final tabs within the Zenodo file [215] to give an idea of relative magnitude. The majority of costs for solutions are expected to be relatively insignificant as it is assumed that some would be already 'built in' to a baseline lagoon, so the additional 'cost' would be related to change in ecosystem service e.g. flushing and sluicing more frequently will not alter the financial cost dramatically but will reduce the ecosystem service provision of energy generation.

Table 13 Scoring system used in the ESA, based on system proposed by Defra

Score	**Assessment of likely impact**
++	Potential significant positive effect
+	Potential positive effect
0	Negligible effect
-	Potential negative effect
--	Potential significant negative effect

Following this, the marginal change to those baseline ecosystem services as a result of solution group implementation was then described. The aim of this is to describe how the ecosystem services (both + and -) are likely to change due to different solution groups being implemented. The marginal change was assessed using the same scoring system as the baseline (Table 13). Each individual solution within each group was assessed in this way. The results show clear indication of whether a solution implementation is likely to have a positive or negative impact on the EsS of a baseline lagoon and provides indication of the likely significance of that change. Here we begin to consider the more global implications of a lagoon, in terms of the ecosystem services they provide. For example, the benefits of climate change and increase in low carbon energy. This assessment feeds directly into the example ecosystem service valuation which attempts to demonstrate that these marginal changes can be monetised, where proportionate and relevant to do so.

5.3.3 Solution Valuation (ESV and CBA)

The ESA will develop a baseline description of the EsS provided by a lagoon with no solutions implemented, whether those EsS were costs (negatives) or benefits (positives) and the likely significance of these. The ESA will also describe the type and significance of the marginal changes to those EsS as a result of implementation of solution groups A and B. The next stage of the research aims to further quantify and monetise these marginal changes to the ecosystem service provision of a lagoon where proportionate and relevant to do so. In this Chapter of the research all of the EsS are described, it is only possible to quantify a few and only proportionate and relevant to monetise fewer still, Figure 33.

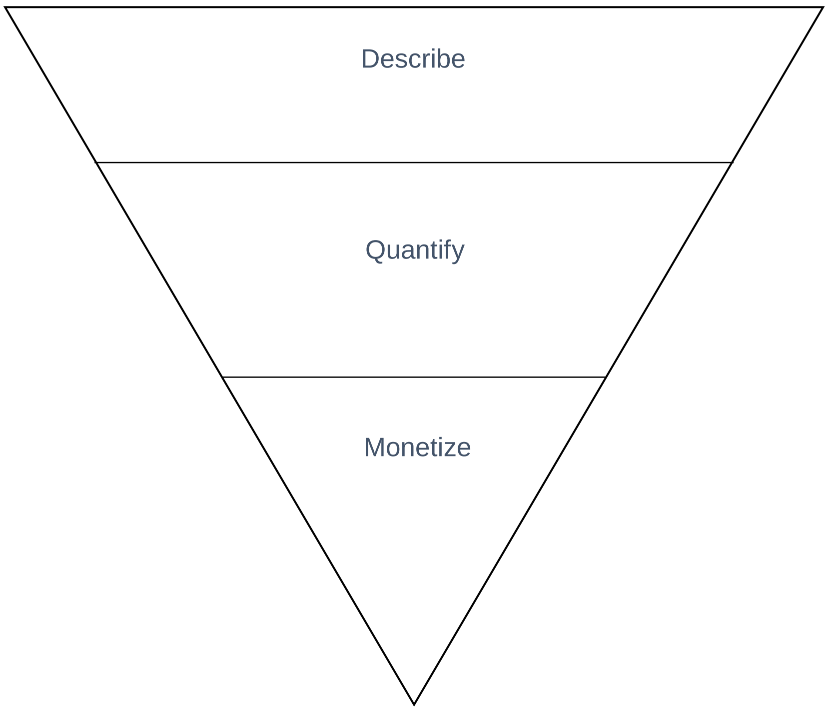


Figure 33 Ecosystem services order of assessment

Table 14 shows a list of the EsS and which of these have been described, quantified and monetised. Table 14 demonstrates that the monetary value result will represent only the few EsS that it was possible, proportionate and relevant to monetise. In particular, the cultural services prove difficult to quantify and monetise, given they are highly subjective, largely qualitative non-market parameters. It is vital that this value is always set back into the context of the qualitative picture built in the ESA and that the monetary values are not taken as stand-alone. The results of the ESV will be presented alongside the ESA and discussed within that context only. If more details of the actual cost figures are required a substantive section has been added to Appendix 11. This is not presented in the main text, in an attempted to keep the focus on the descriptive side of the ESV and not the final monetary figures.

Throughout the ESV and CBA industry-standard guidance from a variety of standards and sources was followed. The main guidance used is by HM Treasury (Green Book) [220], Defra [223], Eftec [224–226], Environment Agency [221] and Natural Resource Wales [218,219]. All of the information used in this analysis is desktop information taken from published literature, i.e. no primary data collection was undertaken. The EsS monetisation methodology involves extraction of values from literature and adapting based on a set of assumptions.

Table 14 List of the ecosystem services used in this research and the level of assessment/valuation undertaken. Green shows level, grey shows those not included.

Ecosystem Service Type	Ecosystem Services Full List	Described	Quantified	Monetised/valued
Provisioning	Food: (Aquaculture)	Yes	Yes	Yes
	Food: (Fish)	Yes	Yes	Yes
	Fibre/Fuel	Not relevant to lagoons	n/a	n/a
	Biochemicals	Not relevant to lagoons	n/a	n/a
	Genetic Resources	Not relevant to lagoons	n/a	n/a
	Ornamental Resources	Not relevant to lagoons	n/a	n/a
	Energy Generation	Yes	Yes	Yes
Regulating	Air Quality	Yes	Yes	Yes
	Climate regulation - CO2e emissions	Yes	Yes	Yes
	Climate regulation - Carbon sequestration	Yes	Yes	Yes
	Erosion/Sediment control	Yes	Yes	Yes
	Water quality	Yes	Yes	Yes
	Water regulation	Duplication with flood protection	n/a	n/a
	Natural Hazard Protection (Flooding)	Yes	Yes	Yes
	Bioremediation	Not relevant to lagoons	n/a	n/a
Cultural	Spiritual/Religious value	Not relevant to lagoons	n/a	n/a
	Inspiration for art	Not relevant to lagoons	n/a	n/a
	Social Relations	Yes	No – subjective and likely insignificant	No – subjective and likely insignificant
	Aesthetic Value	Subject to opinion – cannot say. Solutions not expected to have large aesthetic impact compared to baseline	No - subjective	No - subjective

	Cultural heritage	Yes	Not relevant or possible to quantify	Not relevant or possible to monetise
	Education and Research	Yes	Not relevant or possible to quantify	Not relevant or possible to monetise
	Heritage & archaeology	Yes	Not possible to quantify	Not possible to monetise
	Health Benefits	Yes	Likely duplication with recreation also likely not to provide additional benefits as national scale	Likely duplication with recreation also likely not to provide additional benefits as national scale
	Recreation & Tourism	Yes	Yes	Yes

Table 15 shows the methodology and assumptions for this analysis for all the monetised EsS and associated references, a substantive explanation section has also been added to Appendix 11 should further explanation be required. The full ESV excel file with all the calculations undertaken and all the relevant references can also be viewed on Zenodo [2]. In addition, a full list of literature sources for each solution can be found in a research map in Appendix 11. The following key considerations were kept in mind throughout the analysis:

- All monetary values represent additional change relative to the baseline of a lagoon with no solutions and are therefore marginal values due to solution implementation, not absolute values
- The literature sources of economic values in this analysis and the quality of the methodology used to obtain those economic values is important and only reputable sources with sound methodology were used. All references are provided
- The economic values found in literature may need to be adjusted to represent the project's tidal lagoon application, all assumptions on adjustment are provided
- The risk of double counting and duplication needs to be considered at all stages of valuation. This is documented within the analysis spreadsheet [2].
- The delivery of changes over time cannot be overlooked. This will be taken into consideration in the CBA section
- All changes to EsS are described, some are quantified and some can be monetised. Any monetary results need to be set back into the context of the qualitative description in the ESA
- The valuation contains several assumptions with uncertainty and subjectivity throughout. All assumptions are clearly stated and uncertainty tracked at each stage of the process within the spreadsheet [2].
- The actual financial cost of the solutions themselves is not included directly in the ESV. The analysis aims to weigh up the costs and benefits to the change in ecosystem service provision only. However, the solution financial costs are still considered descriptively in order to provide an idea of relative magnitude of any potential benefits or costs to the ecosystem services (see Zenodo tabs CAPEX and OPEX [215]). It is

expected that the majority of solution financial costs will be relatively insignificant when compared to the baseline. It is assumed for the purposes of this research that the 'costs' are in terms of the change in ecosystem service provisions e.g. flushing and sluicing more frequently to reduce sedimentation will not alter the financial cost dramatically compared to a baseline scenario which already includes this regime, but will reduce the ecosystem service provision of energy generation (which is what is being assessed and compared in this analysis). If this were to be applied in practice accurate industry data on the actual financial cost of solutions could be included within the ESV to directly set the context for any gains or losses in ecosystem services in terms of monetary value, perhaps incorporating expert engagement to allow a more accurate idea of the scale of potential 'value' added to ecosystem service provision and if that is greater than actual solution financial cost. Again, the research aims to focus on the descriptive side of the ESVs and not the actual monetary values. Whilst the financial costs of solutions is considered to set the research into context, it is not an area which is focused on in the research.

Once the changes to the baseline ecosystem services as a result of implementation of the solution group were monetised into per annum figures (+£ and -£) they were then weighed up against each other and set over a 100-year timeline. The Cost Benefit Analysis (CBA) compares the costs (negative values) and benefits (positive values) of the ecosystem service change, using a declining discount rate (starting at 3.5%) over 100 years, as advised by the Green Book and informed by the lifespan of a typical lagoon. The per annum figures used were first converted into 2018 values, as some of the sources of economic values were from older literature.

Table 15 List of methods/assumptions made for each ecosystem service in terms of the baseline and the marginal changes as a result of implementation of the two solution groups, see Appendix 11 for further explanation if required.

Monetised Ecosystem Services	Baseline Assumptions/Method	Group A Assumption/Method	Group B Assumption/Method	Notes	Source	Confidence level
Food (aquaculture)	Overall Benefit. Aquaculture production at the lagoon is expected to be equivalent in value per year as an average Welsh aquaculture enterprise	None of the solutions implemented will influence the baseline	Assumed that urea fertilisation will increase productivity of aquaculture by 33% in the months in which it is applied. Assuming urea fertilisation applied twice a year None of the other solutions in this group are thought to influence food compared to the baseline	Urea fertilisation is not sustainable and the benefits are relatively short term (25 years)	[206,227–230]	LOW- MEDIUM based on ocean fertilisation experiments using urea on sea water in bottles, lots of variation in terms of actual application in the sea, lots of variation per site etc. Medium confidence in aquaculture production information as based on actual data on previous Welsh aquaculture production
Food (fishing)	Overall Benefit. The value of fish caught will be the same as that of a recent study on fish catch at Swansea bay	No change in fish catch as a result of implementation of solutions, only sustainability of fish population to allow continued catch. Expected that fish will be caught elsewhere, no additional change	Assuming urea fertilisation increases primary productivity by 33% and this in turn increases fish population (23%). Assuming 10% lost at each trophic level None of the other solutions in this group are thought to influence food compared to the baseline	Urea fertilisation is not sustainable and the benefits are relatively short term (25 years)	[206,228–231]	LOW based on ocean fertilisation experiments using urea on sea water in bottles, lots of variation in terms of actual application in the sea. In addition, uncertainty around implications moving across trophic levels. Strong confidence in baseline assumptions on fishing industry at Swansea bay
Energy	Overall Benefit. Estimated energy generation from Swansea bay lagoon, TLP	Assuming that flushing and sluicing will pause energy generation. Likely already flushing	None of the solutions in this group are thought to influence energy	None	[9,183,232,233]	LOW-MEDIUM Based on TLP's Technical Notes, could contain some bias. Sedimentation study is

	values. Price for that energy generation from literature source	and sluicing in baseline. Additional 10% assumed for addressing sedimentation impact Temporal zonation assumed to pause energy generation for sporting events. Assuming 3 events a year i.e. 3 days of no energy generation Found in the literature that turbine technology to address fish impacts is as efficient at generating energy as baseline turbines would be The other solutions in this group thought not to impact energy generation	generation when compared to the baseline			based on that required in a barrage/reservoir system and may not be the exact same scale in a lagoon
Air Quality	Overall Benefit. PM10 (Particulate Matter) avoided due to displacement of fossil fuel. PM10 emissions from fossil fuels in 2015 and total GWh of energy from fossil fuels in 2015 to give PM10 per GWh. Use of Swansea GWh estimated generation gives total PM10 avoided. Standard government damage cost of PM10 avoided then used to monetise	Used the change in energy generation of the scenarios as calculation directly linked	Used the change in energy generation of the scenarios as calculation directly linked	None	[46,234–237]	MEDIUM based on energy generation scenarios, DUKES data and UK government emissions data
Carbon Regulation	Overall Benefit. Literature sourced tonne of carbon dioxide equivalent emissions (CO_2e) for each fuel type. Assuming a lagoon would replace gas, value sourced for tCO_2e/MWh of gas production. Swansea Bay	Used the change in energy generation of the scenarios as calculation directly linked	Used the change in energy generation of the scenarios as calculation directly linked	None	[238]	HIGH value taken from up to date literature and applied to Swansea Bay statistics. Scenarios determined based on changes in energy generation already calculated

	energy generation figures used to give total avoided emissions. Predicted carbon prices used to monetise (£/tCO_2e)					
Carbon Sequestration	Overall Negative. Swansea Bay regulation assessment assumed habitat impacted will be sand dunes (20%) and intertidal/subtidal benthic ecology (80%). Assume that a baseline development will result in all habitat sequestration benefits provided currently being lost. Reference found on carbon storage of different habitats. Predicted price of future carbon used to monetise	None of the solutions implemented will influence the baseline	Ecosystem restoration solution in this group assumed to change the carbon sequestration service compared to the baseline. It is assumed that this solution will restore the sand dune habitat lost due to baseline development and therefore save 20% of lost sequestration compared to the baseline. Reducing the severity of the negative impact	Assumed that additional carbon sequestration only occurs when habitat is developing. Once mature it is carbon balance. (first 40 years).	[238–240]	MEDIUM based on habitat regulation assessment for Swansea and standard carbon sequestration values for different habitats by Natural England. Some assumptions made about the exact make up of Swansea Bay lagoon habitat disturbance though, giving medium confidence level and not high. For example, assumed habitat made up of 20% sand dunes and 80% intertidal habitat. Also assumed that restoration will result in 100% of sand dune restoration back to baseline condition and extent
Erosion control/ Sedimentation	Overall Negative. Assumed that sedimentation within the lagoon will occur. TLP report on area of expected dredging required, and that maintenance dredging will occur every two years. Found cost of dredging in paper on sediment management in reservoirs (£/m^3)	The solutions in this group are expected to reduce the need for dredging shown in the baseline scenario by 10%. These include flushing and sluicing and environmental impact dredging. The other solutions are assumed not to influence required dredging activity	The solutions in this group are not thought to have a significant impact on the sedimentation of a lagoon compared to the baseline scenario.	None	[183,241,242]	MEDIUM. TLP's own figures for quantities so high confidence in amount of dredging required. Medium confidence in cost figures as based on US values for dredging of reservoirs. Assumption made that flushing and sluicing will reduce need for dredging by 10%, low confidence in this as depends on the site-specific characteristics and sediment regime
Water Quality	Overall Negative. No baseline is required here as can use the Environment Agency's NWEBS tool which provides monetisation of marginal changes to water quality. It includes assessment	Assumed that 4 receptors are influenced (all excluding recreation and fish) and that these are changed from poor to moderate	Assumed that 4 receptors are influenced (all excluding recreation and fish) and that these are changed from poor to good	The quality of the change was decided	[243]	MEDIUM following the Environment Agency tool on water appraisal. Making assumptions about receptors influenced and quality of the change

	of 6 ecological components: fish, invertebrates, plant communities, water clarity, flow of water and recreation. To avoid duplication recreation and fish are removed from this analysis as monetised elsewhere. The number of receptors and the quality of the improvement changes depending on solution group implemented			based on author opinion		
Flood Protection	Overall Benefit. Likely to be major benefit, difficult to quantify without in-depth flood risk modelling, also baseline estimation is not required as only need to determine marginal change as a result of solution implementation	Expected that flushing, sluicing and dredging in this group will improve the flood protection service provided. However likely that these will already be in the baseline to some extent and impossible to determine the marginal increase of these. It is also expected to be small insignificant increase and so not monetised	Ecosystem based adaption/restoration to protect coastlines from inundation will improve the flood protection ecosystem service compared to the baseline. A case study (Medmerry restoration) showed that a 500ha restoration site can reduce public spend on flood defence maintenance by £300,000/year. Assuming 500ha is restored	None	[85]	LOW big assumption that implementation of restoration in Group B will be similar in scale, extent and success to the Medmerry reserve example.
Tourism & Recreation	Overall Benefit. Expected annual visitors from literature of other tidal tourist sites and TLP own predictions (gives a range). A study found on economic impact of visitors to a lagoon – monetisation values taken from here. The baseline is conservative estimate	Assumed that spatial zonation, safer turbines and relocation/re-routing of vessels will increase visitor numbers due to more opportunity for safe eco-tourism and sporting activities. The optimistic estimate for visitor numbers from the literature was used for this group of solutions	Assumed that promotion of keystone species and building of green corridors may increase eco-tourism at the site marginal above the baseline, but not as much as increase seen in Group A. Medium estimate of visitor numbers used for this group of solutions	None	[18,48]	MEDIUM. Visitor numbers and monetisation of that from literature sources. Actual changes in visitor numbers as a result of solution implementation is own judgement, but is bound within ranges from the literature

5.4 Results

The MCDA allowed for two groups of solutions to be selected from the solutions database created in Chapter 4. Table 16 shows the solution groups selected alongside their relative optimisation score and level of uncertainty. Group A is the 'optimal' solution group, group B is the 'less optimal' group.

Table 16 Results of the MCDA solution selection, see Zenodo for full excel [214]

Group	Key Environmental Impacts	Solutions	Optimisation score and [Uncertainty]				
			1	2	3	4	5
Group A 'Optimal'	Sediment regime changes	Flushing or sluicing				4.4	
	Changing hydrodynamics	Dredging and utilising - dredge and fill beach nourishment reduce hydrodynamic changes impact				4.4	
	Habitat and Biodiversity loss	Use of spatial zonation e.g. leave certain areas untouched for species spawning				4.4	
	Pollution (water and/or sediment)	Relocation or re-routed movement of vessels to reduce increased traffic impact causing increased noise pollution/chance of leakage				4.4	
	Impact on fish and marine mammals	Turbine selection with fish and marine mammals in mind - or advancements in turbine design				4.4	
	Direct impacts of the structure	Use of temporal zonation e.g. temporarily sluice gates to allow ship navigation				4	
Group B 'Less-Optimal'	Sediment regime changes	Use of geoindicators for rapid change response			3.1		
	Changing hydrodynamics	Ecosystem based adaption/restoration to protect coastlines from erosion and inundation			2.9		
	Habitat and Biodiversity loss	Urea fertilisation geoengineering to nutrient poor regions, restoring the natural habitat and biodiversity		1.7			
	Pollution (water and/or sediment)	Site selection close to existing habitats with qualities for improving water - buffering water pollution e.g wetlands			3.1		
	Impact on fish and marine mammals	Catchment land and land slope characteristics used in site selection to reduce risk of run-off related water contamination			2.8		
	Direct impacts of the structure	Selection of keystone or umbrella species to protect or promote via building green infrastructure - use of green/blue corridors and hubs		2.3			

It can be seen in Table 16 that the solution options in group B have lower optimisation scores than in Group A in addition to a higher uncertainty band. The solutions in group B are therefore deemed to be 'less-optimal' in terms of the traditional decision criteria used (solution cost, solution stage of development, solution relevance, solution likely success, level of indirect impacts addressed and level of uncertainty). The start of the ESA included a baseline assessment of the ecosystem services a lagoon with no solution options would influence. The baseline ESA results are shown in Table 17 below.

Table 17 Baseline Ecosystem Service Assessment for a lagoon with no solution options implemented to address its environmental impacts

Ecosystem Service	Benefit or Cost	Assessment	Assumptions
Food: (Aquaculture)	Benefit	Aquaculture production ++	Assumed that the lagoon will be equivalent of a standard aquaculture enterprise in Wales
Food: (Fish)	Benefit	Fishing industry, fish catch +	Big assumption that fishing industry will not be influenced by baseline lagoon. Even though fish may be impacted it is likely that fishing will still occur in other areas. National impact not expected. Potential marginal increase due to walled structure and fish aggregation/protection of nursery populations. Very uncertain assumption, subjective.
Fibre/Fuel	Not relevant to this study	Not relevant to this study	Not relevant to this study
Biochemicals	Not relevant to this study	Not relevant to this study	Not relevant to this study
Genetic Resources	Not relevant to this study	Not relevant to this study	Not relevant to this study
Ornamental Resources	Not relevant to this study	Not relevant to this study	Not relevant to this study
Energy Generation	Benefit	Tidal energy ++	Assumed production of similar scale to Swansea Bay lagoon
Air Quality	Benefit	Displaced fossil fuels, reduced release of PM10 ++	Assumed that energy of lagoon will displace fossil fuel and that all fossil fuels release PM10.
Climate regulation - CO_2e emissions	Benefit	Displacement of fossil fuel CO_2e ++	Assuming that energy of a lagoon will displace energy from the gas industry, displacing CO_2 emissions
Climate regulation - Carbon sequestration	Cost	Overall habitat loss and loss of sequestration of those habitats --	Assuming that loss of land will occur under footprint of the lagoon and loss of these habitats will result in loss of all their ability to sequester carbon
Erosion/Sediment control	Cost	Expected sediment build up within the lagoon --	Dredging plans for Swansea Bay provide indication of likely cost of the impact to be resolved. Solutions which change this cost are assessed.
Water quality	Cost	Expected water quality issues in the water enclosed within the lagoon, similar to those seen at Sihwa barrage before it was updated --	Assuming poor water quality in the baseline lagoon. Assuming that environment agency tool for water appraisal (NWEBS) is sufficient for the analysis
Water regulation	Removed as duplication with Flood Risk	Removed as duplication with Flood Risk	Removed as duplication with Flood Risk
Natural Hazard Protection	Benefit	Flood risk protection ++	Assumed that baseline lagoon provides flood protection through sea wall and control/store of water.
Bioremediation	Not relevant to this study	Not relevant to this study	Not relevant to this study
Spiritual/Religious value	Not relevant to this study	Not relevant to this study	Not relevant to this study
Inspiration for art	Not relevant to this study	Not relevant to this study	Not relevant to this study
Social Relations	Benefit	Increased social activity as a result of increased recreation/tourism etc ++	Assumed baseline lagoon will have increased social activity

Aesthetic Value	Subjective/opinion - cannot say	Subjective/opinion - cannot say	Subjective/opinion - cannot say
Cultural heritage	Cost	Fish impact, culture, pollution etc --	Assumed that cultural heritage may be negatively impacted due to links with key environmental impacts and livelihoods.
Education and Research	Benefit	World's first proves beneficial for education and research ++	Baseline lagoon will increase educational and researching activities, this would be the case for the first lagoon, perhaps decreasingly beneficial when becomes the norm
Heritage & archaeology	Cost	Sediment regime changes likely to disturb or smother sites --	Assumed that baseline lagoon will impact negatively on under water heritage such as shipwrecks etc.
Health Benefits	Benefit ++	Increased recreation due to new walkway and cycle ways, increased health benefits ++	Assumed positive impact on local and regional health, national health not influenced as likely source elsewhere. This has strong duplication risk with recreation
Recreation & Tourism	Benefit ++	Ecotourism, world first attraction, sporting activities, swimming, sailing, triathlons etc ++	Assumed that baseline lagoon will be open to the public and used for recreational activities

From the baseline ESA it is shown that a lagoon with no solutions implemented to address its environmental impacts results in several 'costs' to ecosystem service provision or the goods and services provided to society. These include cost to carbon sequestration as a result of habitat loss, cost of sedimentation and cultural heritage due to changes in the sediment regime, cost to water quality due to pollution and entrapment issues within the lagoon and further costs related to cultural heritage. These descriptions are based on personal judgement from understanding within literature and any assumptions are listed alongside this information.

The baseline also includes numerous benefits in terms of EsS provision, namely recreation and tourism, health benefits, education and research, social relations increase, flood protection, displacement of carbon emissions, renewable energy generation, improvement in air quality and food in the form of fish and aquaculture activity. These benefits arise largely on the assumption that a lagoon will be multi-use. A few of the EsS have been greyed out; these were deemed either not relevant to lagoons or to pose significant risk of duplication with other EsS already assessed.

The next stage of the ESA looked at how the baseline EsS (Table 17) will change as a result of implementation of solutions in groups A and B. Table 18 and Table 19 describe these changes showing the ESA undertaken for solution group A ('optimal') and solution group B ('less-optimal') respectively.

The results show that the 'optimal' group of solutions (A) have negative implications for the energy generation EsS and with that the associated carbon emissions reductions and air quality services provided. Group A solutions do however have a number of benefits, noticeably on fish impact, water quality, social relations, recreation and tourism.

The solutions in group B were thought to be less optimal as selected in the MCDA. The ESA shows that some of the solutions do have minor negative implications for the EsS provided by a lagoon compared to the baseline including on energy generation and therefore associated carbon emissions displacement and air quality improvement. However, this is also the case for the 'optimal' solutions in group A. The solutions in group B are otherwise very positive with additional benefits for 11 of 15 EsS, compared to 9 of 15 for group A noticeable solution in this group is urea fertilisation which results in cost implications to almost all of the EsS when compared to the baseline, if this were to be removed from this group then group B would be even more positive compared to group A in terms of EsS provision.

The ESA provides a qualitative understanding of how the two solution groups compare with each other in terms of change in EsS provision against the baseline. It shows that whilst there are positive and negatives to both, the solutions in Group B (previously understood as 'less-optimal') have more benefits and less costs when compared to Group A (previously understood as 'optimal').

Where relevant, possible and proportionate to do so, some of the changes detailed in the ESA (Table 18 and Table 19) can be monetised. This provides further insight into the optimisation of solution selection i.e. which group is optimal and which is less so. It is important to remember that the values shown represent only the changes in EsS that could be monetised, not all of the changes and so the values should always be set back into the context of the information in the ESA results (Table 18 and Table 19). Table 20 shows the key results of the monetisation of these changes as undertaken within the ESV and CBA, a more detailed explanation can be found in Appendix 11 if required. For the full analysis and section by section results see the working spreadsheet for the ESV and CBA on Zenodo [215].

Table 18 ESA for solution group A 'Optimal' implementation. Assessing the marginal change to EsS compared to the baseline

Ecosystem Services (EsS) Full List	Baseline Benefit or Cost	Change to EsS as a result of implementation of solutions in Group A						
		Flushing or sluicing	Dredging and utilising	Use of spatial zonation	Relocation or re-routed movement of vessels - traffic impact	Turbine selection with fish and marine mammals in mind	Use of temporal zonation	Group A OVERALL
1. Food a (aquaculture)	Benefit	no change	no change	no change	no change	no change	no change	no change
1b. Food (fish)	Benefit	no change	no change	Benefit ++	Cost -	Benefit ++	Benefit ++	Benefit ++
Fibre/Fuel	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
Biochemicals	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
Genetic Resources	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
Ornamental Resources	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
2. Energy Generation	Benefit	Cost -	Cost -	no change	no change	Cost -	Cost -	Cost -
3. Air quality	Benefit	Cost -	Cost -	no change	no change	Cost -	Cost -	Cost -
4. Climate change regulation emissions	Benefit	Cost -	Cost -	No change	No change	Cost -	Cost -	Cost -
5. Climate change regulation sequestration	Cost	no change	no change	no change	no change	no change	no change	no change
6. Erosion/Sediment Control	Cost	Benefit ++	no change	no change	no change	no change	no change	Benefit ++
7. Water Quality	Cost	Benefit +	Cost -	Benefit +	Benefit +	no change	no change	Benefit +

Water regulation	Not included due to duplication risk	Not included due to duplication risk	Not included due to duplication risk	Not included due to duplication risk	Not included due to duplication risk	Not included due to duplication risk	Not included due to duplication risk	Not included due to duplication risk
8. Natural hazard protection (Flood Protection)	Benefit	Benefit +	Benefit +	no change	No change	No change	No change	Benefit +
Bioremediation	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study
Spiritual/Religious value	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study
Inspiration for art	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study
Social relations	Benefit	Cost -	Cost -	Benefit +	Benefit +	Benefit +	Benefit +	Benefit +
Aesthetic Value	Not relevant, highly subjective	Not relevant, highly subjective	Not relevant, highly subjective	Not relevant, highly subjective	Not relevant, highly subjective	Not relevant, highly subjective	Not relevant, highly subjective	Not relevant, highly subjective
Cultural heritage values	Cost	no change	no change	Cost -	Cost -	Benefit +	no change	Cost -
Education and Research	Benefit	no change	no change	no change	no change	no change	no change	no change
Health benefits	Benefit	no change	no change	Benefit ++	Benefit ++	no change	no change	Benefit ++
Heritage & Archaeology	Cost	no change	Benefit ++	no change	no change	no change	no change	Benefit ++
9. Recreation/ecotourism	Benefit	No change	No change	Benefit ++	Benefit ++	No change	Benefit ++	Benefit ++

Table 19 ESA for solution group B 'Less Optimal'. Assessing the marginal change to EsS compared to the baseline

Ecosystem Services (EsS) Full List	Baseline Benefit or Cost	Change to EsS as a result of implementation of solutions in Group B						
		Use of Geoindicators	Ecosystem restoration to protect coastlines from erosion	Urea Fertilisation	Site selection close to natural water purification areas e.g. wetlands	Catchment land selection to reduce run off pollution	Keystone species and blue corridors	Scenario 2 OVERALL SCORE
1. Food a (aquaculture)	Benefit	No change	No change	Benefit ++	No change	Benefit ++	No change	Benefit ++
1b. Food (fish)	Benefit	No change	No change	Benefit ++	No change	no change		Benefit ++
Fibre/Fuel	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
Biochemicals	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
Genetic Resources	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
Ornamental Resources	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
2. Energy Generation	Benefit	No change	No change	No change	Cost -	Cost -	No change	Cost -
3. Air quality	Benefit	No change	No change	No change	Cost -	Cost -	No change	Cost -
4. Climate change regulation emissions	Benefit	No change	No change	No change	Cost -	Cost -	No change	Cost -
5. Climate change regulation sequestration	Cost	No change	Benefit +	No change	No change	No change	No change	Benefit +
6. Erosion/Sediment Control	Cost	Benefit +	No change	No change	No change	No change	No change	Benefit +
7. Water Quality	Cost	No change	Benefit +	Cost -	Benefit +	Benefit +	No change	Benefit +

Water regulation	Not included due to duplication risk	Not included due to duplication risk	Not included due to duplication risk	Not included due to duplication risk	Not included due to duplication risk	Not included due to duplication risk	Not included due to duplication risk	Not included due to duplication risk
8. Natural hazard protection (Flood Protection)	Benefit	No change	Benefit +	No change	No change	No change	No change	Benefit +
Bioremediation	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study
Spiritual/Religious value	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study
Inspiration for art	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study	No relevant to this study
Social relations	Benefit	No change	No change	Cost (-)	No change	Benefit +	No change	Benefit +
Aesthetic Value	Not relevant, highly subjective	Not relevant, highly subjective	Not relevant, highly subjective	Not relevant, highly subjective	Not relevant, highly subjective	Not relevant, highly subjective	Not relevant, highly subjective	Not relevant, highly subjective
Cultural heritage values	Cost	No change	No change	Cost -	Benefit +	Benefit +	Benefit +	Benefit +
Education and Research	Benefit	no change	no change	no change	no change	no change	no change	no change
Health benefits	Benefit	no change	no change	no change	Benefit ++	no change	no change	Benefit ++
Heritage & Archaeology	Cost	Benefit ++	no change	no change	no change	no change	no change	Benefit ++
9. Recreation/ecotourism	Benefit	No change	No change	Cost -	No change	Benefit ++	Benefit ++	Benefit ++

Table 20 Results of the ESV and CBA of the ecosystem services changes compared to the baseline as a result of solution implementation. These figures are for demonstration purposes only, please see Appendix 11 and Zenodo spreadsheet [215] **if further details are required.**

Services	Group A Present Value (£m, 100years)	Group B Present Value (£m, 100 years)
Food Aquaculture	not valued	3.41
Food Fishing	not valued	-0.22
Energy	-8.11	not valued
Air Quality	-0.36	not valued
Carbon CO2	-7.02	not valued
Carbon Sequestration	not valued	0.0003
Erosion/Sedimentation	4.24	not valued
Water Quality	1.60	3.44
Flood Risk	not valued	0.01
Recreation & Tourism	18.47	9.23
Overall Present Value	**8.82**	**15.88**

Note: See full ESV and CBA analysis in spreadsheet on Zenedo [215].

Table 20 shows monetisation of some of the key changes in EsS as a result of solution group implementation and represents the monetary results from the ESV and CBA. It shows that from the EsS changes that could be monetised group B (‘less optimal’) solutions seem to have greater value or ‘worth’ when compared to group A (‘optimal’) in terms of EsS provision. This indicates that changing the parameters used to select solutions could change which are deemed ‘optimal’ or not. Taking into consideration the wider environment, society and economy through use of ecosystem service approach can alter the decisions being made on how to assess the solutions used to address environmental impacts of lagoons. When the wider, more holistic, view of lagoons is taken into account, considering their multi-use opportunities, the solutions likely to be selected will change, i.e. what is deemed as most ‘optimal’ will change.

The values are very sensitive, uncertain and in some areas subjective. The descriptive ESA provides the detail required, without placing definitive values onto the process. The process provides demonstration of an alternative methodology to assess the wider implications of large scale, multi-use developments. The monetary values are for indication only, but they do show that in some cases what is deemed ‘optimal’ in the traditional sense might not always be when considering a more holistic and wider picture and approach. To fully understand the wider approach the descriptive ESA is what should be considered and taken on moving forward.

5.5 Discussion

Tidal lagoons are set to be multi-use, multi-function facilities, making them unique in terms of large scale energy developments. It is vital that any solutions implemented to address their environmental impacts take into account the wider implications lagoons will have on the environment, society and the economy as multi-use facilities. Traditional parameters of solution selection do not consider these wider implications. This section of the research demonstrates use of the ecosystem service approach as a methodology for incorporating the wider implications in solution selection and comparison for tidal lagoon developments. This echoes current understanding that incorporation of the ecosystem service approach in energy policy and decision making is vital for a 'whole systems' approach [99] bridging the link between environmental impacts and socio-economic implications [100]. Demonstration of this approach in a lagoon setting has uncovered that what solutions were deemed 'optimal' under the traditional parameters (solution cost, solution stage of development, solution relevance, solution likely success, level of indirect impacts addressed and level of uncertainty) might no longer be 'optimal' when considering the EsS provision and the wider societal 'value' of lagoons.

It is worth including a sense check of the results to consider its limitations. The monetary values are highly uncertain, subjective and underpinned by numerous assumptions. In addition, the values represent only a small proportion of the EsS present at the site, only those that it was possible and relevant to monetise. With small changes to any of these values the results could be different. If this methodology is to be used in the industry, it is assumed that it will be backed up by primary research input data and not purely as a desktop study as this has been. The process is for demonstration only; the spreadsheet developed could act as a starting point for this process, for tidal lagoons in the future. Despite this uncertainty, if the values are considered back in the context of the qualitative ESA there is enough of a result to warrant further consideration and investigation of alternative methodologies such as this in solution option decision making for tidal lagoons. This is particularly prominent for large scale developments which are likely to be multi-function, such as a tidal lagoon which provides more to society than just its energy generation (e.g. flood protection, recreational facilities, aquaculture, carbon sequestration, air quality improvements etc). A recent study by Holland et al (2018) [99], highlights the use of ecosystem services in the design of future energy systems and the limitations that these types of methodologies can have, some of these limitations also ring true for this research, namely the limited number of ecosystem services that could be realistically monetised.

To obtain the monetary values, the EsS changes had to be described first. Only a few of these could be quantified and fewer still could be realistically monetised. This describe, quantify, monetise is standard practice for EsS valuation [216]. This monetary value represents only a fraction of the overall picture in which it is taken from. It is vital then that this value is taken back into the quantification and description. Figure 34 shows an updated EsS valuation triangle to reflect this additional process, the figure has been developed for this research but is based on understanding of relevant available guidance on EsS valuation [193,221], coined here as the 'egg timer'.

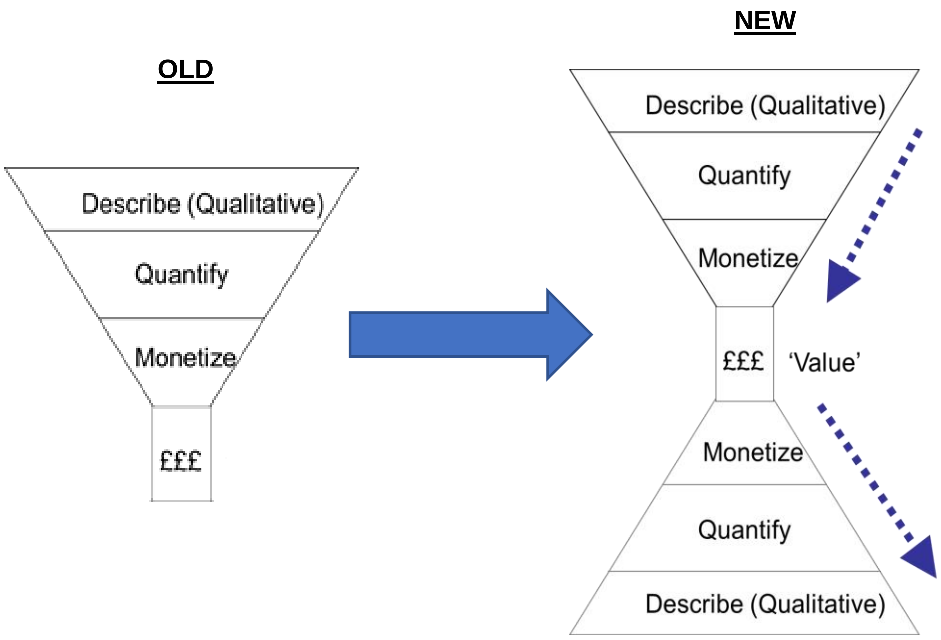


Figure 34 The 'egg timer' ecosystem service valuation. Describe, monetise and quantify as the standard EsS valuation triangle labelled 'OLD', then set the monetary values back into the qualitative context as shown in the egg timer labelled 'NEW'.

The ESA allows an assessment of the two groups of solutions in a different way, in the context of ecosystem services. This aims at capturing the wider environmental, social and economic benefits and costs of solution implementation. The baseline ESA shows that a multi-use lagoon with no solutions implemented brings both benefits in service provision and costs which are linked to the key environmental impacts. The key EsS benefits a lagoon can bring to society in a baseline lagoon include aquaculture (food production), energy generation, leisure and recreation, flood protection, carbon regulation and air quality improvements. The key costs include sedimentation, water quality issues, loss of habitat resulting in carbon sequestration loss and the potential for negative impacts to cultural heritage.

The database of solutions created in Chapter 4 addresses the key environmental impacts of tidal lagoons. This Chapter is considering what the implications are to the wider environment, society and economy of addressing those impacts in terms of EsS provision. Does addressing the environmental impacts actually bring benefits to people? Or just the environment?

The ESA for both solution groups A and B shows that both positive and negative implications occur for the EsS provision, but overall both prove to have a 'net gain'. The ESV reiterates this with positive monetary values for both groups of solutions. It might be deducted then, that it is worth implementing solutions to address the environmental impacts of lagoons not only for the environment but also for society. Implementing solutions is likely to result in net gain in terms of EsS provision to society. This net gain is achieved through enhancement of benefits and reduction of costs when compared to a baseline lagoon with no solutions implemented. The ESV used to demonstrate this process found that a net gain of present value between £8.8m and £15.8m could be achieved over 100 years with solution implementation on a lagoon of approximate parameters to Swansea Bay, depending on whether solution group A or solution group B is chosen. The ESV in this research was purely desktop based and used to provide indication of what the next steps after an ESA might look like for a lagoon development. When we put these indicative ESV values in the context of wider lagoon planning (e.g. £1.3 billion [9] in total for a lagoon development), we can see that the 'value' of these seem relatively minor, however it is worth noting that the monetary values are only a very small part of the overall ecosystem service landscape and therefore further emphasis should be placed on the descriptive side of the ecosystem service process, in this case the ESA.

So if both the solution groups result in positive outcomes for EsS provision when implemented, the next question is how can the positive outcome be maximised? This all depends on the solution combination selected. The results show that solution group B proved of greater EsS 'value' than group A and this was contradictory to the original MCDA labels of 'less-optimal' and 'optimal' decided under traditional selection parameters. This really now becomes a debate about the definition of 'optimal'. Group A is likely to be relatively low cost, certain, well developed, successful etc, but will not bring the most benefits in terms of the wider environment, society and economy. Group B is likely to be more expensive, less certain, less well developed but has a greater opportunity for added value in terms of the wider picture. This is confusing in the context of industry talk about 'value for money', because it really depends on what criteria this is measured against. If the EsS are included then group B is better value for money, you would be getting more for your money in terms of the wider implications to aquaculture, flood risk, leisure and recreation etc. If only the traditional parameters are considered, that group B is very expensive and a bit of a risk compared to the cheaper more certain options in group A.

Although this work does not consider the value of lagoons as a whole within the UK's energy mix, this debate over 'value for money' becomes much larger scale when considering lagoon developments in general as multi-use facilities. The UK government currently believes

Swansea Bay to be not good ‘value for money’ in their cost assessment which considers electricity generation in terms of cost, competitiveness on the market and carbon reductions, whereas TLP’s cost assessment shows Swansea to be very good value for money. Their assessment includes the wider environmental societal and economic aspects of a lagoon as a multi-function development. On an even larger scale, it might be argued that as a society, the focus is on the value of money, not the value for money. This is discussed further in Chapter 6 when all the research findings are pulled together and their place in an industry context detailed. It is worth noting that this research considers only the smaller scale ‘value for money’ debate relating only to solution options to the environmental impacts of lagoons, and so conclusions cannot be drawn which reflect the value of lagoon developments to the UK energy mix.

The ESV section of this research aimed at putting some of the less-measurable wider parameters in the same monetary value to allow context and comparison of information in the same units as the traditional parameters. When this was done the research showed that group B ‘less optimal’ became the best value for money or perhaps most ‘optimal’. This research approach has its limitations and was for demonstration purposes only, but it does allow a process to prompt consideration of the wider picture in future solution option consideration and allows for a conversation starter on what society sees as ‘optimal’ or ‘valuable’.

This research considered only two groups of solutions, which were selected in the MCDA, using traditional selection parameters. The next stage, if this were to be applied in reality, would be to run through this method with multiple different combinations of solutions to see which group of solutions results in the highest ESV value and most positive ESA picture.. This would essentially become the new ‘optimal’ set of solutions. This has not been done in this research as the process was for demonstration only. However, it would be done, for example, when sound primary research can be input into the method and when the exact details and parameters of a lagoon and its site are known. In addition, a number of solutions could be excluded in the first instance based on site/project specifics, budgets, preferences, expertise etc making the process much more streamlined towards the key goals, criteria and objectives of a particular development. The research was also cautious not to publish a set of ‘optimal’ solutions but instead keep the findings high level and warn readers of the site- and project-specific nature of solution success and implications, encouraging this process to be undertaken and tailored to specific needs.

Taking a full circle back to the original solution selection (MCDA), it can be imagined how this could now be improved, given what is now known after the ESA and ESV/CBA. The MCDA is a relatively quick process, especially when a spreadsheet is already set out to enable a user to quickly input their own scoring. If the MCDA could be tailored to allow for some of the wider information to be captured it might allow for a first quick-look into solution selection that is more comprehensive than the original MCDA with only traditional parameters. Including the EsS that seem to be creating the largest differences in value as a result of solution implementation could be one way forward; from this research the suggested ones would impacts on energy generation, leisure and recreation and water quality. Alternatively, EsS might be included for assessment in the MCDA if a development has a particular goal or objective to achieve, for example to provide flood protection to an area or to provide aquaculture facilities.

The process of environmental valuation is controversial and has not always been applied successfully. Whilst in some industries monetary valuation of the environment is endorsed as a core strategy towards tackling environmental issues and incorporating those into decision making regarding solution options, in others it is widely and vigorously contested and rejected as being a capitalist approach forced upon nature conservation when it is not applicable [244–247]. As Büscher et al (2016) [248] wrote to explain the disagreement of environmental valuation: "*To further bring conservation into capitalism, then, is to lay bare the various ecosystemic threads and linkages so that they can be further subjected to separation, marketization, and alienation, albeit in the service of conservation rhetoric*". Due to this controversy it is vital then that any valuation is considered carefully and the implications of its findings are fully understood and set back within the whole system description and not selected, separated and marketed.

In recent years there has been a general shift in focus towards non-monetary valuation and placing more focus on the descriptive side of ecosystem services through ecosystem services assessments in recent years [249–251], and many environmental scientists and ecologists still advocate economic valuation of ecosystem series as a positive, pragmatic, short term strategy for the communication of the value of the environment that reflects dominating economic and political languages [245].

The understanding of the use of valuation for ecosystem services lags behind that of the terrestrial sector [252]. Cavanagh et al (2016) discuss if valuation of marine ecosystems is appropriate and effective by comparing examples in three contrasting systems, which reveals a diversity of valuation approaches with varying rates of success. The recommendation of Cavanagh et al following this research is that valuation should be embedded within existing management structures, rather than being treated as additional mechanisms or alternatives alongside development and sharing of best practice across regions [252].

The research shows that this type of valuation in use for selecting solution options can be used to help bridge the gap between the environment and energy development and policy, this fits in with the wider literature on this topic in other industries [245]. Holland et al (2016) [100], recognise this gap and reiterate the need for the analysis of energy systems to move form a current primary focus on only the environmental indicator of carbon towards inclusion of a broad range of ecosystem services on which human well-being depends [100]. In addition, other authors have highlighted the current lack of understanding of energy systems and their interactions with ecosystem services [253,254]. This research provides an initial consideration of the use of the ecosystem service approach in the application of solution selection to address the environmental impacts of tidal lagoons.

5.6 Conclusions

Through MCDA, ESA, ESV this section of the research has demonstrated a process for selecting, assessing, valuing and comparing solution options that address the environmental impacts of lagoons in a way that aims to capture the wider environmental, societal and economic implications which is well placed within the current wider literature detailing the need for greater understanding of the use of the ecosystem service approach in the energy sector and in the marine environment, despite the ongoing controversial stance on valuation of the environment and environmental economics. The research finds that implementation of solutions to address the key impacts of lagoons is not only beneficial to the environment but also to the EsS provided to society. Solutions have both benefits and costs in terms of EsS provision compared to the baseline of a lagoon with no solution options but overall, they are valuable to the environment and to people.

The research shows that the combination of solutions is important in achieving maximum net gain and that what is deemed traditionally 'optimal' in terms of solution options might not give the highest net gain when the wider EsS provision is considered. The research has a number of key limitations and is based on several assumptions. These assumptions and limitations are discussed and presented throughout the chapter. The main aim of this section of the research is to demonstrate a methodology for selecting, assessing and valuing different solution option combinations to address the environmental impacts of lagoons that captures the wider descriptive picture of lagoons being multi-use facilities with wider benefits and costs to society and the economy.

5.7 Chapter Summary

The Chapter aimed to address the third and final research objective to assess and compare solution option combinations for addressing the key impacts of tidal lagoons. This was achieved through an MCDA for selection of solutions, ESA for assessment of solutions and ESV for valuation which incorporates the wider environmental, social and economic value of EsS provision. This wider ecosystem picture was deemed essential to capture given the multi-use nature expected of tidal lagoons. It is recommended that this research be used as demonstration of a methodology which could be used in selection, assessment and valuation of different solution option combinations to address the environmental impacts of tidal lagoons.

The full process was undertaken on two Excel spreadsheets which are available on Zenodo [215] with more details on the ESV methodology to be found in Appendix 11. The next Chapter will consider how the research from this Chapter and Chapters 3 and 4 fit together and how this relates to the current status of the lagoon industry at present.

6 Summary & Industry Context

In 2015 when this research began there had been recent developments in the industry that meant there was a need to further understand the environmental impacts of tidal lagoons to ease regulatory concerns. This included the awarding of a development consent order from the UK government to Swansea Bay lagoon and a further proposal for a fleet of lagoons around the UK by TLP. The two biggest barriers to development at that time were seen to be cost concerns and uncertainty surrounding the environmental impacts [16,17]. Since the start of this research there have been significant further developments in the sector. This chapter provides a summary of the research and discusses how it now fits into the current state of the industry and comments on the sector progression. This includes consideration of the Hendry review, recent government rejection of Swansea Bay Lagoon, response from TLP and discussion around the lagoon sector in the future. This research started with the aim of reducing the uncertainty surrounding the environmental impacts by investigating what they are, what the solutions to address them could be and the expected cost of these solutions.

6.1 Key Impacts of Lagoons

The first objective of the research was to determine the key impacts of tidal lagoons both positive and negative. With no energy generating lagoons in the world to monitor and a significant lack of lagoon-specific research available on their environmental impacts, it became immediately clear why there was uncertainty surrounding their environmental impacts as there was so little specific documentation on them. This lack of available literature did not reflect the activity in the industry at the time, with the buzz of Swansea Bay's development consent order and significant debates being held over its potential environmental impacts. This presented a clear opportunity for industry engagement, to investigate and document the industry's perspective on the environmental impacts of tidal lagoons. The results of this engagement are written up in Chapter 3 which addresses the first research objective 'Identify the key impacts of tidal lagoons'.

Throughout the engagement it became apparent that there were two groups forming with differences in their responses being seen, the regulatory side and the developer side. In the future it is important that these views are married in order to make sure the differences in opinion do not create a barrier to the industry's development. The industry perspectives (and the differences between them) on the environmental impacts of tidal lagoons are written up as a published paper in the International Journal of Renewable Energy [111] and parts written up alongside a framework for impact identification in a practitioner publication by the Institute of Engineering Technology (IET) the Engineering & Technology Reference [110].

It was very clear from the beginning of the research that lagoons are unique compared to other large-scale energy projects in that they have the opportunity to be multi-use, multi-function facilities that could provide significant benefits to the wider environment, society and economy. Throughout the identification of the environmental impacts through industry engagement both the negative and the positive impacts were considered. It was found that overall the industry believed the key negative impacts to be 'sediment regime changes' and 'hydrodynamic changes' with key positives being 'flood defence and control' and 'area regeneration'. This wider context of weighing up both the positives and negatives of a multi-use facility was kept in mind throughout the research.

The impacts identified in this chapter are the industry's view of the key impacts; they are not monitored or modelled impacts, they are the opinion of experts working in the industry at the time. The actual impacts of lagoons are, as yet, unknown and will not be fully known until a lagoon is developed to allow monitoring opportunities. If the impacts identified in this research are what the industry believes to be most significant then that gives us indication on what is currently being focused on, where work and progress is being directed towards and highlights any gaps or differences between industry groups. Without lagoons to monitor this was deemed the best approach for a holistic, non-site-specific approach to identifying the likely key positive and negative impacts of lagoon. This section of the research allowed a research gap to be filled by providing published documentation covering a holistic industry perspective of the potential key negative and positive impacts of any future tidal lagoons.

6.2 Resource of Solution Options

Tidal lagoons are a new idea, but the concepts making up that idea are not new, for example in infrastructure including sea walls, harbours, barrages, dykes, hydroelectric power etc. During the industry engagement many participants drew on these examples to help explain what key environmental impacts they believed lagoons to have. The next stage of the research was to determine the potential solution options to the impacts of tidal lagoons and it seemed a logical step to investigate transferable solutions from other industries. If these impacts have been dealt with before, then the lagoon industry should be learning from that. Given the lack of information available from tidal lagoons themselves, this was deemed the next best option.

The investigation into solution options started with the industry engagement in Chapter 3. Participants were asked what they deemed to be potential solution options to the key impacts of lagoons. The aim of this was to understand what basis the industry was currently working on, what solutions they were working with at present. It was found that both influencers and developers had strong understanding of the initial engineering design, site and technology selection and compensation and catchment based measures but seemed less knowledgeable of operation and maintenance strategies.

The systematic literature review into transferable solution options to address the environmental impacts of tidal lagoons undertaken as part of this research, detailed in Chapter 4 and published in the Journal of Marine Policy [126], found a vast resource of relevant solution options to the key impact of tidal lagoons from other coastal, marine and river industries. 40% of the solution options found during the literature review were in the operation and maintenance sector. This suggests that the gaps in lagoon industry understanding can be filled with existing literature/understanding from other industries. If one of the key barriers to the lagoon industry is still uncertainty surrounding the environmental impacts, this uncertainty can be dramatically reduced when transferable experience and learning from other decades-old industries can be considered.

The solutions investigation research does not go into significant detail on any one solution as this will be dependent on the environmental impact being addressed and the specific site's characteristics. This section of the research aims only to showcase what information is available as a valuable resource to the nascent lagoon industry to be investigating further. It proves that this resource is worth consideration and could help dramatically reduce the uncertainty currently seen in the lagoon industry.

6.3 Solution Assessment & Valuation

The research up to this point has identified the key impacts of tidal lagoons and presented a valuable resource of potential transferable solution options. The main outputs of this work have been published documentation and databases of key impacts and solutions. Whilst this is useful, solutions still need to be selected, assessed and valued for comparison. It is essential that this process is inclusive of the wider aspects of lagoons as multi-use facilities. In this section of the research, Chapter 5 details a potential methodology for solution selection (MCDA), assessment (ESA) and valuation (ESV) which allows consideration of lagoons as multi-use facilities. This section essentially suggests and demonstrates a way in which addressing the environmental impacts of tidal lagoons could be optimised, enhancing the benefits and reducing the negatives to achieve overall net gain or value in terms of both the environment and society.

Using the ecosystem service approach, it was found that taking this wider context into account changes which solutions were deemed 'optimal' or most 'valuable'. The overall title of this research is 'Optimising tidal lagoons: an environmental focus'; a key aspect of the debate in Chapter 5 was around the real meaning of the word 'optimal'. It was ultimately decided that it depends what criteria you are including or excluding. The overall value of certain solutions to society is much higher when considering the ecosystem service provision of a lagoon as a multi-use facility. Taking this into account or not would therefore change the way solutions to the environmental impacts of lagoons are selected in the future, and it therefore how lagoons are optimised in terms of their environmental impacts.

Whilst this research only draws conclusions on solution options selection and not on the development of lagoons as a whole, there is a very topical debate in the lagoon and energy industry at present on what is deemed 'valuable' and the excluded/included criteria used to determine value. The next subsection of this Chapter considers the recent developments in the lagoon industry and how this research now fits within this setting.

6.4 Industry Context

In 2016 the UK government still had not made a decision on Swansea Bay lagoon and the role of a lagoon industry in the UK energy mix. Despite the awarding of the development consent order for Swansea Bay in 2015 and strong public and Welsh government backing, the UK government had concerns regarding the relative cost of lagoons compared to other energy projects and the implications of this to the taxpayer. In February 2016 the UK government announced the launch of an independent review into the feasibility of tidal lagoons for the UK. This was led by former Energy Minister Charles Hendry and is known as the 'Hendry review' [12]. See section 2.6.2 for background information.

Taking almost a year to investigate, the Hendry review was published in 2017 [18,66]. The outcome was a positive one for the lagoon industry and recommended a path finder project go ahead as soon as 'practically possible'. Swansea Bay was the only serious path finder proposal at the time. As a pathfinder it was understood that it would be more expensive than other larger lagoons as it would not benefit from economies of scale. The Hendry review also highlighted that lagoons could be cost competitive to tax payers when compared to nuclear power when considered over a long period of time (100 years). In addition, the review noted the 'wider benefits' beyond power generation which lagoons could provide and highlighted that any purely economic analysis of lagoons would overlook these benefits and therefore overlook the potential of lagoons as a strategic decision for the UK. For these reasons the review recommended that allocation of development of lagoons for specific sites be open to competitive tender to allow large, complex projects greater flexibility to incorporate other benefits such as flood protection, area regeneration and tourism. The Hendry Review brought home the message of considering lagoons as multi-function facilities that provide many other benefits to society other than energy generation. It recommended lagoons go ahead, that Swansea Bay go ahead and that these wider benefits be encouraged during those developments, with environmental impacts carefully monitored.

After 18 month delay, in June 2018 the UK government rejected the Swansea Bay lagoon development [13]. The reason for the rejection was the project was not seen as value for taxpayer's money following a Department for Business Energy and Industrial Strategy (BEIS) value for money assessment [13,52,255,256]. This assessment is one that is carried out on all large-scale energy generation bids in the UK. It considers the three 'C's of carbon reduction, cost reduction and competitive advantage and it includes electricity generation only [120]. In this way large scale energy projects can be compared against each other, all undergoing the same value for money assessment. From this assessment BEIS concluded that nuclear power is more cost effective than tidal power and that on today's market renewable energy could be bought from cheaper sources such as offshore wind.

BEIS's value for money assessment does not consider a lagoon's long expected lifespan, does not consider cost reductions over time, does not consider decommissioning costs (which will be significant for nuclear) and does not include the wider societal benefits of flood protection, leisure and recreation etc. The actual figures which they present in the analysis report and factsheet [256,257] are therefore only part of the whole picture. Many of the values and figures BEIS present have been contested publicly in a published rebuttal by TLP [15]. One example from this rebuttal is BEIS' headline statement that Swansea Bay lagoon will cost three times as much as Hinkley Point C Nuclear power station. TLP argue that this calculation is based on capital cost only, and therefore does not take into account that Hinkley Point's expected lifespan is 60 years, whereas Swansea Bay's is 120 years [15].

TLP had their own independent cost assessment undertaken by Aurora Energy previously in 2016 [258]. This concluded that tidal power was a cost-effective strategy to meet the UK's energy demands in the future. Both the cost assessments by BEIS and TLP are covered by non-disclosure agreements that they have agreed between themselves. As such the exact detail of their respective cost assessments are unknown, leaving the general public, as 'tax payers', relatively in the dark about the detail of the cost modelling work. What is known is that BEIS's assessment does not include the wider societal benefits of lagoons, whereas TLP's does, and that the BEIS assessment considers lagoons over 35 years and TLP's over 120 years. In this way, it can be deduced that inclusion or exclusion of these wider benefits over a long period is determining whether or not lagoons are seen as 'value for money'. BEIS argue that they cannot put the higher cost of development for wider benefits of leisure and recreation and flood protection onto consumer energy bills, and their current model for assessing the value for money of energy projects is solely for energy generation systems i.e. not flood protection and other societal benefits [120].

It appears that TLP and BEIS disagree on the definition of 'value for money' and what this includes or excludes. Society might say that one development with multiple uses is providing 'more for the money', 'more bang for the buck', 'killing two birds with one stone' and all the societal phrases coined for the advantages of this approach. Or society might say by trying to incorporate more than one function there will be a loss of quality and robustness of individual function e.g. energy generation from a sole function station might be more efficient than from a multi-use station. Either way, a representative decision is being constrained by an arguably outmoded energy policy that does not allow for proper assessment of multi-use energy facilities that could bring benefits across many disciplines, economic, societal and environmental. The UK government currently does not seem to have a system or model to assess the true ‘value’ of lagoons because the Swansea Bay proposal was innovative, i.e. nothing like this has been presented to them before. The sector is no further forward after the recent rejection of Swansea, because nobody really seems to know if Swansea Bay is ‘value for money’. TLP’s analysis is under a non-disclosure agreement and could be open to accusations of bias given they are the developer, and BEIS’s analysis is only a small part of the overall picture with what seems like significant limitations in methodology.

This raises a number of questions relating to the government’s energy policy, some of which were discussed after the Swansea bay rejection [120], but many of which remain unanswered, including: Are multi-use, innovative energy developments being discouraged now because they will fail the traditional energy value for money assessment? Why are the current systems not being adapted as and when tested with new and forward-thinking project proposals? Why was there a significant 18-month delay in this decision, if using an existing model of assessment which has been implemented may times? Was there even a need for the Hendry review, if BEIS just defaulted back to an existing standard methodology for testing energy developments? If looking at what is better for future generations, why are these assessments not over 100 years, to reflect the projects lifetime, or not inclusive of decommissioning? What happens to the assessment results when we include the societal cost of damaging nuclear waste or of rising sea levels? Why is all this work under a non-disclosure agreement, but the public are expected to accept it as now fact and superior to the analysis which TLP has done?

This research has considered the environmental impacts of lagoons, and in 2015 when the research started it was thought that this would be a significant barrier to lagoons alongside the high costs. Now the barriers of lack of transparency and lack of innovation in terms of government assessments can be added to that list. Chapter 5 of the research considered the wider benefits against more traditional criteria and concluded that, for solution option implementation only it was essential to be aware that inclusion or exclusion of these will change what is deemed ‘optimal’ or ‘value for money’. The industry is now also debating what is value for money and it again seems to hinge on the inclusion or exclusion of the wider benefits to society. Whilst this research cannot draw conclusions on how the wider inclusion or exclusion of benefits to society might change what is deemed value for money for lagoons as a whole, it does find that inclusion or exclusion of this criteria changes what is deemed optimal in terms of solution selection to address the environmental impacts lagoons are likely to present.

If the initial hurdles on differences in definition of 'value for money' can be overcome and if the government can adapt, innovate and host the idea of multi-use facilities in order to allow for their proper assessment then the UK might foreseeably be developing lagoons in the future in the UK. In which case, this research would provide information to reduce the uncertainty currently seen around the environmental impacts of tidal lagoons. The proposed Cardiff Bay lagoon is still pushing ahead, and received its grid connection award in September 2017 [49,259,260]. As the industry engagement in Chapter 2 of this research showed there are many other developers in the industry, with lagoons in the planning pipeline. In addition, the Welsh government has made an offer of investment to TLP for Swansea bay lagoon which provides a promising line of investigation for the company [261].

There might be significant benefits for the first mover of the industry and for the country which hosts that development, namely the exporting of skills and knowledge globally and becoming a world leader in the technology. If the UK does not develop lagoons then it is likely that other countries will be primed to capitalise on the UK's inactivity. This research helps to reduce the uncertainty surrounding the environmental impacts of lagoons by increasing the knowledge base in the sector, providing tools to tackle the key industry barriers and demonstrating that 'optimisation' and 'value for money' of solution option implementation is subject to the criteria used in its assessment. In this way, the research contributes towards building a case for continuing to peruse the development of the lagoon sector globally.

7 Conclusions & Further Work

7.1 Further Work

Further research could focus on the public perspective on the key impacts of tidal lagoons, this would allow for further comparison with the developer and influencer perspectives gathered in this research. This would also provide insight into the link between the environmental impacts of tidal lagoons and the flow of benefits or dis-benefits to society as a result of changes to these impacts with solution option implementation i.e. changes to Ecosystem services. In addition, gathering the public perception on solution options and expected ecosystem service provision would allow key beneficiaries to be identified and associated potential funding opportunities.

The excel files developed as part of this research would require further 'clean up' to make them more user friendly, potentially linking them together and having consistent identifying codes for certain impacts or certain solutions.

Another avenue for further research would be to do a site-specific study, considering multiple different developments at one site and comparing these in terms of cost, environmental and societal impact. This kind of further study may first aim to determine if a lagoon could be effective at one particular site and then expand out into feasibility of lagoons at sites around the UK and therefore feasibility of a UK industry.

Using one specific site may also be useful in terms of a study with and without the inclusion of ecosystem service consideration, to further investigate how inclusion of wider environmental and societal information could change decision making.

7.2 Conclusion

This research provides the sector with first identification of influencer and developer views on the environmental impacts of tidal lagoons to address the first research objective i.e. *Identifying the environmental impacts of tidal lagoons.* This gives a snapshot of industry perspectives, identifying what the industry believes to be the key negative and positives of lagoon developments. In doing so, the research uncovers the similarities and more importantly the differences between influencers and developer groups, proactively highlighting a potential future cause for concern and providing recommendations to address this.

It is vital that the views of influencers and developers are aligned if a smooth transition of lagoons from planning to development is to be achieved. This research allows a starting point for the industry to progress into a collaborative approach to tackle the environmental impacts of tidal lagoons moving forward, by presenting what the key impacts and benefits are, the preferred key outcomes of lagoon developments, what solution options might be available and the differences in influencer and developer perspectives. The research directly fills a knowledge gap relating to the lack of lagoon specific research on the environmental impacts and benefits of tidal lagoons through a holistic and whole-systems approach.

In addition, the industry engagement section of the research highlighted the key industry challenges according to influencers and developers likely to be working on future tidal lagoons and suggests how these challenges can be addressed through development of lagoon-specific regulation, reduction in process and consenting times and developing a more targeted approach to solution development. The industry engagement research allowed for gaps in industry knowledge to be highlighted in solution options available to the industry. This gap is then later filled by this research using systematic literature review of solutions from other relevant industries.

To address the second research objective i.e. *Determine solution options to the key impacts of tidal lagoons* the research applied novel use of systematic literature review to allow a large and valuable resource to be discovered on the potential for transferable solution options to address the environmental impacts of lagoons from other relevant coastal, marine and river industries. The database of solutions created as a result of the research justifies the need for the nascent lagoon industry to investigate solution options from other industries further and capitalise on the learning and experience in terms of addressing similar key environmental impacts. Furthermore, the solution options research directly fills a sector knowledge gap which was uncovered in the industry engagement on the types of solution options currently available to the lagoon industry. Highlighting this resource for the sector could allow reduction of the uncertainty surrounding the environmental impact of lagoons through the extraction of confidence from the learning and experience of other relevant industries in the handling of similar environmental impacts. This research is both relevant and timely, given that uncertainty on environmental impacts of lagoons and regulatory concern is currently seen as one of the key barriers to lagoon developments.

The final section of the research addresses the third objective to *Select, assess and value solution option combinations for addressing the key impacts of lagoons.* This provides a workable methodology for selection, assessment and example valuation of solution options to address the environmental impacts of tidal lagoons which allows incorporation of the wider environmental, social and economic aspects of lagoons as multi-use facilities. The research combines the established techniques of MCDA, ESA, ESV and CBA to demonstrate use in a novel way, for assessing the optimisation of lagoon solution options.

In demonstration of the novel approach for tidal lagoons the research finds how sensitive the results are to inclusion or exclusion of the wider ecosystem service aspects of solution implementation. This further highlights that consideration, or not, of the wider benefits of lagoons could underpin what solutions are deemed ‘optimal’ and as such the ‘optimisation’ of lagoons..

In addition to advancement of knowledge in the sector, the research has developed a number of tools to allow for practical application of the new knowledge. These include a lagoon environmental impact and benefits database, solution option look-up tool for key environmental impacts, a solution selection and site parameter MCDA tool and a template for application of an ESA, ESV and CBA to allow inclusion of the wider environmental, socioeconomic aspects in solution appraisal and lagoon environmental optimisation.

At the start of the research in 2015 there was no comprehensive literature on the environmental impacts of lagoons, let alone solution options or a demonstrated methodology for their selection, assessment and example valuation. In addition, there are no tidal lagoons in the world to gain information from and, at the time, very little lagoon specific research in print. This research has identified the environmental impacts of lagoons through industry engagement, investigated solution options to address the key impacts through systematic review of transferable options from other relevant industries and demonstrated a way to select and analyse solutions which considers the wider environment and socio-economic implications of lagoon developments. The research makes contribution towards optimising tidal lagoons with an environmental focus by addressing its overarching aim to *Optimise the selection of solution options to address the key impacts of tidal lagoons.*

8 References

[1] United Nations, Paris Agreement - Status of Ratification, Framew. Conv. Clim. Chang. (2016). http://unfccc.int/2860.php (accessed November 28, 2016).

[2] UK Government, 2050 Pathways - GOV.UK, (n.d.). https://www.gov.uk/guidance/2050-pathways-analysis (accessed September 3, 2018).

[3] Department of Energy & Climate Change (DECC), UK Renewable Energy Roadmap Update 2013, 2013. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/255182/UK_Renewable_Energy_Roadmap_-_5_November_-_FINAL_DOCUMENT_FOR_PUBLICATIO___.pdf.

[4] Parlimentary Business, Parliment Publ. (2016). https://www.parliament.uk/business/committees/committees-a-z/commons-select/energy-and-climate-change-committee/news-parliament-2015/heat-transport-report-published-16-17/ (accessed November 10, 2016).

[5] S. Waters, G. Aggidis, A world first: Swansea Bay tidal lagoon in review, Renew. Sustain. Energy Rev. 56 (2016). doi:10.1016/j.rser.2015.12.011.

[6] Tidal Lagoon Swansea Bay, Environmental Statement: Non-Technical Summary. The Proposed Tidal Lagoon Swansea Bay Order, 2014. http://tidallagoon.opendebate.co.uk/files/TidalLagoon/DCO_Application/6.1_E.pdf.

[7] Tidal Lagoon Power Ltd, Swansea Bay Lagoon ProjectL Project Benefits, (2015). http://www.tidallagoonswanseabay.com/the-project/project-benefits/54/ (accessed September 29, 2015).

[8] D. Mackay, Sustainability without the hot air, UIT Cambridge Ltd, 2009.

[9] Tidal Lagoon Power Ltd, Tidal Lagoon Power: Key Statistics, (2016). http://www.tidallagoonpower.com/about/key-statistics/ (accessed January 1, 2016).

[10] S.P. Neill, A. Angeloudis, P.E. Robins, I. Walkington, S.L. Ward, I. Masters, M.J. Lewis, M. Piano, A. Avdis, M.D. Piggott, G. Aggidis, P. Evans, T.A.A. Adcock, A. Židonis, R. Ahmadian, R. Falconer, Tidal range energy resource and optimization – Past perspectives and future challenges, Renew. Energy. (2018). doi:10.1016/j.renene.2018.05.007.

[11] Tidal Lagoon Power Ltd, Swansea Bay Lagoon Project - Planning, (2015). http://www.tidallagoonswanseabay.com/planning/planning-process/61/ (accessed July 20, 2016).

[12] (DECC) Department of Energy & Climate Change, Review of Tidal Lagoons, (n.d.). https://www.gov.uk/government/news/review-of-tidal-lagoons (accessed July 20, 2016).

[13] G. Clark, Oral Statement to Parliament - Proposed Swansea Bay tidal lagoon 25/6/2018 - GOV.UK, (n.d.). https://www.gov.uk/government/speeches/proposed-swansea-bay-tidal-lagoon (accessed September 3, 2018).

[14] House of Commons Library, Briefing Paper Number 7940 26th June 2018: Tidal Lagoons, 2018.

[15] Tidal Lagoon Power Ltd, Tidal Lagoon Power Rebuttal to BEIS statement ofn Swansea Bay Tidal Lagoon, (2018).

[16] F. Harvey, Severn tidal power barrage plans slammed by MPs, Guardian. (2013). https://www.theguardian.com/business/2013/jun/10/severn-tidal-power-barrage-plans-mps (accessed April 19, 2017).

[17] T. Hooper, M. Austen, Tidal barrages in the UK: Ecological and social impacts, potential mitigation, and tools to support barrage planning, Renew. Sustain. Energy Rev. 23 (2013) 289–298. doi:10.1016/j.rser.2013.03.001.

[18] C. Hendry, THE ROLE OF TIDAL LAGOONS FINAL REPORT, 2016. https://hendryreview.files.wordpress.com/2016/08/hendry-review-final-report-english-version.pdf (accessed February 7, 2017).

[19] J.. Sumich, An introduction to the Biology of Marine Life, sixth, Wm.C.Brown, 1996.

[20] The cause and nature of tides | Land Information New Zealand (LINZ), New Zeal. L. Inf. Website . (2018). https://www.linz.govt.nz/sea/tides/introduction-tides/cause-and-nature-tides (accessed March 27, 2018).

[21] EMEC, Assessment of Tidal Energy Resource, 2009.

[22] N.O. and A.A. US Department of Commerce, NOAA National Ocean Service Education: Tides and Water Levels, (n.d.). https://oceanservice.noaa.gov/education/kits/tides/tides07_cycles.html (accessed March 27, 2018).

[23] Sustainable Development Comission, Turning the Tide: Tidal Power in the UK, 2007. http://www.sd-commission.org.uk/data/files/publications/Tidal_Power_in_the_UK_Oct07.pdf.

[24] Alternative Energy Tutorials, Tidal Barrage and Tidal Barrage Energy Devices, (2018). http://www.alternative-energy-tutorials.com/tidal-energy/tidal-barrage.html (accessed September 14, 2018).

[25] Tidal Electric Inc, History of Tidal Power, (2017). http://www.tidalelectric.com/history-of-tidal-power/ (accessed February 2, 2018).

[26] Tidal Lagoon Power Ltd, History of tidal range technology in the UK, (2017). http://www.tidallagoonpower.com/tidal-technology/history/ (accessed February 2, 2018).

[27] The tide mill living museum, A Brief History: Woodbridge Mill, (2017). http://woodbridgetidemill.org.uk/history/ (accessed February 2, 2018).

[28] East Anglican Film Archive, Craftsmen: The Tide Miller: Archived Footage, (1951). http://www.eafa.org.uk/catalogue/334.

[29] Tidal Power Website, Hisotry of Tidal Power, (2017). http://tidalpower.co.uk/history-of-tidal-power (accessed February 2, 2018).

[30] Vincent de Laleu, La Rance Tidal Power Plant. 40 year operation feedback - lessons learnt, in: BHA Annu. Conf., Liverpool, 2009. http://www.british-hydro.org/downloads/La Rance-BHA-Oct 2009.pdf.

[31] J. White, Parliment Publication.Energy and Climate Change Committee. Written evidence submitted by Jonathon White (SEV 54), (2013). http://www.publications.parliament.uk/pa/cm201314/cmselect/cmenergy/194/194vw49.htm.

[32] T.. Shaw, La Rance tidal power barrage, ecological observations relevant to a severn barrage project., n.d.

[33] TETHYS, Annapolis Tidal Station | Tethys, (2016). https://tethys.pnnl.gov/annex-iv-sites/annapolis-tidal-station (accessed February 27, 2018).

[34] M. Schneeberger, Sihwa tidal - turbines and generators for the world's largest tidal power plant, in: Andritz Hydro. Brisitsh Hydropower Assoc. 2008, Bristol, UK, 2009.

[35] N. Park, Sihwa Tidal Power Plant: a success of environment and energy policy in Korea, in: Korea Univ., n.d. http://www.eer.wustl.edu/McDonnellMayWorkshop/Presentation_files/Saturday/Saturday/Park.pdf.

[36] IRENA, Tidal Energy Tehcnology Brief, 2014. http://www.irena.org/documentdownloads/publications/tidal_energy_v4_web.pdf.

[37] DECC, Severn Tidal Power: Feasibility Study Conclusions and Summary Report, 2010. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/50064/1._Feasibility_Study_Conclusions_and_Summary_Report_-_15_Oct.pdf.

[38] C. Peters, Severn Estuary Tidal Power, 2010. http://www.assembly.wales/Research Documents/Severn Estuary Tidal Power - Research paper-10052010-180289/10-011-English.pdf (accessed May 26, 2018).

[39] Parsons Brinckerhoff Ltd, Black & Veatch, SEVERN TIDAL POWER -SEA ENVIRONMENTAL REPORT, (2010). http://webarchive.nationalarchives.gov.uk/20121217225059/http://www.decc.gov.uk/assets/decc/what we do/uk energy supply/energy mix/renewable energy/severn-tp/622-severn-tidal-power--sea-environmental-report.pdf (accessed May 26, 2018).

[40] 4cOffshore, Annapolis Royal Generating Station - 4C Offshore, (n.d.). http://www.4coffshore.com/windfarms/tidal-annapolis-royal-generating-station-canada-tidalid129.html (accessed February 27, 2018).

[41] Electrical Line, Nova Scotia Power. Tidal Power Pioneer, 2002. http://electricalline.com/images/mag_archive/18.pdf (accessed February 27, 2018).

[42] Nova Scotia Power, Annapolis Tidal Station | Nova Scotia Power, (n.d.). https://www.nspower.ca/en/home/about-us/how-we-make-electricity/renewable-electricity/annapolis-tidal-station.aspx (accessed February 27, 2018).

[43] yun ha kim, Technology case study: Sihwa Lake tidal power station | International Hydropower Association, Int. Hydropower Assoc. (2016). https://www.hydropower.org/blog/technology-case-study-sihwa-lake-tidal-power-station (accessed February 27, 2018).

[44] The Crown Estate, UK wave and tidal key resource areas project, 2012. http://www.thecrownestate.co.uk/media/5476/uk-wave-and-tidal-key-resource-areas-project.pdf.

[45] C. Baker, Tidal power, Energy Policy. 19 (1991) 792–797. doi:10.1016/0301-4215(91)90049-T.

[46] Department of Energy & Climate Change (DECC), Digest of UK energy statistics (DUKES): Chapter 5: Electricity, 2016. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/552059/Chapter_5_web.pdf.

[47] Tidal Lagoon Power Ltd, Tidal Lagoon Swansea Bay, (2018). http://www.tidallagoonpower.com/projects/swansea-bay/ (accessed March 20, 2018).

[48] M. Munday, C. Jones, Turning Tide: the economic significance of the Tidal Lagoon Swansea Bay, (2013). http://tidallagoon.opendebate.co.uk/files/TidalLagoon/Cardiff_Business_School_Report.pdf (accessed February 23, 2018).

[49] Tidal Lagoon Power Ltd, Tidal Lagoon Cardiff, (2018). http://www.tidallagoonpower.com/projects/cardiff/ (accessed March 20, 2018).

[50] S. Messenger, Tidal lagoon “has offered government new deal on price” - BBC News, BBC News. (2018). http://www.bbc.co.uk/news/uk-wales-south-west-wales-43159608 (accessed June 5, 2018).

[51] BBC news, £1.3bn Swansea tidal lagoon “too big a prize to give up” - BBC News, BBC. (2018). https://www.bbc.co.uk/news/uk-wales-politics-44337310 (accessed June 5, 2018).

[52] S. Hinson, Briefing Paper Tidal Lagoons, 2018.

[53] Tidal Lagoon Power Ltd, Tidal lagoon Newport, (2018). http://www.tidallagoonpower.com/projects/newport/ (accessed March 20, 2018).

[54] Tidal Lagoon Power Ltd, Tidal lagoon Colwyn, (2018). http://www.tidallagoonpower.com/projects/colwyn-bay/ (accessed March 20, 2018).

[55] Tidal Lagoon Power Ltd, Tidal Lagoon West Cumbria, (2018). http://www.tidallagoonpower.com/projects/west-cumbria/ (accessed March 20, 2018).

[56] Tidal Lagoon Power Ltd, Tidal Lagoon Bridgewater Bay, (2018). http://www.tidallagoonpower.com/projects/bridgwater-bay/ (accessed March 20, 2018).

[57] North Wales Tidal Energy, North Wales Tidal Energy Concept, (2018). https://www.northwalestidalenergy.com/concept (accessed March 20, 2018).

[58] Tidal Energy Today, North West Energy Squared, (2018). https://tidalenergytoday.com/tag/north-west-energy-squared/ (accessed March 20, 2018).

[59] Morecambe Bay Barrage has potential, The Vistor. (2017). https://www.thevisitor.co.uk/news/morecambe-bay-barrage-has-potential-1-8350723 (accessed March 20, 2018).

[60] Solway Gateway, Solway Electric Bridge, (2018). http://www.solwayenergygateway.co.uk/ (accessed March 20, 2018).

[61] Natural Energy Wyre, (2018). http://naturalenergywyre.co.uk/ (accessed March 20, 2018).

[62] Ecotricity, Ecotricity set to launch tidal energy bid, (2018). https://www.ecotricity.co.uk/news/news-archive/2016/ecotricity-set-to-launch-tidal-energy-bid (accessed March 20, 2018).

[63] LongBay SeaPower, West Somerset Lagoon, (2018). https://www.westsomersetlagoon.com/ (accessed March 20, 2018).

[64] Tidal Electric Ltd, Tidal Electric, (2018). http://www.tidalelectric.com/#tidal-electric (accessed March 20, 2018).

[65] VerdErg, VETT turbine, (2018). http://www.verdergrenewableenergy.com/ (accessed March 20, 2018).

[66] C. Hendry, The Hendry Review Summary of Reccomendations, 2017. https://hendryreview.files.wordpress.com/2016/08/summary-of-recommendations.pdf.

[67] Department of Energy and Climate Change (DECC), South West RDA, Welsh Assembly Government, Severn Tidal Power Feasibility Study: Conclusions and Summary Report, 2010. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/50064/1._Feasibility_Study_Conclusions_and_Summary_Report_-_15_Oct.pdf (accessed May 26, 2018).

[68] T. a. Adcock, S. Draper, T. Nishino, Tidal power generation - A review of hydrodynamic modelling, Proc. Inst. Mech. Eng. Part A J. Power Energy. 0 (2015) 1–17. doi:10.1177/0957650915570349.

[69] R. Ahmadian, R. a. Falconer, B. Bockelmann-Evans, Comparison of hydro-environmental impacts for ebb-only and two-way generation for a Severn Barrage, Comput. Geosci. 71 (2014) 11–19. doi:10.1016/j.cageo.2014.05.006.

[70] A. Angeloudis, R. Ahmadian, R. a. Falconer, B. Bockelmann-Evans, Numerical model simulations for optimisation of tidal lagoon schemes, Appl. Energy. 165 (2016) 522–536. doi:10.1016/j.apenergy.2015.12.079.

[71] I. Fairley, R. Ahmadian, R. a. Falconer, M.R. Willis, I. Masters, The effects of a Severn Barrage on wave conditions in the Bristol Channel, Renew. Energy. 68 (2014) 428–442. doi:10.1016/j.renene.2014.02.023.

[72] J. Xia, R. a. Falconer, B. Lin, Hydrodynamic impact of a tidal barrage in the Severn Estuary, UK, Renew. Energy. 35 (2010) 1455–1468. doi:10.1016/j.renene.2009.12.009.

[73] J. Xia, R. a. Falconer, B. Lin, Impact of different tidal renewable energy projects on the hydrodynamic processes in the Severn Estuary, UK, Ocean Model. 32 (2010) 86–104. doi:10.1016/j.ocemod.2009.11.002.

[74] M.J. Lewis, S.P. Neill, a J. Elliott, Interannual Variability of Two Offshore Sand Banks in a Region of Extreme Tidal Range, J. Coast. Res. 31 (2014) 1–12. doi:10.2112/JCOASTRES-D-14-00010.1.

[75] J.S. Pethick, R.K. a Morris, D.H. Evans, Nature conservation implications of a Severn tidal barrage - A preliminary assessment of geomorphological change, J. Nat. Conserv. 17 (2009) 183–198. doi:10.1016/j.jnc.2009.04.001.

[76] M. Kadiri, R. Ahmadian, B. Bockelmann-Evans, R. a. Falconer, D. Kay, An assessment of the impacts of a tidal renewable energy scheme on the eutrophication potential of the Severn Estuary, UK, Comput. Geosci. 71 (2014) 3–140. doi:10.1016/j.cageo.2014.07.018.

[77] M. Kadiri, R. Ahmadian, B. Bockelmann-Evans, W. Rauen, R. Falconer, A review of the potential water quality impacts of tidal renewable energy systems, Renew. Sustain. Energy Rev. 16 (2012) 329–341. doi:10.1016/j.rser.2011.07.160.

[78] C. Lyddon, A. Plater, J. Brown, T. Prime, J. Worlf, The impact of tidal lagoons on future flood Risk on the North Wirral and Conwy coastline, UK, in: National Oceanography Centre (Ed.), Eur. Geosci. Union Gen. Assem., 2017.

[79] T. Baker, Tidal Range Developments: How could several tidal lagoons interact and affect one another?, in: Chief Eng. - Mar. Energy Black Veatch, All Energy 2016, Glasgow, 2016. http://www.all-energy.co.uk/en/Sessions/27104/Wave-and-Tidal-Seminar-Theatre-Day-1.

[80] J. Cousineau, I. Nistor, A. Cornett, Hydrodynamic impacts of tidal lagoons in the Bay of Funday, Coast. Eng. 33 (2012).

[81] S. Petley, G. Aggidis, Swansea Bay tidal lagoon annual energy estimation, Ocean Eng. 111 (2016). doi:10.1016/j.oceaneng.2015.11.022.

[82] A. Angeloudis, R.A. Falconer, Sensitivity of tidal lagoon and barrage hydrodynamic impacts and energy outputs to operational characteristics, Renew. Energy. (2016). doi:10.1016/j.renene.2016.08.033.

[83] S. Waters, G. Aggidis, Tidal range technologies and state of the art in review, Renew. Sustain. Energy Rev. 59 (2016). doi:10.1016/j.rser.2015.12.347.

[84] G. Rajgor, Time for tidal lagoons?, Renew. Energy Focus. 17 (2016). doi:10.1016/j.ref.2016.08.010.

[85] Tidal Lagoon Power, Ecosystem Enhancement Programme (EEP), 2016. http://www.tidallagoonpower.com/wp-content/uploads/2016/08/TLP-EEP-Strategy_June-2016.pdf (accessed February 23, 2018).

[86] J. Wang, Y. Jung, Z. C, J. Zhao, Review on multi-criteria decision analysis aid in sustainable energy decision-making, Renew. Sustain. Energy Rev. 13 (2009) 2263–2278.

[87] J. Dodgson, M. Spackman, A. Pearman, L. Phillips, Multi-criteria analysis: a manual, (2009) 168. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/7612/1132618.pdf.

[88] O. Omitaomu, Adapting a GIS-based multicriteria decision analysis approach for evaluating new power generating sites., Appl. Energy. 96 (2012) 292–301.

[89] M. Anwarzai, K. Nagasaka, Utility-scale implementable potential of wind and solar energies for Afghanistan using GIS multi-criteria decision analysis, Renew. Sustain. Energy Rev. 71 (2016) 150–160.

[90] N. Maslov, D. Brosset, C. Claramunt, J.-F. Dé, R. Charpentier, Geo-Information A Geographical-Based Multi-Criteria Approach for Marine Energy Farm Planning, ISPRS Int. J. Geo-Inf. 3 (2014) 781–799. doi:10.3390/ijgi3020781.

[91] JNCC, Ecosystem Approach, (2018). http://jncc.defra.gov.uk/default.aspx?page=6276 (accessed July 11, 2018).

[92] Millennium Ecosystem Assessment : Ecosystems and Human Well being synthesis, Washington DC Island Press, 2005.

[93] Millennium Ecosystem Assessment: Ecosystems and human well-being, (2005). http://millenniumassessment.org/en/Index-2.html (accessed March 23, 2015).

[94] European Environment Agency, Common International Classification of Ecosystem Services. Version 4.3., (2013). https://cices.eu/ (accessed September 17, 2018).

[95] UNEP, UK National Ecosystem Assessment (UKNEA), 2011. http://uknea.unep-wcmc.org/Resources/tabid/82/Default.aspx.

[96] C. Brown, M. Walpole, L. Simpson, M. Tierney, UKNEA Introduction to the UK National Ecosystem Assessment, 2011. http://uknea.unep-wcmc.org/LinkClick.aspx?fileticket=BNpVOJWKNxA%3D&tabid=82 (accessed July 11, 2018).

[97] E. Papathanasopoulou, N. Beaumont, T. Hooper, J. Nunes, A.M. Queirós, Energy systems and their impacts on marine ecosystem services, Renew. Sustain. Energy Rev. 52 (2015). doi:10.1016/j.rser.2015.07.150.

[98] T. Börger, N.J. Beaumont, L. Pendleton, K.J. Boyle, P. Cooper, S. Fletcher, T. Haab, M. Hanemann, T.L. Hooper, S.S. Hussain, R. Portela, M. Stithou, J. Stockill, T. Taylor, M.C. Austen, Incorporating ecosystem services in marine planning: The role of valuation, Mar. Policy. 46 (2014). doi:10.1016/j.marpol.2014.01.019.

[99] R.A. Holland, N. Beaumont, T. Hooper, M. Austen, R.J.K. Gross, P.J. Heptonstall, I. Ketsopoulou, M. Winskel, J. Watson, G. Taylor, Incorporating ecosystem services into the design of future energy systems, Appl. Energy. 222 (2018) 812–822. doi:10.1016/j.apenergy.2018.04.022.

[100] R.A. Holland, K. Scott, E.D. Hinton, M.C. Austen, J. Barrett, N. Beaumont, T. Blaber-Wegg, G. Brown, E. Carter-Silk, P. Cazenave, F. Eigenbrod, K. Hiscock, T. Hooper, A. Lovett, E. Papathanasopoulou, P. Smith, A. Thomas, R. Tickner, R. Torres, G. Taylor, Bridging the gap between energy and the environment, Energy Policy. 92 (2016) 181–189. doi:10.1016/J.ENPOL.2016.01.037.

[101] G. Dalton, G. Allan, N. Beaumont, A. Georgakaki, N. Hacking, T. Hooper, S. Kerr, A.M. O'Hagan, K. Reilly, P. Ricci, W. Sheng, T. Stallard, Economic and socio-economic assessment methods for ocean renewable energy: Public and private perspectives, Renew. Sustain. Energy Rev. 45 (2015) 850–878. doi:10.1016/J.RSER.2015.01.068.

[102] N.J. Beaumont, M.C. Austen, J.P. Atkins, D. Burdon, S. Degraer, T.P. Dentinho, S. Derous, P. Holm, T. Horton, E. van Ierland, A.H. Marboe, D.J. Starkey, M. Townsend, T. Zarzycki, Identification, definition and quantification of goods and services provided by marine biodiversity: Implications for the ecosystem approach, Mar. Pollut. Bull. 54 (2007) 253–265. doi:10.1016/J.MARPOLBUL.2006.12.003.

[103] T. Hooper, N. Beaumont, C. Hattam, The implications of energy systems for ecosystem services: A detailed case study of offshore wind, Renew. Sustain. Energy Rev. 70 (2017). doi:10.1016/j.rser.2016.11.248.

[104] K. Elliott, Risk and Opportunities Register, (2018). doi:10.5281/ZENODO.1294919

URL:https://zenodo.org/record/1294919.

[105] K. Elliott, Questionnaire tracking excel, (2018). doi:10.5281/ZENODO.1294932 URL https://zenodo.org/record/1294932.

[106] K. Elliott, QSR NVivo Industry Engagament Analysis File, (2018). doi:10.5281/ZENODO.1294946 URL:https://zenodo.org/record/1294946.

[107] K. Elliott, Recorded Interviews, (2018). doi:10.5281/ZENODO.1294959 URL:https://zenodo.org/record/1294959.

[108] K. Elliott, Industry Engagament Analysis, (2018). doi:10.5281/ZENODO.1294952 URL:https://zenodo.org/record/1294952.

[109] K. Elliott, Transcribed Interviews with Developers, (2018). doi:10.5281/ZENODO.1421179.

[110] K. Elliott, H.C.. Smith, F. Moore, Optimising Tidal Lagoons: Environmental Interactions, 2016. https://energyhub.theiet.org/users/56863-kathryn-mackinnon/posts/18658-tidal-lagoon-environmental-interactions-regulator-perspective-solution-options-and-industry-challenges.

[111] K. Elliott, H.C.M. Smith, F. Moore, A.H. van der Weijde, I. Lazakis, Environmental interactions of tidal lagoons: A comparison of industry perspectives, Renew. Energy. 119 (2018) 309–319. doi:10.1016/J.RENENE.2017.11.066.

[112] P. Bazeley, K. Jackson, Qualitative Data Analysis with NVivo, Second, SAGE publications, 2013.

[113] H. Bernard, G. Ryan, Analyzing qulaitative data: systematic approaches, SAGE, Thousand Oaks, CA, 2010.

[114] G. Gibbs, C. Taylor, How and what to code, Online QDA Website Univ. Huddersf. (2010). http://onlineqda.hud.ac.uk/Intro_QDA/how_what_to_code.php (accessed November 10, 2016).

[115] K. Punch, Introduction to social research: quantitative and qualitative approaches, 2nd ed., London Sage, 2005.

[116] Wyre Tidal, Wyre Tidal Energy: The Team, (n.d.). http://www.wyretidalenergy.com/the-team/ (accessed November 21, 2016).

[117] P.S. Moschella, M. Abbiati, P. Åberg, L. Airoldi, J.M. Anderson, F. Bacchiocchi, F.

Bulleri, G.E. Dinesen, M. Frost, E. Gacia, L. Granhag, P.R. Jonsson, M.P. Satta, A. Sundelöf, R.C. Thompson, S.J. Hawkins, Low-crested coastal defence structures as artificial habitats for marine life: Using ecological criteria in design, Coast. Eng. 52 (2005) 1053–1071. doi:10.1016/j.coastaleng.2005.09.014.

[118] S. Waters, G. Aggidis, Tidal range technologies and state of the art in review, Renew. Sustain. Energy Rev. (2016). doi:10.1016/j.rser.2015.12.347.

[119] Tidal Lagoon Power Ltd, Swansea Bay Lagon Project Website, (2015). http://www.tidallagoonswanseabay.com/ (accessed September 30, 2015).

[120] BEIS and Welsh Affairs Committee, Parliment TV: Swansea Bay Lagoon, (2018). https://parliamentlive.tv/Event/Index/9e16ee80-cbb3-4107-aa8b-b664c5527d3d (accessed June 25, 2018).

[121] IRENA, Tidal Energy Technology Brief, (2014). doi:10.1016/B978-0-12-810448-4.00003-3.

[122] Sustainable Development Comission, research Report 3 - Severn Barrage Proposals, 2007. http://www.sd-commission.org.uk/data/files/publications/TidalPowerUK3-Severn_barrage_proposals.pdf.

[123] eftec, Economic Valuation of the Effect of the Shortlisted Tidal Options on the Ecosystem Services of the Severn Estuary, 2010. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/51157/11._Ecosystems_Valuation_-_Technical_Report.pdf.

[124] JNCC, JNCC Severn Estuary SPA description, (n.d.). http://jncc.defra.gov.uk/default.aspx?page=2066 (accessed November 21, 2016).

[125] Ocean Energy Forum, Ocean Energy Strategic Roadmap 2016, building ocean energy for Europe, 2016.

[126] K. Elliott, H. Smith, F. Moore, I. Lazakis, H. Adriaan, A systematic review of transferable solution options for the environmental impacts of tidal lagoons, Mar. Policy. (2018).

[127] D. Moher, A. Liberati, J. Tetzlaff, D. Altman, The PRISMA Group, Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement, Ann Intern Med. 151 (2009). http://annals.org/aim/article/744664/preferred-reporting-items-systematic-reviews-meta-analyses-prisma-statement?resultClick=3.

[128] Collaboration for Environmental Evidence, Guidelines and Standards for Evidence

synthesis in Environmental Management., Version 5.0. (2018). www.environmentalevidence.org/information-for-authors (accessed April 11, 2018).

[129] C. Liquete, C. Piroddi, et al, Current Status and Future Prospects for the Assessment of Maine and Coastal Ecosystem Services: A Systematic Review, PLoS One. 8 (2013).

[130] B.C. O'Leary, H.R. Bayliss, N.R. Haddaway, Beyond PRISMA: Systematic reviews to inform marine science and policy, Mar. Policy. 62 (2015) 261–263. doi:10.1016/J.MARPOL.2015.09.026.

[131] P.C. Sierra-Correa, J.R. Cantera Kintz, Ecosystem-based adaptation for improving coastal planning for sea-level rise: A systematic review for mangrove coasts, Mar. Policy. 51 (2015) 385–393. doi:10.1016/J.MARPOL.2014.09.013.

[132] R. Cochard, Chapter 12 – Coastal Water Pollution and Its Potential Mitigation by Vegetated Wetlands: An Overview of Issues in Southeast Asia, in: Redefining Divers. Dyn. Nat. Resour. Manag. Asia, Vol. 1, 2017: pp. 189–230. doi:10.1016/B978-0-12-805454-3.00012-8.

[133] W. Pei, Y.Y. Zhu, L. Zeng, S.X. Liu, X.J. Wang, Z.J. An, The remote sensing identification of marine oil spill based on oil fingerprinting, 2013. doi:10.1007/978-3-642-45025-9_74.

[134] R. Schulz, Field studies on exposure, effects, and risk mitigation of aquatic nonpoint-source insecticide pollution, J. Environ. Qual. (2004). https://dl.sciencesocieties.org/publications/jeq/articles/33/2/419?highlight=&search-result=1 (accessed January 16, 2017).

[135] I.A. Thomas, P. Jordan, P.-E. Mellander, O. Fenton, O. Shine, D. Ó hUallacháin, R. Creamer, N.T. McDonald, P. Dunlop, P.N.C. Murphy, Improving the identification of hydrologically sensitive areas using LiDAR DEMs for the delineation and mitigation of critical source areas of diffuse pollution, Sci. Total Environ. 556 (2016) 276–290. doi:10.1016/j.scitotenv.2016.02.183.

[136] M. Gavrilescu, K. Demnerová, J. Aamand, S. Agathos, F. Fava, Emerging pollutants in the environment: Present and future challenges in biomonitoring, ecological risks and bioremediation, N. Biotechnol. 32 (2015). doi:10.1016/j.nbt.2014.01.001.

[137] G. Lofrano, G. Libralato, D. Minetto, S. de Gisi, F. Todaro, B. Conte, D. Calabrò, L. Quatraro, M. Notarnicola, In situ remediation of contaminated marinesediment: an overview, Environ. Sci. Pollut. Res. (2016). doi:10.1007/s11356-016-8281-x.

[138] Y. Del-Pilar-Ruso, E. Martinez-Garcia, F. Giménez-Casalduero, A. Loya-Fernández, L.M. Ferrero-Vicente, C. Marco-Méndez, J.A. de-la-Ossa-Carretero, J.L. Sánchez-Lizaso, Benthic community recovery from brine impact after the implementation of mitigation measures, Water Res. 70 (2015) 325–336. doi:10.1016/j.watres.2014.11.036.

[139] S. Sheavly, K. Register, Marine debris & plastics: environmental concerns, sources, impacts and solutions, J. Polym. Environ. (2007). http://link.springer.com/article/10.1007/s10924-007-0074-3 (accessed January 16, 2017).

[140] M. Kirby, R. Law, Accidental spills at sea–Risk, impact, mitigation and the need for co-ordinated post-incident monitoring, Mar. Pollut. Bull. (2010). http://www.sciencedirect.com/science/article/pii/S0025326X10001050 (accessed January 16, 2017).

[141] C. Price, K.D. Black, B.T. Hargrave, J.A. Morris, Marine cage culture and the environment: Effects on water quality and primary production, Aquac. Environ. Interact. 6 (2014). doi:10.3354/aei00122.

[142] Y.K. Carrillo-Guerrero, K. Flessa, O. Hinojosa-Huerta, L. López-Hoffman, From accident to management: The Cienega de Santa Clara ecosystem, Ecol. Eng. 59 (2013). doi:10.1016/j.ecoleng.2013.03.003.

[143] M. Poustie, R.R. Brown, A. Deletic, Receptivity to sustainable urban water management in the South West Pacific., J. Water Clim. Chang. 5 (2014). http://doi.org/10.2166/wcc.2013.242.

[144] S. Suzdalev, S. Gulbinskas, V. Sivkov, T. Bukanova, Solutions for effective oil spill management in the south-eastern part of the Baltic sea, Baltica. 27 (2014). doi:10.5200/baltica.2014.27.09.

[145] B. Moshtagh, K. Hawboldt, Production of biodispersants for oil spill remediation in Harsh environment using glycerol from the conversion of fish oil to biodiesel, in: 2014 Ocean. - St. John's, Ocean. 2014, 2015. doi:10.1109/OCEANS.2014.7003019.

[146] J.-P. Debenay, C. Marchand, N. Molnar, A. Aschenbroich, T. Meziane, Foraminiferal assemblages as bioindicators to assess potential pollution in mangroves used as a natural biofilter for shrimp farm effluents (New Caledonia), Mar. Pollut. Bull. 93 (2015). doi:10.1016/j.marpolbul.2015.02.009.

[147] T. Soomere, N.C. Delpeche-Ellmann, T. Torsvik, B. Viikmäe, Towards a new

generation of techniques for the environmental management of maritime activities, 2015. doi:10.1007/978-94-017-9538-8_8.

[148] J. Dabrowski, S. Peall, A. Reinecke, Runoff-related pesticide input into the Lourens River, South Africa: basic data for exposure assessment and risk mitigation at the catchment scale, Water, Air, Soil. (2002). http://link.springer.com/article/10.1023/A:1014705931212 (accessed January 16, 2017).

[149] S. Ludwig, R. Kreimeyer, M. Knoll, Comparison of PAM systems for acoustic monitoring and further risk mitigation application, 2016. doi:10.1007/978-1-4939-2981-8_79.

[150] A. Murray, E. Peeler, A framework for understanding the potential for emerging diseases in aquaculture, Prev. Vet. Med. (2005). http://www.sciencedirect.com/science/article/pii/S0167587704002120 (accessed January 16, 2017).

[151] K. Kostow, Factors that contribute to the ecological risks of salmon and steelhead hatchery programs and some mitigating strategies, Rev. Fish Biol. Fish. (2009). http://link.springer.com/article/10.1007/s11160-008-9087-9 (accessed January 16, 2017).

[152] S.J. Dolman, M. Jasny, Evolution of marine noise pollution management, Aquat. Mamm. 41 (2015). doi:10.1578/AM.41.4.2015.357.

[153] U.K. Verfuss, C.E. Sparling, C. Arnot, A. Judd, M. Coyle, Review of offshore wind farm impact monitoring and mitigation with regard to marine mammals, 2016. doi:10.1007/978-1-4939-2981-8_147.

[154] N. Teichert, A. Borja, G. Chust, A. Uriarte, M. Lepage, Restoring fish ecological quality in estuaries: Implication of interactive and cumulative effects among anthropogenic stressors, Sci. Total Environ. 542 (2016). doi:10.1016/j.scitotenv.2015.10.068.

[155] D. Houser, A method for modeling marine mammal movement and behavior for environmental impact assessment, IEEE J. Ocean. Eng. (2006). http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1645245 (accessed January 16, 2017).

[156] T. Jefferson, S. Hung, B. Würsig, Protecting small cetaceans from coastal development: Impact assessment and mitigation experience in Hong Kong, Mar. Policy. (2009). http://www.sciencedirect.com/science/article/pii/S0308597X08001255

(accessed January 16, 2017).

[157] C.J. Brown, Social, economic and environmental effects of closing commercial fisheries to enhance recreational fishing, Mar. Policy. 73 (2016). doi:10.1016/j.marpol.2016.08.010.

[158] R. Costanza, O. Pérez-Maqueo, M. Martinez, The value of coastal wetlands for hurricane protection, Hum. Environ. (2008). http://www.bioone.org/doi/abs/10.1579/0044-7447(2008)37[241:TVOCWF]2.0.CO;2 (accessed January 18, 2017).

[159] M. Ruckelshaus, S.C. Doney, H.M. Galindo, J.P. Barry, F. Chan, J.E. Duffy, C.A. English, S.D. Gaines, J.M. Grebmeier, A.B. Hollowed, N. Knowlton, J. Polovina, N.N. Rabalais, W.J. Sydeman, L.D. Talley, Securing ocean benefits for society in the face of climate change, Mar. Policy. 40 (2013). doi:10.1016/j.marpol.2013.01.009.

[160] N. Touili, J. Baztan, J.-P. Vanderlinden, I.O. Kane, P. Diaz-Simal, L. Pietrantoni, Public perception of engineering-based coastal flooding and erosion risk mitigation options: Lessons from three European coastal settings, Coast. Eng. 87 (2014) 205–209. doi:10.1016/j.coastaleng.2014.01.004.

[161] S. Luo, F. Cai, H. Liu, G. Lei, H. Qi, X. Su, Adaptive measures adopted for risk reduction of coastal erosion in the People's Republic of China, Ocean Coast. Manag. 103 (2015). doi:10.1016/j.ocecoaman.2014.08.008.

[162] F. Ferrario, M.W. Beck, C.D. Storlazzi, F. Micheli, C.C. Shepard, L. Airoldi, The effectiveness of coral reefs for coastal hazard risk reduction and adaptation, Nat. Commun. 5 (2014). doi:10.1038/ncomms4794.

[163] E.M. Bitner-Gregersen, S.K. Bhattacharya, I.K. Chatjigeorgiou, I. Eames, K. Ellermann, K. Ewans, G. Hermanski, M.C. Johnson, N. Ma, C. Maisondieu, A. Nilva, I. Rychlik, T. Waseda, Recent developments of ocean environmental description with focus on uncertainties, Ocean Eng. 86 (2014) 26–46. doi:10.1016/j.oceaneng.2014.03.002.

[164] R. Marsooli, P.M. Orton, N. Georgas, A.F. Blumberg, Three-dimensional hydrodynamic modeling of coastal flood mitigation by wetlands, Coast. Eng. 111 (2016) 83–94. doi:10.1016/j.coastaleng.2016.01.012.

[165] N. Tri, W. Adger, P. Kelly, Natural resource management in mitigating climate impacts: the example of mangrove restoration in Vietnam, Glob. Environ. Chang. (1998). http://www.sciencedirect.com/science/article/pii/S095937809700023X (accessed January 18, 2017).

[166] H. Srinivas, Y. Nakagawa, Environmental implications for disaster preparedness: lessons learnt from the Indian Ocean Tsunami, J. Environ. Manage. (2008). http://www.sciencedirect.com/science/article/pii/S0301479707001430 (accessed January 18, 2017).

[167] J.J. Waggitt, P.W. Cazenave, R. Torres, B.J. Williamson, B.E. Scott, Predictable hydrodynamic conditions explain temporal variations in the density of benthic foraging seabirds in a tidal stream environment, ICES J. Mar. Sci. 73 (2016). doi:10.1093/icesjms/fsw100.

[168] T. Islam, J. Ryan, T. Islam, J. Ryan, Chapter 2 – Mitigation Rules and Regulations, in: Hazard Mitig. Emerg. Manag., 2016: pp. 37–68. doi:10.1016/B978-0-12-420134-7.00002-3.

[169] S. Idllalène, N. Van Cauwenbergh, Improving legal grounds to reduce vulnerability to coastal flooding in Morocco – A plea for an integrated approach to adaptation and mitigation, Ocean Coast. Manag. 120 (2016) 189–197. doi:10.1016/j.ocecoaman.2015.11.012.

[170] A.R. Davis, A. Broad, W. Gullett, J. Reveley, C. Steele, C. Schofield, Anchors away? The impacts of anchor scour by ocean-going vessels and potential response options, Mar. Policy. 73 (2016) 1–7. doi:10.1016/j.marpol.2016.07.021.

[171] B. Ahr, M. Farris, C.G. Lowe, Habitat selection and utilization of white croaker (Genyonemus lineatus) in the Los Angeles and Long Beach Harbors and the development of predictive habitat use models, Mar. Environ. Res. 108 (2015). doi:10.1016/j.marenvres.2015.04.005.

[172] J. Wilson, M. Elliott, The habitat-creation potential of offshore wind farms, Wind Energy. (2009). http://onlinelibrary.wiley.com/doi/10.1002/we.324/full (accessed January 16, 2017).

[173] J. Petersen, T. Malm, Offshore windmill farms: threats to or possibilities for the marine environment, AMBIO A J. Hum. Environ. (2006). http://www.bioone.org/doi/abs/10.1579/0044-7447(2006)35[75:OWFTTO]2.0.CO;2 (accessed January 16, 2017).

[174] T.C. Weber, W.L. Allen, Beyond on-site mitigation: An integrated, multi-scale approach to environmental mitigation and stewardship for transportation projects, Landsc. Urban Plan. 96 (2010) 240–256. doi:10.1016/j.landurbplan.2010.04.003.

[175] Z. Kyriazi, R. Lejano, F. Maes, S. Degraer, Bargaining a net gain compensation

agreement between a marine renewable energy developer and a marine protected area manager, Mar. Policy. 60 (2015). doi:10.1016/j.marpol.2015.06.005.

[176] H. Tallis, C.M. Kennedy, M. Ruckelshaus, J. Goldstein, J.M. Kiesecker, Mitigation for one & all: An integrated framework for mitigation of development impacts on biodiversity and ecosystem services, Environ. Impact Assess. Rev. 55 (2015) 21–34. doi:10.1016/j.eiar.2015.06.005.

[177] A. Bas, C. Jacob, J. Hay, S. Pioch, S. Thorin, Improving marine biodiversity offsetting: A proposed methodology for better assessing losses and gains, J. Environ. Manage. 175 (2016) 46–59. doi:10.1016/j.jenvman.2016.03.027.

[178] M.G. Stigner, H.L. Beyer, C.J. Klein, R.A. Fuller, S. Carvalho, Reconciling recreational use and conservation values in a coastal protected area, J. Appl. Ecol. 53 (2016). doi:10.1111/1365-2664.12662.

[179] T. Zuliani, A. Mladenovič, J. Ščančar, R. Milačič, Chemical characterisation of dredged sediments in relation to their potential use in civil engineering, Environ. Monit. Assess. 188 (2016). doi:10.1007/s10661-016-5239-x.

[180] D. Bush, W. Neal, R. Young, O. Pilkey, Utilization of geoindicators for rapid assessment of coastal-hazard risk and mitigation, Ocean Coast. Manag. (1999). http://www.sciencedirect.com/science/article/pii/S0964569199000277 (accessed January 18, 2017).

[181] T.K. Frost, J.L. Myrhaug, M.K. Ditlevsen, H. Rye, Environmental monitoring and modeling of drilling discharges at a location with vulnerable seabed fauna: Comparison between field measurements and model simulations, in: Soc. Pet. Eng. - SPE Int. Conf. Heal. Saf. Environ. 2014 Journey Contin., 2014.

[182] C. Peterson, M. Bishop, Assessing the environmental impacts of beach nourishment, Bioscience. (2005). http://bioscience.oxfordjournals.org/content/55/10/887.short (accessed January 18, 2017).

[183] K. Mahmood, Reservoir sedimentation: impact, extent, and mitigation. Technical paper, (1987). http://www.osti.gov/scitech/biblio/5564758 (accessed January 18, 2017).

[184] O. Frihy, The necessity of environmental impact assessment (EIA) in implementing coastal projects: lessons learned from the Egyptian Mediterranean Coast, Ocean Coast. Manag. (2001). http://www.sciencedirect.com/science/article/pii/S096456910100062X (accessed

January 16, 2017).

[185] L. Saussaye, H. Hamdoun, L. Leleyter, E. van Veen, J. Coggan, G. Rollinson, W. Maherzi, M. Boutouil, F. Baraud, Trace element mobility in a polluted marine sediment after stabilisation with hydraulic binders, Mar. Pollut. Bull. 110 (2016). doi:10.1016/j.marpolbul.2016.06.035.

[186] S.C. Gonçalves, J.C. Marques, Assessement and management of environmental quality conditions in marine sandy beaches for its sustainable use—Virtues of the population based approach, Ecol. Indic. 74 (2017) 140–146. doi:10.1016/j.ecolind.2016.11.024.

[187] V.J. Hendrick, Z.L. Hutchison, K.S. Last, Sediment burial intolerance of marine macroinvertebrates, PLoS One. 11 (2016). doi:10.1371/journal.pone.0149114.

[188] P. Erftemeijer, R. Lewis, Environmental impacts of dredging on seagrasses: a review, Mar. Pollut. Bull. (2006). http://www.sciencedirect.com/science/article/pii/S0025326X06003778 (accessed January 16, 2017).

[189] K. Elliott, Systematic Review Screening Record& & Analysis, (2018). doi:10.5281/ZENODO.1297037.

[190] C. Jacob, S. Pioch, S. Thorin, The effectiveness of the mitigation hierarchy in environmental impact studies on marine ecosystems: A case study in France, Environ. Impact Assess. Rev. 60 (2016) 83–98. doi:10.1016/j.eiar.2016.04.001.

[191] The Nature Conservancy, Achieving Conservation and Development. 10 principles for applying the mitigation hierarchy, 2015. https://www.nature.org/ourinitiatives/applying-the-mitigation-hierarchy.pdf (accessed April 16, 2018).

[192] C. Jacob, S. Pioch, S. Thorin, The effectiveness of the mitigation hierarchy in environmental impact studies on marine ecosystems: A case study in France, Environ. Impact Assess. Rev. 60 (2016) 83–98. doi:10.1016/j.eiar.2016.04.001.

[193] L.: Tso, THE GREEN BOOK Appraisal and Evaluation in Central Government Treasury Guidance, (n.d.).

[194] L. Weilgart, The impacts of anthropogenic ocean noise on cetaceans and implications for management, Can. J. Zool. (2007). http://www.nrcresearchpress.com/doi/abs/10.1139/z07-101 (accessed January 18, 2017).

[195] B. Zanuttigh, E. Angelelli, G. Bellotti, A. Romano, Y. Krontira, D. Troianos, R. Suffredini, G. Franceschi, M. Cantù, L. Airoldi, F. Zagonari, A. Taramelli, F. Filipponi, C. Jimenez, M. Evriviadou, S. Broszeit, Boosting blue growth in a mild sea: Analysis of the synergies produced by a multi-purpose offshore installation in the Northern Adriatic, Italy, Sustain. 7 (2015). doi:10.3390/su7066804.

[196] M.P. Schramm, M.S. Bevelhimer, C.R. DeRolph, A synthesis of environmental and recreational mitigation requirements at hydropower projects in the United States, Environ. Sci. Policy. 61 (2016) 87–96. doi:10.1016/j.envsci.2016.03.019.

[197] E.S. Brondizio, N.D. Vogt, A.V. Mansur, E.J. Anthony, S. Costa, S. Hetrick, A conceptual framework for analyzing deltas as coupled social–ecological systems: an example from the Amazon River Delta, Sustain. Sci. 11 (2016). doi:10.1007/s11625-016-0368-2.

[198] A. Copping, H. Battey, J. Brown-Saracino, M. Massaua, C. Smith, An international assessment of the environmental effects of marine energy development, Ocean Coast. Manag. 99 (2014). doi:10.1016/j.ocecoaman.2014.04.002.

[199] A. Copping, C. Smith, L. Hanna, H. Battey, J. Whiting, M. Reed, J. Brown-Saracino, P. Gilman, M. Massaua, Tethys: Developing a commons for understanding environmental effects of ocean renewable energy, Int. J. Mar. Energy. 3 (2013) 41–51. doi:10.1016/j.ijome.2013.11.004.

[200] L.G. Torres, T.D. Smith, P. Sutton, A. Macdiarmid, J. Bannister, T. Miyashita, From exploitation to conservation: Habitat models using whaling data predict distribution patterns and threat exposure of an endangered whale, Divers. Distrib. 19 (2013). doi:10.1111/ddi.12069.

[201] A. Yáñez-Arancibia, J.W. Day, E. Reyes, Understanding the coastal ecosystem-based management approach in the gulf of Mexico, J. Coast. Res. 63 (2013). doi:10.2112/SI63-018.1.

[202] A.M. Knights, G.J. Piet, R.H. Jongbloed, J.E. Tamis, L. White, E. Akoglu, L. Boicenco, T. Churilova, O. Kryvenko, V. Fleming-Lehtinen, J.-M. Leppanen, B.S. Galil, F. Goodsir, M. Goren, P. Margonski, S. Moncheva, T. Oguz, K.N. Papadopoulou, O. Setälä, C.J. Smith, K. Stefanova, F. Timofte, L.A. Robinson, An exposure-effect approach for evaluating ecosystem-wide risks from human activities, ICES J. Mar. Sci. 72 (2015). doi:10.1093/icesjms/fsu245.

[203] F. Goodsir, H.J. Bloomfield, A.D. Judd, F. Kral, L.A. Robinson, A.M. Knights, A spatially

resolved pressure-based approach to evaluate combined effects of human activities and management in marine ecosystems, ICES J. Mar. Sci. 72 (2015). doi:10.1093/icesjms/fsv080.

[204] K.L. Yates, D.S. Schoeman, C.J. Klein, Ocean zoning for conservation, fisheries and marine renewable energy: Assessing trade-offs and co-location opportunities, J. Environ. Manage. 152 (2015). doi:10.1016/j.jenvman.2015.01.045.

[205] D. Sánchez-Quiles, A. Tovar-Sánchez, Are sunscreens a new environmental risk associated with coastal tourism?, Environ. Int. 83 (2015) 158–170. doi:10.1016/j.envint.2015.06.007.

[206] J. Mayo-Ramsay, Environmental, legal and social implications of ocean urea fertilization: Sulu sea example, Mar. Policy. 34 (2010) 831–835. doi:10.1016/j.marpol.2010.01.004.

[207] D.A. Friess, J. Phelps, E. Garmendia, E. Gómez-Baggethun, Payments for Ecosystem Services (PES) in the face of external biophysical stressors, Glob. Environ. Chang. 30 (2015). doi:10.1016/j.gloenvcha.2014.10.013.

[208] VerdErg, VETT Basic Prinicples, (2016). http://www.verdergrenewableenergy.com/basic-VETT-principles/basic-principles (accessed August 11, 2016).

[209] VerdErg, Q.A.. Brujin, H. Vis, J.. Kemper, Test on fish survivability of the “Venturi Enhanced Turbine Technology,” 2013. http://www.verdergrenewableenergy.com/files/documents/VA2012_33_Test_on_fish_survivability_of_the_VETT.pdf.

[210] West Country Rivers Trust, Payment for Ecosystem Services Pilot Project: The Fowey River Improvement Auction, 2013. file:///C:/Users/ELL80626/Downloads/11542_FoweyAuctionFinalReportNe0131.pdf.

[211] RSPB, The Feasibility of a Nitrogen PES Scheme in the Poole Harbour Catchment, 2013. file:///C:/Users/ELL80626/Downloads/11599_FinalReport,PooleHarbourPESFeasibility.pdf.

[212] F. Bulleri, M. Chapman, The introduction of coastal infrastructure as a driver of change in marine environments, J. Appl. Ecol. 47 (2009) 26–35. http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2664.2009.01751.x/abstract.

[213] B.C. O'Leary, H.R. Bayliss, N.R. Haddaway, Beyond PRISMA: Systematic reviews to inform marine science and policy, Mar. Policy. 62 (2015) 261–263. doi:10.1016/J.MARPOL.2015.09.026.

[214] K. Elliott, Solution Selection MCDA, (2018). doi:10.5281/ZENODO.1325928.

[215] K. Elliott, Solution Assessment and Valuation (ESA, ESV, CBA), (2018). doi:10.5281/ZENODO.1419171.

[216] Ecosystem Service Valuation, (2011).

[217] R.K. Turner, J. Paavola, P. Cooper, S. Farber, V. Jessamy, S. Georgiou, Valuing nature: Lessons learned and future research directions, Ecol. Econ. (2003). doi:10.1016/S0921-8009(03)00189-7.

[218] Natural Resource Wales, Introducing Sustainable Management of Natural Resources, 2014. https://naturalresources.wales/media/678317/introducing-smnr-booklet-english.pdf (accessed July 11, 2018).

[219] Natural Resource Wales, The State of Natural Resources Report (SoNaRR): Assessment of the Sustainable Management of Natural Resources. Technical Report. Chapter 4: Reislient Ecosystems, 2016.

[220] H.M treasury, The Green Book: Appraisal and Evaluation in Central Government, (2011) 57–58.

[221] Environment Agency, Ecosystem Benefits Inventory Guidance, 2018.

[222] DEFRA, An introductory guide to valuing ecosystem services, 2007. www.defra.gov.uk.

[223] Defra_2007_ValuingESS, (n.d.).

[224] Eftec_2006_ValuingNature, (n.d.).

[225] Eftec_2005_ESS_Guide, (n.d.).

[226] eftec, Valuing Environmental Impacts : Practical Guidelines for the Use of Value Transfer in Policy and Project Appraisal, Department for Environment Farming and Rural Affairs (DEFRA), 2009.

[227] T. Ellis, R. Gardiner, M. Gubbins, A. Reese, D. Smith, C. Weymouth, Aquaculture statistics for the UK, with a focus on England and Wales 2012, (n.d.).

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/405469/Aquaculture_Statistics_UK_2012.pdf (accessed February 20, 2018).

[228] P. Williamson, D.W.R. Wallace, C.S. Law, P.W. Boyd, Y. Collos, P. Croot, K. Denman, U. Riebesell, S. Takeda, C. Vivian, Ocean fertilization for geoengineering: A review of effectiveness, environmental impacts and emerging governance, Process Saf. Environ. Prot. 90 (2012) 475–488. doi:10.1016/j.psep.2012.10.007.

[229] P.M. Glibert, R. Azanza, M. Burford, K. Furuya, E. Abal, A. Al-Azri, F. Al-Yamani, P. Andersen, D.M. Anderson, J. Beardall, G. Mine Berg, L. Brand, D. Bronk, J. Brookes, J.M. Burkholder, A. Cembella, W.P. Cochlan, J.L. Collier, Y. Collos, R. Diaz, M. Doblin, T. Drennen, S. Dyhrman, Y. Fukuyo, M. Furnas, J. Galloway, E. Granéli, D.V. Ha, G. Hallegraeff, J. Harrison, P.J. Harrison, C.A. Heil, K. Heimann, R. Howarth, C. Jauzein, A.A. Kana, T.M. Kana, H. Kim, R. Kudela, C. Legrand, M. Mallin, M. Mulholland, S. Murray, J. O 'neil, G. Pitcher, Y. Qi, N. Rabalais, R. Raine Ao, S. Seitzinger, P.S. Salomon, C. Solomon, D.K. Stoecker, G. Usup, J. Wilson, K. Yin, M. Zhou, M. Zhu, Ocean urea fertilization for carbon credits poses high ecological risks, Mar. Pollut. Bull. 56 (2008) 1049–1056. doi:10.1016/j.marpolbul.2008.03.010.

[230] I.S.F. Jones, Contrasting micro- And macro-nutrient nourishment of the ocean, Mar. Ecol. Prog. Ser. 425 (2011) 281–296. doi:10.3354/meps08882.

[231] Tegen Mor Fisheries Consultants, Swansea Bay Fishing Industry Research Study, 2015.

[232] Lagoon cost "same as Hinkley" - Wave and Tidal | reNEWS - Renewable Energy News, ReNews. (2018). http://renews.biz/103387/lagoon-cost-same-as-hinkley/ (accessed February 22, 2018).

[233] Tidal Lagoon Swansea Bay plc, Selection of turbine technology to minimise impacts on fish 1.0 Introduction, 2015. http://www.pasas.org.uk/Technical Note Turbine selection-minimising impacts on fish including CF....pdf (accessed February 22, 2018).

[234] UK Government, Trends Air Emissions 2015 Excel Data, (2015). https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/579201/trends_air_emissions_2015.csv/preview.

[235] Defra National Statistics Release: Emissions of air pollutants in the UK, (n.d.). https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/681445/Emissions_of_air_pollutants_statistical_release_FINALv4.pdf (accessed February 23, 2018).

[236] The costs of reducing PM 10 and NO 2 emissions and concentrations in the UK: Part 1: PM 10, (2001). https://uk-air.defra.gov.uk/assets/documents/reports/empire/aeat-env-r-0342.pdf (accessed February 23, 2018).

[237] Office for National Statistics, Annex 1: Background and methods for experimental pollution removal estimates - Office for National Statistics, Environ. Accounts. (2016). https://www.ons.gov.uk/economy/environmentalaccounts/methodologies/annex1backgroundandmethodsforexperimentalpollutionremovalestimates (accessed May 9, 2018).

[238] E. and I.S. Department of Business, VALUATION OF ENERGY USE AND GREENHOUSE GAS (GHG) EMISSIONS, 2018. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/671205/Valuation_of_energy_use_and_greenhouse_gas_emissions_for_appraisal_2017.pdf (accessed February 23, 2018).

[239] Natural England, Carbon storage by habitat: Review of the evidence of the impacts of management decisions and condition of carbon stores and sources - NERR043, 2012. http://publications.naturalengland.org.uk/publication/1412347 (accessed February 23, 2018).

[240] Department of Energy and Climate Change, RECORD OF THE HABITATS REGULATIONS ASSESSMENT UNDERTAKEN UNDER REGULATION 61 OF THE CONSERVATION OF HABITATS AND SPECIES REGULATIONS 2010 (AS AMENDED). & ASSESSMENT OF THE PROJECT UNDER ARTICLE 4.7 DEROGATION FOR THE WATER FRAMEWORK DIRECTIVE. Project Title: Tidal Lagoon Swansea Bay, (2015). https://infrastructure.planninginspectorate.gov.uk/wp-content/ipc/uploads/projects/EN010049/EN010049-003136-Tidal Lagoon (Swansea Bay) HRA and WFD assessment.pdf (accessed February 23, 2018).

[241] G.M. Kondolf, Y. Gao, G.W. Annandale, G.L. Morris, E. Jiang, J. Zhang, Y. Cao, P. Carling, K. Fu, Q. Guo, R. Hotchkiss, C. Peteuil, T. Sumi, H.-W. Wang, Z. Wang, Z. Wei, B. Wu, C. Wu, C.T. Yang, Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents, Earth's Futur. 2 (2014) 256–280. doi:10.1002/2013EF000184.

[242] Tidal Lagoon Swansea Bay, Tidal Lagoon Swansea Bay Habitats Regulations Assessment Updated Screening Report Tidal Lagoon Swansea Bay plc, 2014. https://infrastructure.planninginspectorate.gov.uk/wp-content/ipc/uploads/projects/EN010049/EN010049-001598-Updated HRA Screening Report (Appendix 2) July 14 (4).pdf (accessed February 23, 2018).

[243] Environment Agency, Environment Agency Water Appraisal Guidance NWEBS, 2018.

[244] G. Kallis, E. Gómez-Baggethun, C. Zografos, To value or not to value? That is not the question, Ecol. Econ. 94 (2013) 97–105. doi:10.1016/J.ECOLECON.2013.07.002.

[245] E. Gómez-Baggethun, M. Ruiz-Pérez, Economic valuation and the commodification of ecosystem services, Prog. Phys. Geogr. Earth Environ. 35 (2011) 613–628. doi:10.1177/0309133311421708.

[246] E. Gomez-Baggethun, B. Martin-Lopez, Ecological economics perspectives on ecosystem services valuation, in: Handb. Ecol. Econ., Edward Elgar Publishing, 2015: pp. 260–282. doi:10.4337/9781783471416.00015.

[247] A.L. Fanning, Contrasting values in the sustainability debate: limitations of economic valuations and their role in decision-making, Int. J. Sustain. Dev. 19 (2016) 185. doi:10.1504/IJSD.2016.077205.

[248] B. Büscher, S. Sullivan, K. Neves, J. Igoe, D. Brockington, Towards a Synthesized Critique of Neoliberal Biodiversity Conservation, Capital. Nat. Social. 23 (2012) 4–30. doi:10.1080/10455752.2012.674149.

[249] B. Martín-López, D.N. Barton, E. Gomez-Baggethun, F. Boeraeve, F.L. McGrath, K. Vierikko, D. Geneletti, K.J. Sevecke, N. Pipart, E. Primmer, P. Mederly, S. Schmidt, A. Aragão, H. Baral, R.H. Bark, T. Briceno, D. Brogna, P. Cabral, R. De Vreese, C. Liquete, H. Mueller, K.S.-H. Peh, A. Phelan, A.R. Rincón, S.H. Rogers, F. Turkelboom, W. Van Reeth, B.T. van Zanten, H.K. Wam, C.-L. Washbourne, A new valuation school: Integrating diverse values of nature in resource and land use decisions, Ecosyst. Serv. 22 (2016) 213–220. doi:10.1016/J.ECOSER.2016.11.007.

[250] K.M.A. Chan, P. Balvanera, K. Benessaiah, M. Chapman, S. Díaz, E. Gómez-Baggethun, R. Gould, N. Hannahs, K. Jax, S. Klain, G.W. Luck, B. Martín-López, B. Muraca, B. Norton, K. Ott, U. Pascual, T. Satterfield, M. Tadaki, J. Taggart, N. Turner, Opinion: Why protect nature? Rethinking values and the environment., Proc. Natl. Acad. Sci. U. S. A. 113 (2016) 1462–5. doi:10.1073/pnas.1525002113.

[251] S. Diíaz, IPBES Webinar Series – Webinar 2: The IPBES Conceptual Framework Host:The IPBES task force and technical support unit on capacity-building, (n.d.).

[252] R.D. Cavanagh, S. Broszeit, G.M. Pilling, S.M. Grant, E.J. Murphy, M.C. Austen, Valuing biodiversity and ecosystem services: a useful way to manage and conserve marine resources?, Proceedings. Biol. Sci. 283 (2016). doi:10.1098/rspb.2016.1635.

[253] P.A.J. Bonar, I.G. Bryden, A.G.L. Borthwick, Social and ecological impacts of marine energy development, Renew. Sustain. Energy Rev. 47 (2015) 486–495. doi:10.1016/j.rser.2015.03.068.

[254] A.A. Lovett, T.L. Dockerty, E. Papathanasopoulou, N.J. Beaumont, P. Smith, A framework for assessing the impacts on ecosystem services of energy provision in the UK: An example relating to the production and combustion life cycle of UK produced biomass crops (short rotation coppice and Miscanthus), Biomass and Bioenergy. 83 (2015) 311–321. doi:10.1016/J.BIOMBIOE.2015.10.001.

[255] Tidal Lagoon Power Ltd, BEIS statement on Swansea Bay Tidal Lagoon, 2018. http://www.tidallagoonpower.com/wp-content/uploads/2018/07/BEIS-statement-on-Swansea-Bay-Tidal-Lagoon.pdf.

[256] BEIS, TLP Tidal Lagoon Programme: Factsheet, 2018. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/719189/tidal-lagoon-programme-factsheet.pdf.

[257] BEIS, Swansea Bay tidal lagoon: value for money assessment, 2018. https://www.gov.uk/government/publications/swansea-bay-tidal-lagoon-value-for-money-assessment.

[258] Aurora Energy, The impact of tidal lagoons on the GB power market, 2016. http://www.tidallagoonpower.com/wp-content/uploads/2018/07/Aurora-Energy-Research-Tidal-lagoon-valuation-220916.pdf.

[259] Marine Energy Biz, Cardiff tidal lagoon secures grid connection | Marine Energy, (2017). https://marineenergy.biz/2017/09/11/cardiff-tidal-lagoon-secures-grid-connection/ (accessed September 17, 2018).

[260] WaveHub, Cardiff tidal lagoon secures grid connection, (n.d.). https://www.wavehub.co.uk/latest-news/cardiff-tidal-lagoon-secures-grid-connection (accessed September 17, 2018).

[261] BBC news, Pension funds “game-changing” for £1.3bn tidal lagoon bid - BBC News, (2018). https://www.bbc.co.uk/news/uk-wales-south-west-wales-42540950.

[262] Outline World Map, Outline World Map, (2009). http://www.outline-world-map.com/political-white-world-map-b6a (accessed May 16, 2017).

Appendix 1: IET Engineering & Technology Reference Paper

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Tidal lagoon environmental interactions: regulator perspective, solution options and industry challenges

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Abstract

Tidal range energy is an attractive renewable energy option, particularly in areas of high tidal range, such as the UK. Historically one of the main barriers to tidal range developments in the UK, specifically tidal barrages, has been regulatory environmental concerns and uncertainty surrounding environmental impacts. Tidal lagoons are often suggested as a means of reducing the environmental impact of barrage options. Recent developments in the lagoon sector mean it is now more important than ever to further consider the environmental impacts arising from tidal lagoons and the potential constraints these impacts may pose to the industry's future growth. Environmental impacts and their interactions are complex, often making them difficult to understand and manage. Here, the authors develop a conceptual framework to categorise impacts, present results from consultation with regulatory and policy organisations and discuss potential impact and enhancement solution options. This study includes a number of case studies to present lessons learnt, opportunities, cautions and successful implementation of past solutions. In the absence of operational tidal lagoons, these case studies are based on barrages and other relevant developments.

Introduction

Renewable energy technologies are being developed and deployed globally to tackle climate change. Marine energy, comprising wave and tidal resources, is currently un-tapped in the UK to a significant degree. Tidal energy consists of two energy extraction types: tidal stream and tidal range. Tidal range energy can utilise both barrage and lagoon technologies. Fig. 1 shows a basic breakdown of this categorisation.

Tidal barrages contain turbines within a barrier that extends between the banks of an estuary or river. Tidal lagoons differ as they contain bodies of water in a basin, which is either constructed along one side of an estuary or river, or located completely offshore [1].

Both tidal barrages and lagoons extract energy from the tides by creating an artificial difference in water levels, or head. Higher water levels are constrained by the lagoon walls and sluice gates; when these are opened, the flow of water drives turbines to generate electricity.

In the UK alone, tidal lagoon energy could contribute up to 8% of the current electricity demand, assuming six tidal lagoons are constructed [2]. Tidal lagoons have additional advantages such as a 100-year life span, reduced uncertainty through the use of proven technology, a high level of predictability and the opportunity to phase shift energy generation around a coastline. These advantages alone make tidal lagoons an attractive renewable energy option for the UK.

However, despite the advantages, there are currently no operational man-made, energy generating tidal lagoons in the world. The reasons for this include the lack of serious project proposals in the past, in addition to concerns regarding reduced energy output when compared with barrage systems.

Recent developments, including the awarding of a development consent order to Tidal Lagoon Swansea Bay in June 2015 [3] and the announcement of the government review into the feasibility of tidal lagoons for the UK [4], mean that it is now more important

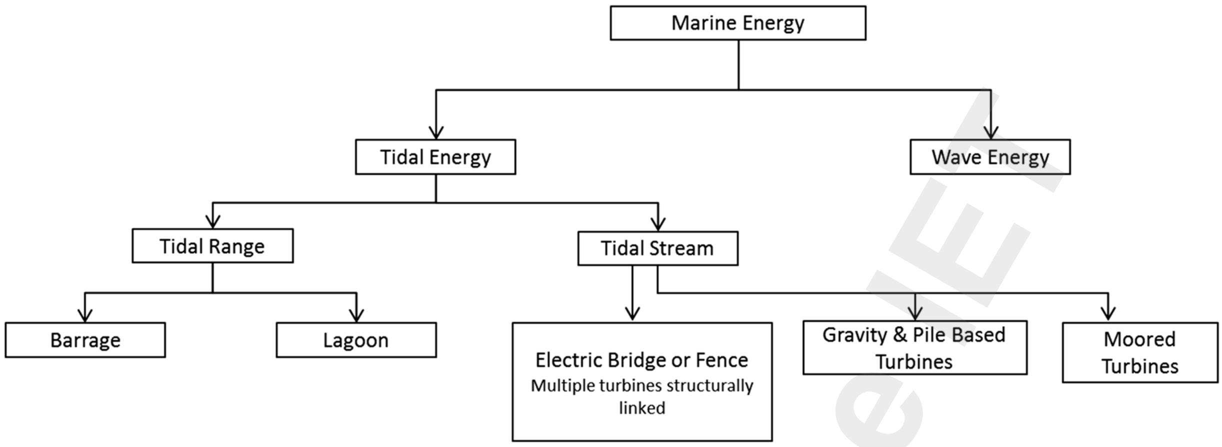

Fig. 1 *Basic categorisation of tidal lagoons within marine energy*

than ever to consider lagoons as a key player in the energy market.

Given the recent developments in the industry it is vital that the interactions of a lagoon with the environment are further understood and solutions to address impacts are sought. Further understanding will allow impacts to be effectively managed, reducing the chance of environmental constraints hindering the industry's growth in the future.

Environmental interactions of tidal lagoons are discussed below, given the absence of any operational tidal lagoons all case studies presented in the paper are based around tidal barrage developments or other relevant projects.

Lagoon environmental interactions

Assessing the environmental impacts of a tidal lagoon is a complex activity. Ecosystems are a detailed web of interactions between the physical, or abiotic, environment and the living, or biotic, environment. Further complexity is added through the site- and design-specific nature of any interactions, the potential cumulative impacts and the fact that these interactions are in a constant state of flux. As a result of this, any environmental impacts of a lagoon will be site specific, will have knock-on implications through the ecosystem, society and local economy, and are likely to alter over the course of a lagoon's 100-year life span.

Rather than attempting to list all of the potential environmental impacts of tidal lagoons, this paper proposes a conceptual framework (Fig. 2) and provides examples of impacts to illustrate this framework. Fig. 2 shows the grouping of environmental impacts in the framework and how these are linked to the lagoon development, society and the economy. The arrows in Fig. 2 describe the links, often two-way, between each of the groups, for example, the abiotic environmental impacts will have a two-way interaction with the biotic impacts. These interactions are discussed further below.

Abiotic interactions

Research to date has focused on abiotic impacts including the alteration of hydrodynamics and tidal range resource [5–10], morphodynamics [11–15] and water quality [16, 17]. Abiotic impacts are strongly linked to each other, for example changing hydrodynamics is a driver for changing sediment regime. Abiotic impacts also significantly influence biotic impacts such as how water quality might influence the marine biodiversity. In addition to this, abiotic impacts have the potential to impact the lagoon itself, such as sediment build up influencing energy extraction performance or maintenance strategies.

Case study – La Rance siltation: The La Rance barrage, built in 1966 has a capacity of 240 MW and stretches 750 m across the Rance River in Brittany, France [18]. Since its construction and operation, changes to the sediment regime have been observed, with around 30,000 m^3 of silt added to the marine basin each year [19]. This is thought to have been caused by the increase in slack water times and therefore a reduced current [19]. The La Rance operation now includes maintenance dredging, particularly in the

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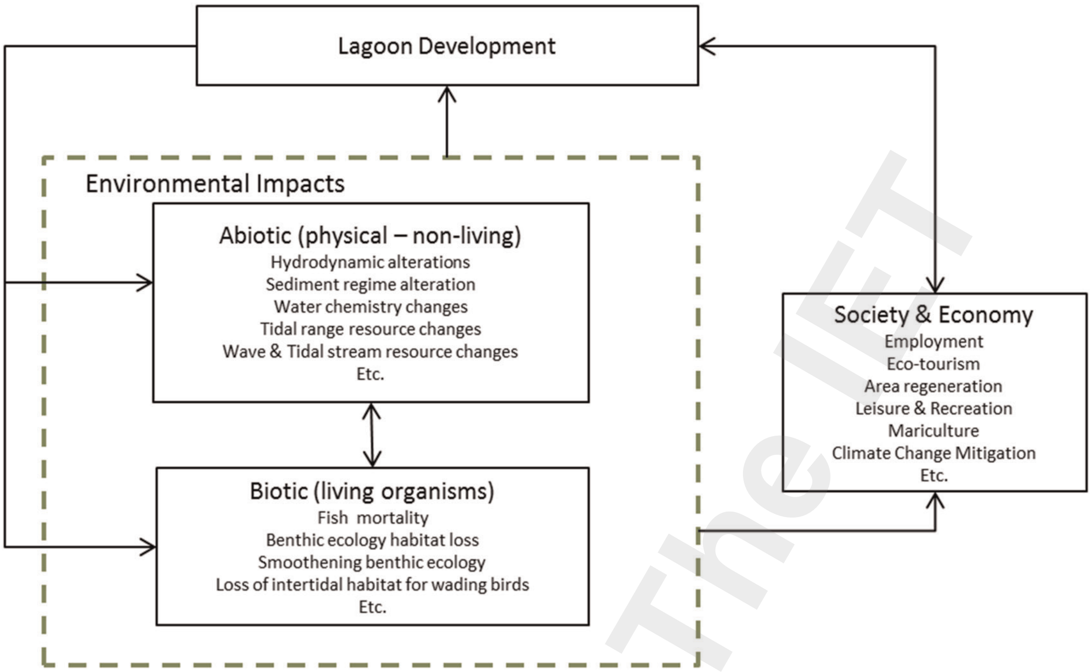

Fig. 2 *Grouping of environmental impacts and interactions with tidal lagoon developments, society and economy*

navigational channels towards the estuary head [20]. This abiotic change is therefore increasing the barrage's operation and maintenance activities, increasing the amount of dredging required and thereby increasing operational costs.

Biotic interactions

Biotic impacts of tidal lagoons, sometimes referred to as ecological impacts, are less well understood. A few papers have considered the ecological interactions and linked these with society [21, 22], but Hooper and Austen's [22] paper was the only one found to comprehensively review the impacts of tidal range schemes along with discussing societal and economic factors related to them. Whilst it focused on tidal barrages, some of the impacts will be transferable to tidal lagoons.

As with any food chain interaction, biotic impacts will influence a web of other biotic parameters across all the trophic levels of an ecosystem, such as how overfishing of sand eels has led to a decline in their predator populations of seabirds the Arctic Tern and Puffin [23]. Perhaps a less obvious interaction is that of biotic impacts influencing abiotic parameters. An example here might be biofouling altering the hydrodynamics around a structure, or biotic waste from fish farming altering the local water quality [24]. These interactions are likely to result in a chain of effects, where a change in the abiotic environment will lead to a biotic change, which in turn results in a secondary abiotic change and so on. It is therefore important to consider the wider knock-on effects of any environmental impact that a development may have.

Case study – Sihwa Barrage impact chains: Sihwa Barrage in South Korea was built as a dam in 1984 [25]. The dam blocked the natural flow of the river and altered its sediment regime. This abiotic change led to a deterioration in water quality, including excessive phytoplankton growth (eutrophication) [26], a biotic impact which potentially had knock-on implications for the abiotic environment in deeper water, for example decreased sunlight penetration and temperature changes. In 2012, the dam was opened as a retrofitted tidal barrage allowing the reintroduction of sea water through turbines, reinstating the flow of water, improving the ecological water quality and generating renewable energy [27].

Environmental benefits

With all changes to the environment there will be winners and losers. Often overlooked in the industry are the potential environmental benefits and, as such, beneficiaries (people, society and the environment). As with all other interactions, these may be a consequence of positive abiotic or biotic impacts.

There will be a number of benefits of lagoon developments; the most obvious of these is the new habitats presented for species colonisation. This assumes a net gain in habitat area and condition over and above any initial habitat loss.

A well-known example of an abiotic positive impact is that of reduced local coastal erosion. Marine sediment transportation is sensitive to changes in the coastline form; introduction of a lagoon may reduce coastal erosion. It should not go unmentioned that it could also exacerbate coastal erosion if the local processes are not fully understood and incorporated into early lagoon planning and design.

Flood protection could also be a potential abiotic benefit provided by tidal lagoons, again, this is a complex issue as it assumes positive manipulation of a sensitive environmental process. A lagoon that is not implemented well could increase flood risk to a local area through siltation of inflows and a raised water table. It is therefore essential to fully understand the local processes prior to assessing the true benefits that could be provided by a lagoon.

Case study – Thames Barrier flood protection: The Thames Barrier crosses 520 m of the River Thames and has the sole purpose of providing flood protection to central London [28], similar to the protection which could be provided by a tidal lagoon. It has 10 steel gates that can be raised across the river preventing tidal surges from the sea, or lowered to relieve the pressure of river flooding within the catchment [28]. Lowering the gates also allows for tidal current flow through the barrier and access for marine traffic. Careful management of the Thames Barrier therefore allows for flood protection and control of the catchment services which could be provided by the tidal lagoon industry.

Key impacts – the regulator perspective

Identifying the 'most significant' impacts is subjective and, as already mentioned, complex. Interestingly the regulators' perspective on what they believe to be the key outcomes, impacts and benefits may differ from the tidal industry and societal perspective. Marrying these different perspectives is part of the challenge of realising the successful deployment of tidal lagoon projects in the UK, especially given that one of the key barriers to tidal barrage developments has historically been regulatory environmental concerns [29]. In this section, we present a snapshot of the environmental issues that are at the forefront of regulators' minds.

A short online questionnaire was sent to regulatory, policy and conservation organisations. This was targeted at participants in decision-making roles within relevant organisations. The main aims were to determine what regulators perceived to be the most desired outcomes of future tidal lagoon developments, the key impacts (positive and negative) and how they believed developers should focus on improving the environmental status of future tidal lagoons. Four key questions were asked as follows:

(i) What *outcomes* do you believe to be the most important for future tidal lagoon developments?'
(ii) What do you consider to be the most *significant environmental* impact of tidal lagoon developments?
(iii) Other than low carbon energy and direct economic benefits, what are the *priority opportunities* a lagoon could provide?
(iv) Where should developers be *focusing* their efforts to enhance the environmental status of tidal lagoons?

The questionnaire received a 51% response rate with a total of 21 different organisations contributing (Fig. 3).

Participants believed the most desired outcomes for future tidal lagoon developments to be a 'cost competitiveness' and a 'good environmental status' (Fig. 4). Good environmental status here was defined as reducing negative impacts and enhancing positive impacts where possible. This is not linked to the marine strategy framework directive which defines 'good environmental status' differently [30].

Participants deemed the three most significant environmental impacts to be 'sediment regime alterations', 'changing hydrodynamics' and 'restricted passage and migration', as shown in Fig. 5. It is important to remember here that these impacts will interact with each other, the wider biotic and abiotic environment, society, economy and even the lagoon itself.

Benefits can be provided 'naturally' from the lagoon or by providing solutions to address impacts that go over and above regulatory drivers. The questionnaire asked participants about the potential benefits that could arise from both of these sources. Flood defence and control along with leisure and recreation featured highly in the 'natural' benefits mentioned by

Eng. Technol. Ref., pp. 1–10
doi: 10.1049/etr.2016.0125

Organisations participating in the questionnaire:
BMT Group
Centre for Environment, fishing and aquaculture science (Cefas)
Energy Technologies Institute (ETI)
Environment Agency
Jersey Government (States of Jersey)
John Muir Trust (JMT)
Lloyds Register
Marine Management Organisation
Marine Scotland
Natural England
Natural Resource Wales
New Economics Foundation
Ofgem
ORE Catapult
Scottish Government
Scottish Natural Heritage
Sustainable Energy Authority of Ireland (SEAI)
The Carbon Trust
The Crown Estate
The Wildlife Trusts
Welsh Government

Fig. 3 *Organisations participating in the questionnaire*

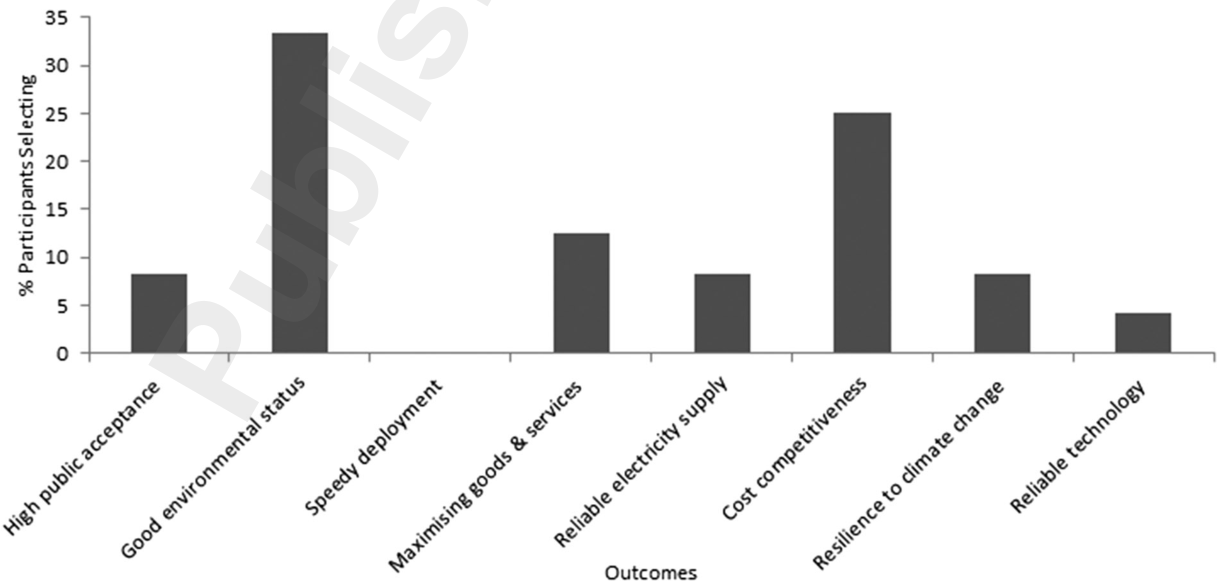

Fig. 4 *Response to question: 'What outcomes do you believe to be the most important for future tidal lagoon developments?'*

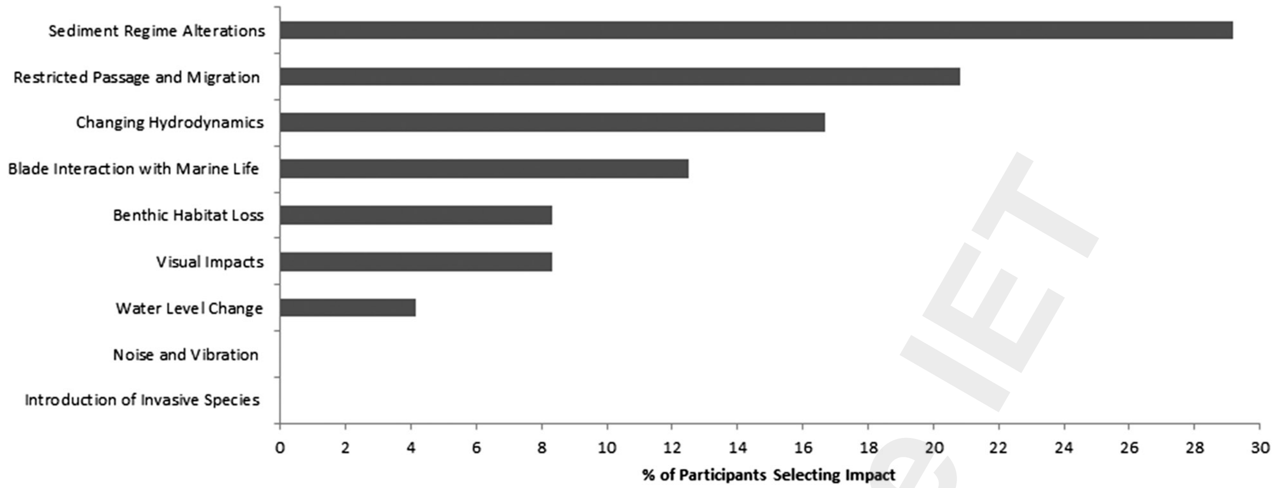

Fig. 5 *Response to question: 'What do you consider to be the most significant environmental impact of tidal lagoon developments?'*

participants. Of the additional benefits mentioned by participants, habitat protection, creation and enhancement of biodiversity were mentioned most frequently.

These questions provided an idea of the outcomes, impacts and benefits in the minds of the participants at the time of taking the questionnaire. The next step was to determine where regulators believed developers should focus their efforts in terms of improving the environmental status of future lagoons. A variety of responses to this question were given. However, there was a key theme throughout the majority of responses and that was that there should be a focus on site selection to avoid impacts in the first instance.

Range of solution options

Whilst avoiding impacts should be a priority there are a range of other solution options to be aware of. Typically, negative impacts are addressed and positive enhancements sought working down the mitigation hierarchy. The mitigation hierarchy is a strategy for addressing impacts; it works to first avoid impacts, then reduce and then finally compensate or offset. There is also potential to harness benefits in this way, by delivering enhancements at each stage of the hierarchy to offset the negative impacts. Within the hierarchy, strategies for impact solutions such as site selection, engineering design and technology, biodiversity offsetting by restoration, creation of habitat and catchment-based measures such as payment for ecosystem services (PES) schemes can be categorised (Fig. 6).

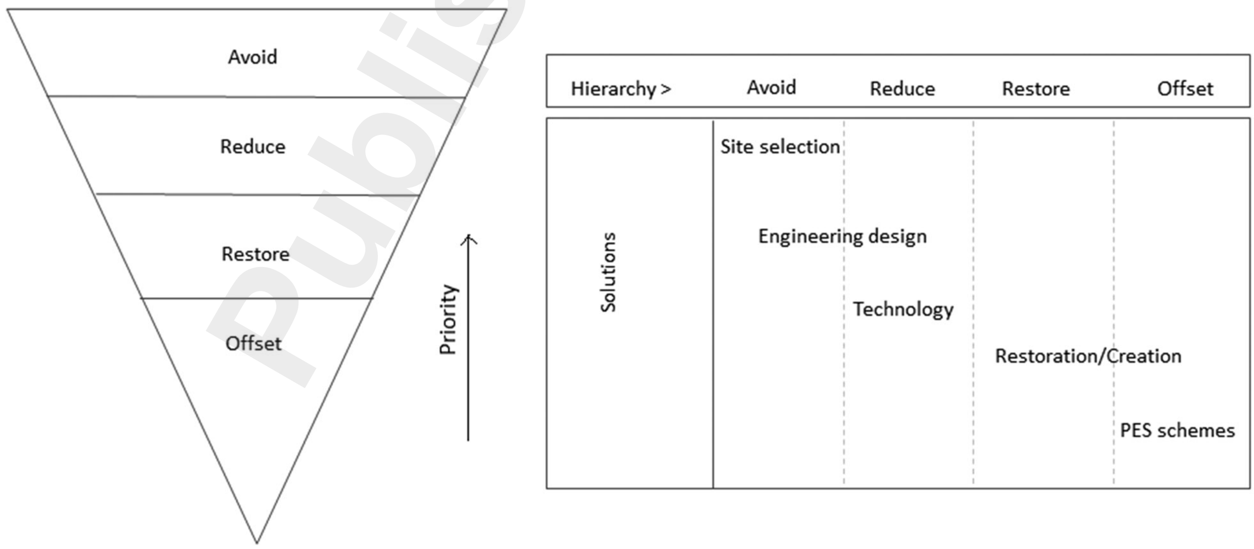

Fig. 6 *Mitigation hierarchy and potential strategies at each level*

Eng. Technol. Ref., pp. 1–10
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Fig. 7 *Built-in rock pools in Sydney Harbour walls. Source: [35]*

Case study – Venturi-enhanced turbine technology (VETT) turbines and impact avoidance: A key concern with tidal energy schemes is the impact of fish mortality. The first stage of the mitigation hierarchy is to avoid impacts, with one strategy being through careful technology choice. The VETT being developed by VerdErg is based on the Bernoulli principle and exposes no moving parts to the water channel [31]. VerdErg have achieved excellent results in recent tests, showing no impact on fish mortality with passage through the VETT's primary flow path [32]. This is therefore an example of a potential technology choice which could reduce the impact of a tidal energy development on fish mortality.

Case study: river Fowey PES scheme: An example of a catchment-led approach to addressing environmental problems is that of the River Fowey PES auction. The River Fowey had issues with water pollution as a result of cumulative agricultural run-offs [33]. The West Country Rivers Trust, as part of the 'Upstream Thinking' initiative, distributed funding to farmers via a competitive bidding auction to deliver land-based measures which in turn improved the river's water quality [33]. Similarly, PES has the potential to help reduce nutrient levels in coastal waters e.g. nitrogen levels in Poole Harbour as per the Defra PES pilot project [34]. This type of approach could be applied to not only offset any negative environmental impacts which may arise due to tidal lagoon development, but to help to deliver an overall net gain in the environmental impact of a lagoon development.

Achieving a good environmental status is not only about addressing negative impacts but also about enhancing positive impacts wherever possible. This allows a project to work towards an environmental net gain. Environmental enhancements can be developed within the lagoon design itself or through later compensatory or offsetting stages of the hierarchy.

Case studies – built-in enhancements, Sydney Harbour: Adding new infrastructure in the sea will be a driver for change in the marine environment [35]. Building in enhancements early on in the engineering design can increase the positive environmental impacts of a development, contributing towards achieving environmental net gain. An example here is the intertidal habitats created in seawalls in Sydney Harbour. The designs do not compromise the engineering requirements or cost but do increase the diversity of species able to live on the sea walls [35]. Fig. 7 shows a photograph of their construction.

Remaining industry challenges

Whilst environmental impacts are a prominent challenge for consideration, it is important not to lose sight of balancing these with a lagoon's primary goals. As a business model a lagoon is dependent on its ability to generate and sell energy. Therefore, any strategies to address impacts need to ensure that a lagoon's energy efficiency and power generation are not compromised.

A key challenge for lagoons, and one that is currently under review, is cost [4]. There needs to be a balance between enhancing the environmental status of a development and keeping a project cost efficient. Any mitigation or enhancement strategies need to be environmentally worthwhile in order to balance the cost implications they present.

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Another point for consideration is the overarching benefit of a lagoon as a means of displacing fossil fuel power stations. Analysing the local environmental impacts is vital in order not to undo the environmental, economic and societal benefits created by increasing renewable energy capacity as a means of combating climate change.

Every tidal lagoon will have environmental impacts, both positive and negative. If the positive impacts outweigh the negative impacts then an environmental 'net gain' can be achieved. This allows a development to have an overall positive impact on the environment.

The ecosystem services assessment framework [36, 37] offers a way to assess, quantify and value environmental changes and determine what they mean for societal and economic wellbeing. When incorporated into the established environmental impact assessment (EIA) process, the framework provides a means to identify potential environmental mitigation and enhancement options. The eftec study in 2010 made some progress in this area, by valuing habitat loss in the context of tidal range developments [38]. Despite this progresses, multiple challenges still remain in developing a fully integrated cost–benefit analysis, to include economic, societal and environmental interactions.

There would be benefit in allowing environmental information to be incorporated into economic appraisals to represent environmental costs and benefits within developments from an early stage; arguably it is market failure not to do so. This would allow developers to find cost-effective means (financially and environmentally) to achieve an environmental net gain in a way that goes over and above the regulatory drivers.

As it stands, lagoons are suggested as environmentally advantageous alternatives to tidal barrage developments [22]. Individual lagoons are typically much smaller scale than individual barrage options and so their environmental impacts are limited by comparison. However, multiple lagoons would be required to provide energy generation at a strategic level, as such the cumulative environmental impacts of multiple lagoons will be a remaining challenge for consideration. The UK Strategic Environmental Assessment, including cumulative impact assessments of all project EIAs will go some way into managing this concern. However, knowledge surrounding the issue is still limited; hence the government's review into tidal lagoons is currently seeking evidence to address it [4].

Dealing with uncertainty

One of the key challenges is identifying the impacts and dealing with the uncertainty associated with them. Here we can consider impacts as 'knowns', 'known unknowns' and 'unknown unknowns'.

- *The knowns* are impacts we are aware of and can therefore work towards developing solutions for. Whilst these are understood, there are no operational lagoons and so there is still a level of uncertainty surrounding the extent of these impacts.
- *The known unknowns* are impacts we know that we have little knowledge about. These can be managed through targeted research and survey work to reduce their uncertainty. In this way, they can move to the 'knowns' category and solutions can then be developed to address them.
- *The unknown unknowns* will only come to light when there is an operational tidal lagoon. At present these are not likely to present a regulatory barrier given that the regulators will not know what they are in order to regulate them. This does not mean that they are not an industry concern. Early stage monitoring of lagoon developments will be required here to move these impacts into the 'known unknowns' category and eventually the 'knowns' category.

Dealing with uncertainty surrounding impacts is a challenge, with ongoing industry attempts to address the key research gaps. An example of this is the Offshore Renewables Joint Industry Programme's Forward look for the wave and tidal sectors [39]. Developing solutions to 'knowns', investigating further the 'known unknowns' and careful monitoring of the 'unknown unknowns' will allow the industry to manage environmental uncertainty and push the growth of the sector forward.

Conclusions

Tidal lagoons are an attractive marine renewable energy option for the UK. Recent developments in the sector mean it is now more important than ever to further understand and manage impacts in order to reduce the potential constraints they may pose on the industry. A lagoon's interaction with the environment is complex. Abiotic and biotic environmental impacts (positive and negative) will interact with each other, the wider ecosystem, the lagoon itself, society and the economy. Environmental impacts can also accumulate, have knock-on impacts and can change significantly in extent and type over time. There is usefulness in using a conceptual framework

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to understand and manage environmental impacts and their interactions.

Regulator consultation revealed that environmental status and cost competitiveness are at the forefront of regulators minds for tidal lagoon's future outcomes. The key negative impacts were believed to be 'hydrodynamic changes', 'sediment regime alterations' and 'restricted passage and migration'. Potential environmental benefits noted by the consultation include 'flood defence and control', 'leisure and recreation' and 'habitat protection or enhancement of biodiversity'. The consultation provided a snapshot of the impacts and benefits currently taking priority in the regulatory industry.

Whilst avoiding impacts should be the first point of call, there are a number of different solution and enhancement options working down the mitigation hierarchy. A number of these solution options have already been successfully demonstrated in other industries and could be translated to the future lagoon industry. The remaining industry challenges are around creating project environmental net gain, balancing environmental concerns with project cost and energy efficiency and dealing with impact uncertainties.

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REFERENCES

[1] Sustainable Development Commission: 'Turning the tide – tidal power in the U.K', 2007. Available at http://www.sd-commission.org.uk/publications.php?id=607

[2] Tidal Lagoon Power Ltd: 'Swansea bay lagoon projectL project benefits', 2015. Available at http://www.tidallagoonswanseabay.com/the-project/project-benefits/54/, accessed 29 September 2015

[3] Tidal Lagoon Power Ltd: 'Swansea bay lagoon project – planning', 2015. Available at http://www.tidallagoonswanseabay.com/planning/planning-process/61/, accessed 20 July 2016

[4] (DECC) Department of Energy & Climate Change: 'Review of tidal lagoons'. Available at https://www.gov.uk/government/news/review-of-tidal-lagoons, accessed 20 July 2016

[5] Xia, J., Falconer, R.A., Lin, B.: 'Hydrodynamic impact of a tidal barrage in the Severn Estuary, UK', *Renew. Energy*, 2010, **35**, (7), pp. 1455–1468

[6] Xia, J., Falconer, R.A., Lin, B.: 'Impact of different tidal renewable energy projects on the hydrodynamic processes in the Severn Estuary, UK', *Ocean Model.*, 2010, **32**, (1–2), pp. 86–104

[7] Ahmadian, R., Falconer, R.A., Bockelmann-Evans, B.: 'Comparison of hydro-environmental impacts for ebb-only and two-way generation for a Severn Barrage', *Comput. Geosci.*, 2014, **71**, (C), pp. 11–19

[8] Angeloudis, A., Ahmadian, R., Falconer, R.A., *et al.*: 'Numerical model simulations for optimisation of tidal lagoon schemes', *Appl. Energy*, 2016, **165**, pp. 522–536

[9] Fairley, I., Ahmadian, R., Falconer, R.A., *et al.*: 'The effects of a Severn Barrage on wave conditions in the Bristol Channel', *Renew. Energy*, 2014, **68**, pp. 428–442

[10] Adcock, T.A., Draper, S., Nishino, T.: 'Tidal power generation – a review of hydrodynamic modelling', *Proc. Inst. Mech. Eng. A, J. Power Energy*, 2015, **229**, (7), pp. 775–771

[11] Neill, S.P., Jordan, J.R., Couch, S.J.: 'Impact of tidal energy converter (TEC) arrays on the dynamics of headland sand banks', *Renew. Energy*, 2012, **37**, (1), pp. 387–397

[12] Neill, S.P., Litt, E.J., Couch, S.J., *et al.*: 'The impact of tidal stream turbines on large-scale sediment dynamics', *Renew. Energy*, 2009, **34**, (12), pp. 2803–2812

[13] Robins, P.E., Neill, S.P., Lewis, M.J.: 'Impact of tidal-stream arrays in relation to the natural variability of sedimentary processes', *Renew. Energy*, 2014, **72**, pp. 311–321

[14] Lewis, M.J., Neill, S.P., Elliott, A.J.: 'Interannual variability of two offshore sand banks in a region of extreme tidal range', *J. Coast. Res.*, 2014, **31**, (June), pp. 1–12

[15] Pethick, J.S., Morris, R.K.A., Evans, D.H.: 'Nature conservation implications of a Severn tidal barrage – a preliminary assessment of geomorphological change', *J. Nat. Conserv.*, 2009, **17**, (4), pp. 183–198

[16] Kadiri, M., Ahmadian, R., Bockelmann-Evans, B., *et al.*: 'A review of the potential water quality impacts of tidal renewable energy systems', *Renew. Sustain. Energy Rev.*, 2012, **16**, (1), pp. 329–341

[17] Kadiri, M., Ahmadian, R., Bockelmann-Evans, B., *et al.*: 'An assessment of the impacts of a tidal renewable energy scheme on the eutrophication potential of the Severn Estuary, UK', *Comput. Geosci.*, 2014, **71**, pp. 3–140

[18] de Laleu, V.: 'La Rance Tidal Power Plant. 40 year operation feedback – lessons learnt'. BHA Annual Conf., 2009

[19] White, J.: 'Parliment publication energy and climate change committee. Written evidence submitted by Jonathon White (SEV 54)', 2013

[20] Shaw, T.: 'La Rance tidal power barrage, ecological observations relevant to a severn barrage project'

[21] Wolf, J., Walkington, I., Holt, J., *et al.*: 'Environmental impacts of tidal power schemes', *Marit. Eng.*, 2009, **162**, (4), pp. 165–177

[22] Hooper, T., Austen, M.: 'Tidal barrages in the UK: ecological and social impacts, potential mitigation, and tools to support barrage planning', *Renew. Sustain. Energy Rev.*, 2013, **23**, pp. 289–298

[23] Marine Life: 'Threats facing the marine environment: overfishing', 2016. Available at http://www.marine-life.org.uk/conservation/threats-facing-the-marine-environment/overfishing, accessed 11 October 2016

[24] Wu, R.S., Lam, K., Mackay, D., *et al*.: 'Impact of marine fish farming on water quality and bottom sediment: a case study in the sub-tropical environment', *Mar. Environ. Res.*, 1994, **38**, (2), pp. 115–145
[25] Schneeberger, M.: 'Sihwa tidal – turbines and generators for the world's largest tidal power plant'. Andritz Hydro. British Hydropower Association 2008, 2009
[26] Park, N.: 'Sihwa tidal power plant: a success of environment and energy policy in Korea'. Korea University
[27] IRENA: 'Tidal energy technology brief', 2014
[28] Environment Agency: 'UK government. Environmental management guidance – the Thames Barrier'. UK government, 2016. Available at https://www.gov.uk/guidance/the-thames-barrier, accessed 11 August 2016
[29] Baker, T.: 'Tidal range developments: how could several tidal lagoons interact and affect one another?'. Chief Engineer – Marine Energy Black & Veatch, 2016
[30] European Commission: 'Marine strategy framework directive (MSFD) good environmental status', 2016. Available at http://ec.europa.eu/environment/marine/good-environmental-status/index_en.htm, accessed 15 August 2016
[31] VerdErg: 'VETT basic prinicples', 2016. Available at http://www.verdergrenewableenergy.com/basic-VETT-principles/basic-principles, accessed 11 August 2016
[32] VerdErg, Q.A., Brujin, H., Vis, Kemper, J.: 'Test on fish survivability of the 'Venturi Enhanced Turbine Technology'', 2013
[33] West Country Rivers Trust: 'Payment for ecosystem services pilot project: the Fowey river improvement auction', 2013
[34] RSPB: 'The feasibility of a nitrogen PES scheme in the Poole harbour catchment', 2013
[35] Bulleri, F., Chapman, M.: 'The introduction of coastal infrastructure as a driver of change in marine environments', *J. Appl. Ecol.*, 2009, **47**, (1), pp. 26–35
[36] 'Millennium Ecosystem Assessment: Ecosystems and human well-being', 2005. Available at http://millenniumassessment.org/en/Index-2.html, accessed 23 March 2015
[37] DEFRA: 'An introductory guide to valuing ecosystem services', 2007
[38] eftec: 'Economic valuation of the effect of the shortlisted tidal options on the ecosystem services of the severn estuary', 2010
[39] ORJIP ocean energy: 'The forward look; an ocean energy environmental research strategy for the UK', 2016
[40] 'Industrial doctoral centre for offshore renewable energy (IDCORE)', 2016. Available at http://www.idcore.ac.uk/, accessed 11 October 2016
[41] Elliott, K.: 'All energy conference proceedings', 2016. Available at http://www.all-energy.co.uk/RXUK/RXUK_All-Energy/2016/Presentations2016/Wave and Tidal Seminar Theatre/KathrynElliott.pdf?v=635995931892352844, accessed 11 October 2016

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Appendix 2: Journal Publication: Renewable Energy

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Environmental interactions of tidal lagoons: A comparison of industry perspectives

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ABSTRACT

Tidal lagoons are an attractive renewable energy option that could aid the UK in meeting its ambitious renewable energy targets. One of the main barriers to tidal range development in the UK to date has been regulatory environmental concern. In order for the nascent lagoon industry to move forward into development, the views of the developers and other influential stakeholders such as government bodies, regulators, conservationists and practitioners (herein referred to as 'influencing stakeholders' or 'influencers') need to be aligned. This study is the first of its kind using online questionnaires and semi-structured interviews to present and compare the views of both developers and influencing stakeholders on the environmental interactions of tidal lagoons. We find that, whilst both influencers and developers are working towards the common goal of a good environmental outcome for tidal lagoons, there are mismatches in their views in terms of the priorities given to the key environmental impacts, benefits and potential solution options. The work provides insight into what is at the forefront of developers' and influencers' minds, highlighting the key themes within their views and transforming this information into policy recommendations that will help the industry's development move forward.

1. Introduction

The deployment of renewable energy is regarded as a strategy to combat climate change through the displacement of fossil fuel energy sources and therefore the reduction of carbon emissions. There have been a number of global agreements aiming to mitigate the impact of climate change, the most recent being the 2015 Paris Agreement. To date, 114 of 174 parties have signed this historic agreement and begun to adopt climate change strategies into their own national agendas [1]. Nationally, the UK has a target to provide 15% of its energy needs from renewable sources by 2020 [2]. There needs to be an increase in the rate of deployment of renewable energy in the UK if it is to achieve this target within the next 3 years. Under 'business as usual' conditions it will fail to achieve this target [3].

There are a variety of renewable energy options that the UK could deploy to meet these ambitious targets. Often overlooked is the vast amount of marine energy available around the UK coastlines, the majority of which is currently untapped. This article focuses on tidal lagoon energy as part of the marine energy sector; Fig. 1 shows a breakdown classification of marine energy and how tidal lagoons are placed within this.

Tidal range technologies harness the energy available in the rise and fall of the tides. Traditionally tidal range energy consists of tidal barrages and tidal lagoons. A tidal barrage typically extends the banks of a river or estuary, whilst a tidal lagoon forms a loop attached to one side of an estuary or is completely offshore [5]. Fig. 2 shows a basic sketch describing this difference.

Tidal range schemes, including both barrages and lagoons have a theoretical resource potential of 121 TWh/year in the UK [6]. To put this into perspective, in 2015 the UK produced 339 TWh of electricity [7]. In theory, although not necessarily in practice, tidal range

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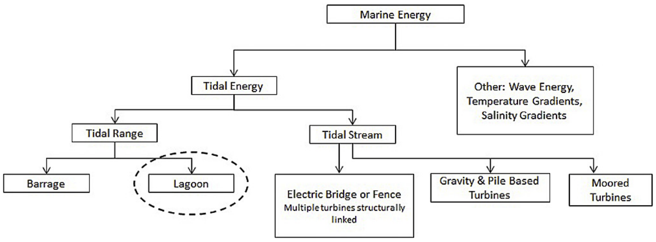

Fig. 1. Marine energy classification. Source [4].

schemes could contribute up to 36% of the UK's electricity production, with lagoons contributing 7.4pp, of that figure. Tidal Lagoon Power Ltd, one of a number of companies investigating options for tidal lagoon development, has a framework plan for the UK to develop a fleet of 6 tidal lagoons. It is estimated these could contribute 8% to the UK's total electricity supply [8].

Lagoons therefore have the potential to contribute significantly to the UK's electricity mix. They also have a number of other advantages in terms of their energy production, including a high level of predictability, the differing times of tides around the UK allowing a phase shift for continuous energy generation and a long expected life span (120 years) [9].

Despite these advantages, there is currently no energy generating tidal lagoon in the world. The main barriers to date have been a lack of serious proposals, high capital costs and environmental concerns. There is now a serious proposal, with Tidal Lagoon Power presenting the first of their tidal lagoon developments: Tidal Lagoon Swansea Bay. Swansea Bay was awarded a Development Consent Order (DCO) in June 2015 [10]. The costs of lagoons were investigated in a government commissioned review considering the overall feasibility of lagoons for the UK energy market. This review, published in December (2016), concluded that lagoons did have a cost effective role to play in the UK and recommended that a focus should be on a small pilot scheme initially with sufficient time to allow for environmental monitoring [11]. Whilst tidal lagoons have previously been presented as a more environmentally friendly alternative to barrages [12], the environmental impacts of lagoons are still a concern for the industry, as highlighted by the recent government review [11]. As such, environmental concerns are likely to present additional hurdles in the industry's future development. Consenting and licensing issues are often seen as cross cutting barriers to marine energy [13]; an example in the lagoon industry is the current delays being seen in awarding of a Marine License to the Swansea Bay Tidal lagoon.

Whilst progress has been made in identifying and estimating the potential environmental impacts of tidal range projects, such as the hydrodynamic changes [12–17], morphodynamics [18,19] and water quality [20–23], ecological interactions with society [12] and environmental interactions with each other [4], there has been little focus on the industry's view of these environmental impacts. These key environmental changes noted in the literature will have multiple associated environmental, societal and economic implications. Whilst these are too many to document here some examples include; coastal erosion or sediment deposition, increased flood risk, extensive habitat or biodiversity loss, displacement or injury to marine mammals, damage to fish populations, damage or displacement of bird populations, impacts for local marine industry and recreation, impact on underwater marine heritage and changes to local water quality including potential impacts on the water table. Mackinnon et al. (2016) [4] describes a framework to identify and further understand the complex interactions between the environmental impacts of tidal lagoons.

The tidal lagoon industry is in its infancy; there is therefore little tidal lagoon specific research to date and hence finding information through direct industry engagement is appropriate. An additional implication of the nascent lagoon industry is the lack of tidal lagoon specific environmental regulatory guidance. This could present a further issue unless clear communication between influential stakeholders such as government bodies, regulators, conservationists and practitioners (herein referred to as 'influencing stakeholders' or 'influencers') and developers is undertaken and respective views understood.

In order for the sector to move forward in a sustainable and timely way it is therefore essential that the influencer and developer perspectives on the environmental impacts of lagoons are aligned. This will reduce any potential delays in the development process and provide the best chance for future tidal lagoons to contribute positively to the environment through an effective balance of positive and negative impacts (net gain). This study is the first of its kind, analysing the differing views of influencing stakeholders and developers within the nascent lagoon industry, providing understanding of why these views arise and how awareness of them can aid with the industry's future development.

Whilst there are tidal barrage developments elsewhere in the world [24,25], the UK is making significant progress in the lagoon sector, building on its desirable resource potential and recent industry advancements. This study therefore focuses on the UK tidal lagoon industry, and as such, on associated UK developers and influencers. The paper presents an assessment and comparison of the current influencer and developer views on the environmental impacts of tidal lagoon developments in the UK. It has three initial objectives:

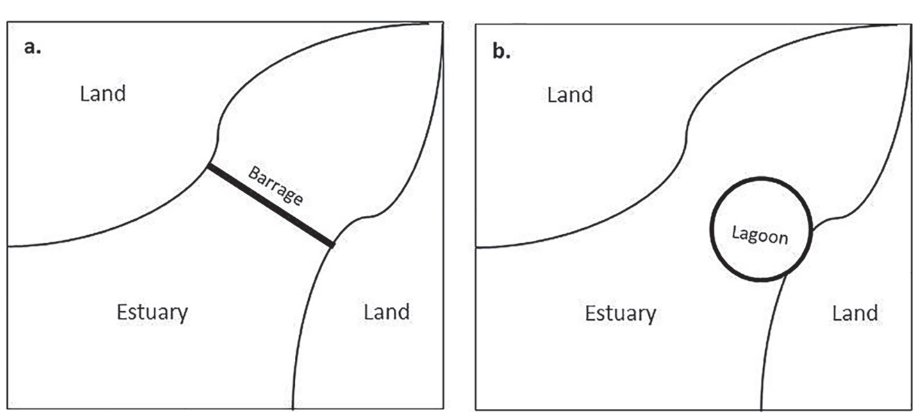

Fig. 2. Basic difference between a tidal barrage and a tidal lagoon, both of which provide tidal range energy.

1. Survey the views of professional individuals within government, regulatory, conservation, policy, think-tank and practitioner roles (referred to as the 'influencers') on the environmental impacts, benefits, challenges and key outcomes of tidal lagoon developments, through an online questionnaire.
2. Ascertain the views of key individuals within the development industry (referred to as the 'developers') on the environmental impacts, benefits, challenges and key outcomes of tidal lagoon developments, through semi-structured interviews.
3. Compare and contrast the views of the influencers and the developers.

Doing this, we find areas of consensus between influencers and developers and areas where different placements of priorities have been given. We find that whilst influencers and developers agree on a broad level that lagoons should work towards achieving a good environmental status, the details on achieving this outcome presented some contrasting views. The study highlights the main barriers and challenges still facing influencers and developers and outlines how information provided by their views can be used to determine policy and regulation that can stimulate further development of the sector.

The next section describes the methodology used to address these objectives, with the key results of the study highlighted in Section 3. These are discussed in detail in Section 4 with the paper concluding with a set of recommendations in Section 5.

2. Methods

2.1. Data collection

The data collection consisted of web-based questionnaires for influencers and semi-structured interviews for developers. Due to the infancy of the industry and therefore relatively small pool of potential participants, the focus of the engagement was on including all of the relevant participants within key industry organisations rather than obtaining a large sample size of non-relevant participants.

The questionnaires included a mix of closed and open questions and were conducted using an online survey tool 'Typeform' [26]. The questionnaires targeted individuals in decision making roles and focused on obtaining a range of different government (33%), conservation (19%), regulatory (29%) and practitioner (19%) organisations, referred to in this paper as the influencers. Participants were sent an email with the questionnaire link and a cover letter explaining the research objectives. An email reminder was also sent following initial contact. The questionnaire received a 51% participant response rate, with a total of 24 individuals from 21 different organisations participating (see Table 1). This response was deemed sufficient to allow for descriptive analysis and conclusions to be drawn.

In order to gain a deeper insight into the industry perspective, semi-structured interviews were conducted with developers. The semi-structured interviews consisted of a select few open questions to guide the participants towards particular topics (Table 2), but no other direction was given. Interviews were conducted face to face or via Skype. Participants were sought from tidal lagoon developers in addition to related industries, such as tidal barrages, tidal fence or bridges and hydroelectric projects. Each interview was recorded and later transcribed for analysis. A total of 8 developers from key organisations participated in the interviews (see Table 1).

The data collection consisted of two different methods for influencers and developers. Questionnaires were deemed suitable for influencers given the higher number of participants from a range of non-lagoon specific backgrounds. Interviews as opposed to questionnaires were appropriate for developers given the smaller number of participants and the specific and detailed sector knowledge that they have. The data was collected differently and as such has been analysed differently to reflect this. Whilst the different methods may pose differences in the results, the general perspectives of both the influencers and developers were obtained and these general perspectives are what is being compared.

The participants were asked to answer questions in their professional opinion and not on behalf of the organisations they are employed within. Due to the infancy of the lagoon sector many organisations do not yet have a standard stance or practice for lagoons. Therefore by selecting individuals in key decision making roles within relevant organisations the collected data provides the best representation of the industry's current perspectives on tidal lagoons. For privacy reasons, the identities of the questionnaire and interview participants are not disclosed.

2.2. Data analysis & presentation

Software QSR NVivo 10 was used to code the interview transcripts and open ended questionnaire responses [27]. Coding is a method of qualitative data analysis, where passages of text are assigned a code-label relating to a particular theme or topic, and passages with the same label are judged to be of the same topic. This method allows patterns to be identified within qualitative data [28]. Some code-labels were pre-determined based on previous questionnaire topics and literature review (A priori codes) [29]; others were developed based on the new findings arising within the data itself (grounded theory) [29].

Descriptive statistics such as percentage distributions were used to analyse the closed question data and subsequently the coded qualitative data from the interviews and open ended questions. It was not deemed appropriate to use more rigorous statistical analysis given the exploratory nature of the research and the lack of an empirical hypothesis to validate [30]. Reflecting the analysis, the results are presented as percentages; either as percentage mention, percentage selecting, or percentage participants to mention. Table 2 shows a summary of the questions asked, the type of question and

Table 1
List of participating organisations.

Influencer Participant Organisations	Developer Participant Organisations
BMT Group	Tidal Lagoon Power Ltd
Centre for Environment, Fishing and Aquaculture Science (Cefas)	North Wales Tidal Energy
Energy Technologies Institute (ETI)	North West Energy Squared
Environment Agency	Electric Mountain
Jersey Government (States of Jersey)	Solway Energy Gateway
John Muir Trust (JMT)	Wyre Tidal Energy
Lloyds Register	VerdErg
Marine Management Organisation	Cardiff University – Associated with Severn Barrage
Marine Scotland	
Natural England	
Natural Resource Wales	
New Economics Foundation	
Ofgem	
ORE Catapult	
Scottish Government	
Scottish Natural Heritage	
Sustainable Energy Authority of Ireland (SEAI)	
The Carbon Trust	
The Crown Estate	
The Wildlife Trusts	
Welsh Government	

Table 2
Summary of the methods, including data collection, analysis and presentation.

		Collection, Analysis and Presentation of Data							
		Question Asked		Question Type		Data Analysis		Data Presentation	
		Interview (developers)	Questionnaire (influencers)	Interview	Questionnaire	Interview	Questionnaire	Interview	Questionnaire
Engagement Topic	Outcome	If you had to say the project had one goal, mission or priority outcome, what would you say that was?	Of the outcomes below, please select one which you believe to be the most important for future tidal lagoon developments. [a]	Structured	Multiple choice[a]	Coded response to question	Number of options selected	% mention	% to select
	Impact	What do you consider to be the top three environmental impacts?	What do you consider to be the top three most significant direct environmental impacts of tidal lagoons?[b]	Structured	Multiple Choice[b]	Coded response to question	Number of options selected	% mention	% to select
	Benefits	Participants spoke freely about the benefits	Other than low carbon electricity and the direct economic benefits, what would you consider priority opportunities that a tidal lagoon could offer?	Non-structured	Open ended	Coded benefits section of transcripts	Coded question responses	% mention	% mention
	Solutions	Participants spoke freely about solution options	Please select ways in which environmental impacts could be addressed through technological or environmental solutions.	Non-structured	Open ended	Coded solutions section of transcripts	Coded question responses	% participants to mention	% Participants to mention
	Challenges & Developer Focus	Participants spoke freely about industry challenges. They were also asked: "suggest how the regulatory process could be improved"	In your professional opinion, where should developers be focusing to reduce the environmental impacts posed by tidal lagoon developments?	Non-structured	Open ended	Coded challenges and improvement sections	Coded question responses	% Participants to mention	% Participants to mention
	Participant Background or Role	Participants spoke freely about themselves	What broad category would you place your current role into?[c]	Non-structured	Multiple choice[c]	Coded introductions	Number of options selected	% local connection	% to select

[a] High public acceptance, good environmental status, speedy deployment, maximizing public goods and services, reliable supply of electricity, cost competitiveness of produced electricity, providing resilience to climate change, reliable technology.
[b] Sediment regime alteration, changing hydrodynamics, restricted passage and migration, blade interaction with marine life, noise and vibration, introduction of invasive species, benthic habitat loss, other.
[c] Engineering, environmental, technological, policy, financial, socio-economics, other.

how the results have been analysed and presented.

Within the questionnaire there were a number of multiple choice questions, the options of which were developed around information obtained from a general literature review. The code-labels for the solutions or the categories are very broad and encompass many different individual solution strategies and as such need further explanation. Table 3 provides definitions of the multiple choice options where the meanings are not immediately obvious, in addition to definitions and examples for the broad solution categories.

3. Results

The results provide an insight into what is currently at the forefront of the influencers' and developers' minds, regarding the environmental impacts of tidal lagoons. We will discuss participant backgrounds, lagoon outcomes, impacts and benefits and finally solution options and further industry development in that order.

3.1. Participant background

In order to understand the industry's perspective on environmental impacts of tidal lagoons, it is first important to consider the angle from which the participants are coming. Fig. 3 shows how influencers categorised their current role. Of the influencers who participated, 67% are from either an environmental or policy role, with the remainder residing in technological or socio-economic categories.

The review of developer backgrounds shows a pattern of strong local connections between developers and the local area of the proposed or planned project or development, with over half of the developers mentioning this local connection whilst introducing themselves in the interviews. It was often the case that the developer organisations were formed from locals, local business people or local forums, as opposed to large multi-national organisations which is often the case in other energy sectors. An example here is Wyre Tidal Energy which was formed by three local business-men passionate about the local area of Fleetwood and its regeneration [31].

3.2. Priority lagoon outcomes

Participants were asked about which outcomes they believed to be a priority for a future tidal lagoon development (Fig. 4). Influencers selected 'Good Environmental Status' and 'Cost Competitiveness' as the key outcomes. 'Good Environmental Status' here is defined as reducing the environmental impacts and enhancing environmental benefits where possible.[1]

For developers, 'Area Regeneration & Wealth' received the highest percentage mentions with 'Reliable Electricity Supply' and 'Good Environmental Status' in joint second. Neither influencers nor developers considered 'Speedy Deployment' as an important outcome at the time of engagement. There are other differences

[1] This is not related to the Marine Strategy Framework Directive (MSFD) which defines 'Good Environmental Status' differently [38].

Table 3
Definitions and examples of multiple choice options needing further explanation and solution categories requiring more background information.

Topic	Option Choice	Definition/Examples
Outcome	Good Environmental Status	Reducing environmental impacts and enhancing benefits as far as possible to achieve the best environmental status
Outcome	Maximizing Public Goods & Services	Providing services or goods through the development of the lagoon in which the general public would benefit from e.g. leisure and recreation, area regeneration, positive aesthetics
Impact	Restricted Passage and Migration	Restricting any migratory route or passage of any species of fish or marine mammal
Impact	Introduction of invasive species	The accidental introduction of a non-native species through development of a lagoon or the 'natural corridor' effect that the lagoon might have, connecting different habitats to each other and allowing the movement of species into habitats that they would not normally reside in
Solution	Engineering Design & Technology	Any solution mentioned that is related to changing the initial engineering design or the choice or design of the technology itself with the view to avoiding environmental impacts. E.g. Turbine blade number, shape of the lagoon wall, material used for the wall, built in additional habitats etc.
Solution	Operation & Maintenance	Any activity undertaken after the construction phase which attempts to reduce or restore environmental impacts e.g. Zonation activities based on breeding seasons, temporarily pausing generation to allow species migration, manipulation of the water levels within the basin for environmental benefits such as flood control rather than purely for energy generation.
Solution	Compensation & Catchment Measures	Any activity based on compensation or offsetting of impacts through the use of offsite areas. E.g. habitat creation or restoration, Payment for Ecosystem Services (PES) schemes, catchment management measures.

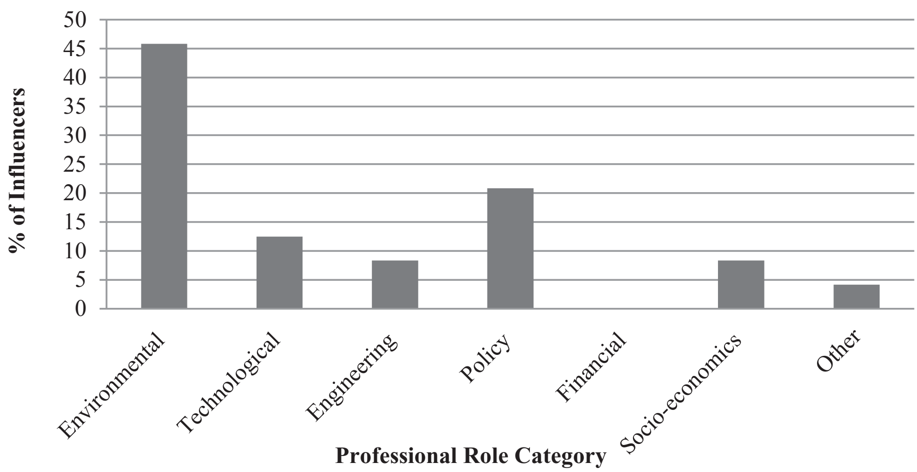

Fig. 3. Influencer's professional backgrounds displayed as percentage number of influencers.

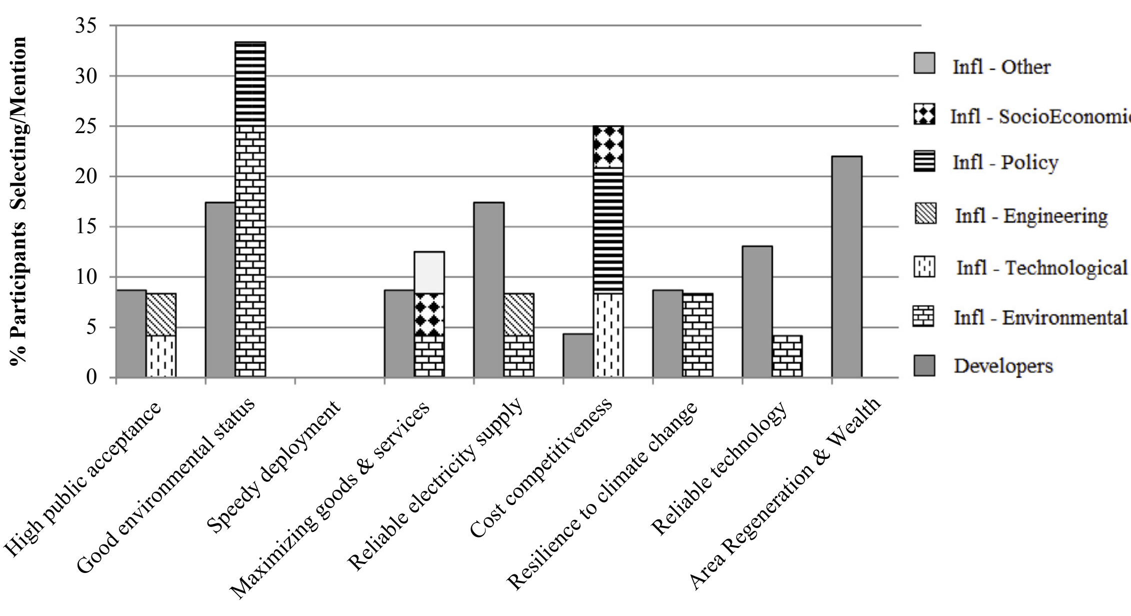

Fig. 4. Participants desired outcomes for future tidal lagoons. Developers and Influencers shown, with influencers shown as stacked bar representing the different professional background categories.

seen here, for example, with 'Cost Competiveness' and 'Reliable Technology' showing different levels of priority for influencers compared to developers.

Fig. 4 shows what influencers believe to be the key outcomes based on their respective professional backgrounds (stacked bars). We can see from this that the majority of participants selecting a good environmental status are from an environmental background and that participants with technology, policy or socio-economic backgrounds found cost competiveness a key priority outcome.

3.3. Environmental impacts & benefits

Whilst both influencers and developers agree that a 'Good Environmental Status' is a priority outcome for tidal lagoons, it is important to further understand which specific environmental impacts and benefits are underlining this outcome and how the regulator and developer views compare on these specifics.

Fig. 5 shows what participants believe to be the top three environmental impacts of tidal lagoon developments. The top two most significant impacts in the view of both the influencers and the developers are 'Sediment Regime Alterations' and 'Changing Hydrodynamics'.

Developers and influencers selected different options for their third most important impact. Developers believe that 'Water Quality' is the third most significant impact of lagoon developments, whilst influencers selected 'Restricted Passage & Migration' for that position. Although the two impacts are linked, 'Water Quality' was not mentioned at all by influencers (a box for 'Other' impacts was provided in the questionnaire), despite it being in the top three environmental impacts for developers. Whilst influencers placed more weight on 'Restricted Passage & Migration', developers still had this impact in mind, with it lying in fourth position in terms of its significance as an impact.

Participants were asked what they deemed to be the priority opportunities a tidal lagoon could offer aside from low carbon electricity and any direct economic benefits (Table 4). Influencers' most mentioned benefits include 'Flood Defence & Control', 'Habitats & Biodiversity' and 'Leisure & Recreation'. In contrast, developers most mentioned benefits were 'Area Regeneration & Socio-economics', 'Local Employment' and a 'Local Economy Boost'. These benefits were also areas of high percentage difference in mention between influencers and developers (green cells Table 4). This further suggests that influencers and developers have different priorities when considering the benefits of tidal lagoons. Benefits which had little to no difference in the percentage mention (red cells Table 4), suggesting an overall consensus in the priority given to them by influencers and developers include 'Base load potential', 'Multiple use opportunities', 'Tourism' and 'UK image'.

3.4. Impact solutions

Environmental impact solutions can be grouped into three broad categories; 'Engineering Design & Technology', 'Operation & Maintenance' and 'Compensation & Catchment Measures' (see Table 3 for further definitions). Both developers and influencers were asked about what the potential solutions could be to addressing environmental impacts, and the responses are summarised in Fig. 6.

Due to the infancy of the lagoon sector the solution options identified by participants (both developers and influencers) were often around transferable solutions from other industries. For example under engineering design there are multiple strategies, one example of which is using ecological criteria in the building design, such as the rock pools built into Sydney Harbour wall [32]. Numerous operation and maintenance strategies arose throughout the engagement with both influencers and developers; these were largely based around the pausing and restarting of generation depending on important ecological seasons, temporal or spatial zonation of activities and control of in-basin water levels for environmental gains. Measures based around habitats and biodiversity creation and restoration were mentioned by both influencers and developers for the compensation and catchment based measures solution option.

Overall developers had a broader view of the potential solution options than influencers, demonstrated by the larger triangle of representation in Fig. 6. All of the developers interviewed mentioned some form of solution under the 'Engineering & Technology' category, with 75% also mentioning a 'Compensation & Catchment Measures' solution. These two categories were also identified by influencers, 67% of them mentioning a solution in both 'Engineering design & Technology' and 'Compensation & Catchment Measures'. 'Operation & Maintenance' was mentioned the least by both influencers and developers, with 50% and 22% mentioning them respectively.

3.5. Further industry development

Influencers were asked to suggest areas in which developers should be focusing their efforts to reduce environmental impacts of tidal lagoons. A variety of suggestions arose; however, a clear theme

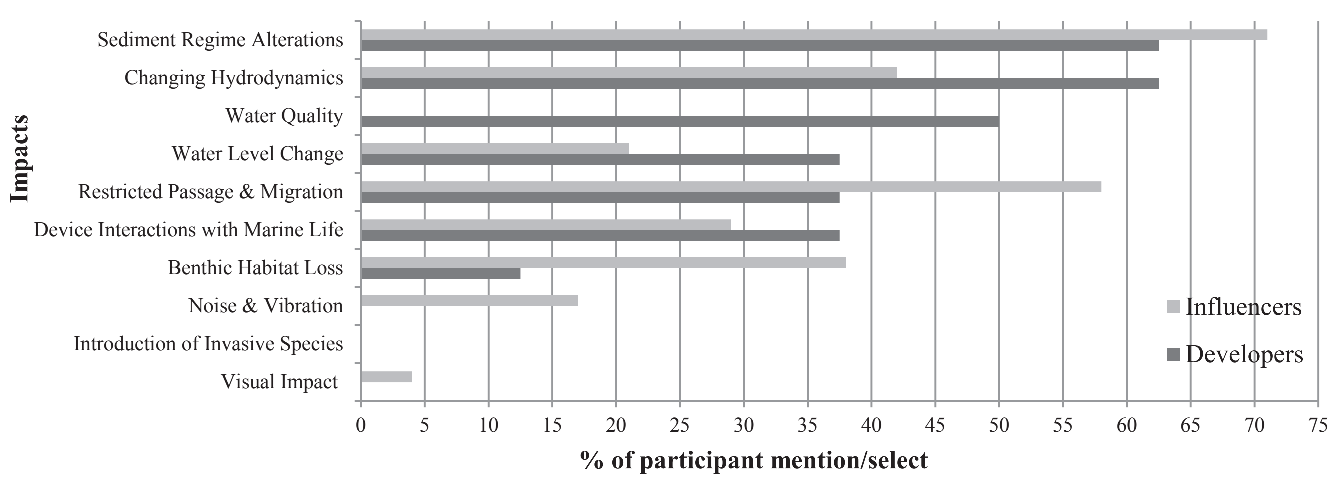

Fig. 5. Participants key environmental impacts of tidal lagoon developments.

Table 4
The benefits of tidal lagoons as % mention by developers and influencers. Colour is assigned to the highest % mention for each benefit between influencers and developers, i.e if the colour is on developer side then developers mentioned this benefit the most. The actual colour depends on the scale of this % difference, (Green = ≥5% difference in % mention, Amber = ≥2% ≤ 4%, Red = <2%).

Benefits	% mention Influencers	% mention Developers
Area Regeneration & Socio Economic Benefits	6	14
Coastal Erosion Protection	8	4
Community Share	2	4
Education & Research	5	7
Energy Base Load	3	4
Export Opportunities	3	4
Flood Defense & Control	16	9
Habitat Biodiversity	14	6
Leisure & Recreation	13	4
Local Economy Boost	3	9
Local Employment	3	11
Multiple Use	6	6
Renewable Energy Acceptance	6	0
Supply Chain	3	5
Tourism	6	7
Transport & Connectivity	0	5
UK Image	3	2

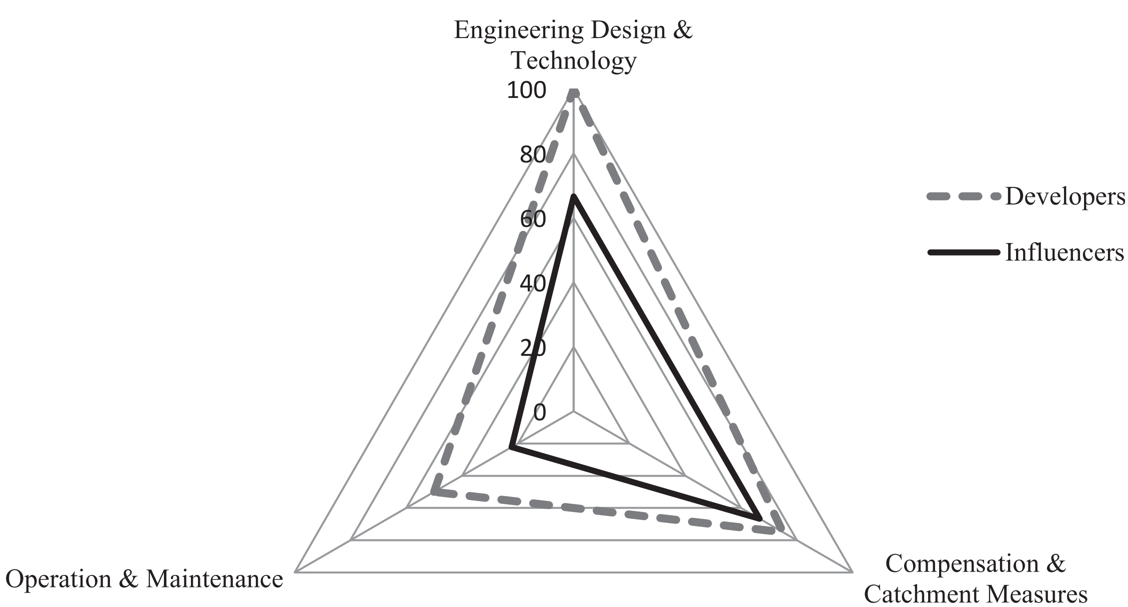

Fig. 6. Developer and influencer suggested solution options for environmental impacts grouped into three broad categories and presented as % participant mention.

relating to location developed with 29% of influencers suggesting a focus on site selection to avoid impacts in the first instance. Of equal focus (29%), influencers wanted to see developers focusing on the issues of intertidal habitat loss.

When developers were asked what they believe to be the key challenges in the industry 33% mentioned finding a suitable site. Whilst influencers wanted to see a focus on site selection, developers believe this to be one of their key challenges. Other key challenges for developers were found to be lack of information and experience in the lagoon sector, maintaining interest in lagoons as a form of energy generation and securing funding.

When developers were asked specifically where improvements could be made in the regulatory process, 50% stated that clearer more accessible lagoon-specific policy or guidance was required, with 63% suggesting a reduced process time for consents.

4. Discussion

The industry is collectively considering achieving a 'good environmental status' as the lagoon sector begins its development. Whilst both the influencers and developers are working towards this outcome, previous research has yet to explore whether their views on the details of the environmental impacts of lagoons are aligned. Aligning their views on these details such as the key impacts, benefits, solutions and key challenges would allow for a smoother transition from lagoon planning to development and towards achieving a good environmental status in future lagoons. This study provides the first step towards achieving this industry aim, by identifying the views of the influencers and developers, considering the areas of contrast and consensus and providing recommendations on how to move the industry forward in light of this information.

The priority outcomes selected by influencers and developers reflect their likely key objectives. For example the nature of an environmental influencer's role in the industry is to protect the environment, where as a developer is most concerned with generating a reliable and predictable supply of electricity and to obtain the associated revenue. Many developers also have strong local connections to the area of a development and as such their priorities with local area regeneration and wealth is also not surprising.

'Speedy Deployment' was not a priority for influencers or developers at the time of engagement. It is clear that other outcomes are a priority for tidal lagoons at this stage. This is surprising given the current urgency towards transitioning to a low carbon economy. There is also a risk that ocean energy will not be sufficiently mature before that capacity is taken up by other forms of renewable energy, hence the need for a speedy deployment should not be overlooked. The relative infancy of the lagoon sector and the fact that there has yet to be a single tidal lagoon development in the world could provide the reasoning behind the lack of priority on speedy deployments. The consensus suggests that it is better to go slow with the first development and ensure that other higher priority outcomes are achieved first and foremost to bolster investor certainty and set a sustainable precedent for future tidal lagoon development.

This is further reinforced by the solution options participants are considering. Developers are currently concerned largely with the engineering design and environmental solution options, whilst influencers are considering the future compensation considerations should lagoons be constructed. Neither party in the industry is yet in the position where they are prioritising operation and maintenance strategies. This does not mean to say that considering these strategies early on would not be advantageous in allowing the maximum environmental net-gain in future lagoons to be achieved. It is therefore a recommendation that further focus be placed on these strategies to reduce the shortfall currently seen in the industry.

The environment is at the forefront of both influencers' and developers' minds in terms of a priority outcome for lagoon developments. However there are also a number of other outcomes seen as priorities by the industry. It is vital that whilst the industry strives towards a positive interaction with the environment it does not lose sight of a lagoon's primary purpose; to generate low carbon electricity at a cost competitive rate. In addition, whilst there will be a number of local environmental impacts, there is an overarching environmental benefit which should not be forgotten; that tidal lagoons are contributing towards tackling global climate change.

4.1. Impacts & benefits

An ecosystem is a complex web of interactions amongst the living (biotic) and non-living (abiotic) environment. Any environmental impacts of a tidal lagoon will therefore have a complex impact on inter-tidal, marine and terrestrial ecosystems. It will also have knock-on implications for the wider environment, people, society and economics. In this sense, determining the top three environmental impacts allows us only to scrape the surface of this vast web of interactions. However, there is use in asking influencers and developers to consider the top three, as this shows us what impacts are currently being focused on in the industry, and therefore in practice.

Sediment regime and hydrodynamics are seen as key abiotic drivers of an ecosystem, this may suggest why they have been selected as key impacts by both developers and influencers. These impacts also interact with each other, with changing hydrodynamics influencing the sediment regime and a change in the seabed morphology as a result of sediment regime change influencing the local hydrodynamics. These impacts are also well studied [14–21], which could explain why they are at the forefront of the industry's mind. Or perhaps that is why the impacts are well studied; because the industry has been placing a focus on them. Never-the-less, this does represent an area of consensus between influencers and developers.

Conversely, the impact of 'Water Quality' represents an area of differing prioritisation amongst developers and influencers. This was a key impact raised by developers and was not mentioned directly by influencers. This question to influencers was a multiple choice question in which 'Water Quality' was not an option, although an 'other' box was provided for influencers to raise the issue this style of questioning may have resulted in the differences seen. The water quality impact here is related to the entrapment of water in a basin, which may also entrap pollutants, similar to the eutrophication issue previously seen at Sihwa Barrage [33]. This impact could potentially be worsened by run off from surrounding land. It could be that the influencers who were questioned are not aware of this issue, or, that they do not consider this issue to be of higher concern than the other impacts. Influencers did consider 'Restricted passage and migration' as a key issue, which can be linked to issues of water quality; this may also explain the difference seen in prioritising key impacts.

Environmental impacts can be categorised into knowns, known unknowns and unknown unknowns [4]. All of the impacts in this engagement have to be knowns or known unknowns, and the uncertainty surrounding impacts may have been one of the factors influencing participants' choices. The engagement work cannot take into account the unknown unknowns and these will only become apparent if a tidal lagoon is given the go-ahead, in which case careful monitoring will be required.

Often overlooked, tidal lagoons will also have a number of positive environmental impacts or benefits, and therefore beneficiaries such as people, society and the wider environment. The key benefits mentioned by influencers and developers were different and as such would have different beneficiaries. Developers mentioned key benefits where the beneficiaries will mostly be the local area, the local economy and the local people. In contrast, the influencers' priority benefits provided a spread of beneficiaries across society, the local ecosystem and individuals.

This result can partly be explained by the participants' backgrounds. Over half of the developers had local connections to the area of the project or development they were associated with; it is not surprising then that they chose benefits that would ultimately provide opportunities for the local area and its community. In addition, local benefits are likely to increase local support for a project, reducing public opposition. As influencers are not necessarily linked to an individual project's locality, they are more likely to take a more holistic view and consider the wider potential benefits of a project.

If the positive environmental impacts can outweigh the negative for a particular development then an overall net gain can be achieved for society in terms of the overall impact a lagoon might have on the environment. For this to be achieved a holistic approach needs to be taken with the wider implications and beneficiaries of both impacts and potential solution options considered. Environmental impacts can be described, appraised and valued [34] then incorporated into economic appraisals to allow developers to find a financially and environmentally effective means of providing environmental net gain that goes over and above regulatory requirements.

4.2. Solutions & industry development

Environmental impact solution options are often applied working down the mitigation hierarchy (Fig. 7). Within this, avoidance of an impact is addressed first, then reduce, restore and finally looking to offset as a last resort. Arguably, what is missing from this list is to enhance potential environmental benefits, and for a project to leave a lasting 'net gain' legacy. There are a number of solution options within these hierarchy steps (Fig. 7) and for simplicity they were grouped for the study into the three broad categories: 'Engineering Design & Technology', 'Operation & Maintenance' and 'Compensation & Catchment Measures'.

Both influencers and developers are considering solutions at the top end of the mitigation hierarchy in terms of the avoidance of impacts through engineering design and technology choice. There is yet to be a lagoon developed and so it is understandable that the industry is looking to avoid as many impacts as possible in the first instance through these solutions. Given the relative infancy of the industry, the majority of work to date has been on the engineering design and technology planning and so this might explain the large

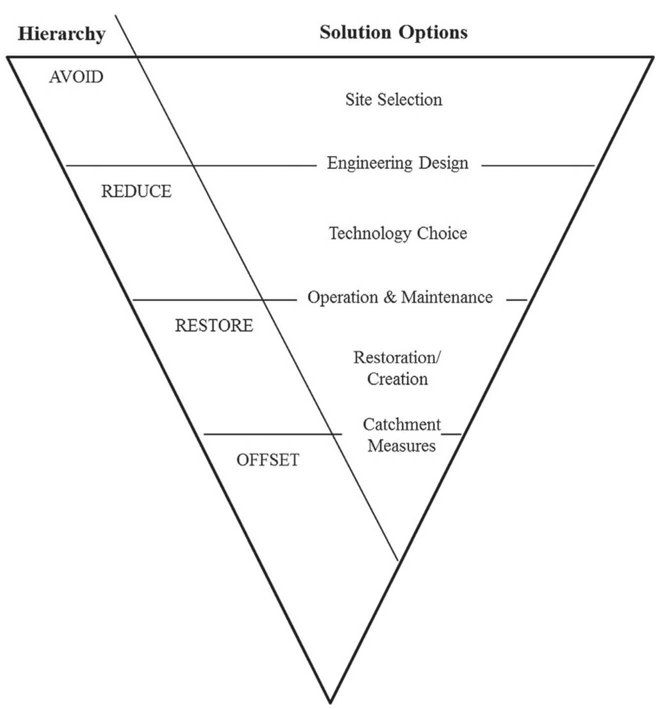

Fig. 7. Mitigation hierarchy for environmental impacts. Hierarchy adapted from source: [39].

percentage of industry participants mentioning these solution options, in particular the developers.

Alongside this, site selection as another avoidance strategy is also being taken into consideration by all of the participants. Influencers believe developers should place more focus on this, whilst developers consider choosing a suitable site to be one of their biggest challenges. An issue arises here in that the areas with the best tidal range often provide a unique habitat to be protected e.g. the Severn Estuary [35], therefore selecting a site that has the best resource for energy generation and that also avoids sensitive habitat is a challenging endeavour. Conundrums like this allow for other solutions further down the mitigation hierarchy to come into play.

The results suggest that the industry is considering either avoiding impacts or compensating them via strategies such as changing lagoon wall design, turbine technology or habitat creation. The middle section of the hierarchy to 'reduce' and 'restore', for example through operation and maintenance strategies, is not being highlighted as a focus in the industry's minds at the time of engagement. This could represent an area where further research is required to fill the gaps in the solution options being considered. Further attention on the reducing and restoring strategies such as 'Operation & Maintenance' would allow a full mitigation hierarchy of solutions to be provided to the industry, thereby reducing the environmental impacts of tidal lagoons as much as possible. An example of potential operation and maintenance strategies that could address the key environmental impacts of hydrodynamic and sediment regime changes are managing ebb and flood generation times and considerate dredging techniques.

The scope within solution option 'Compensation & Catchment Measures' is wider than the suggestions arising from participants or by this study thus far. There is an opportunity here to consider innovative solutions such as Payment for Ecosystem Services (PES) for example. Incorporating the benefits these solution options might have in terms of enhancement over and above that of regulatory requirements for the environment, society and the economy would allow for a stronger case for tidal lagoons in the future. A vital avenue for further research is therefore the consideration of the overall environmental and economic benefit of differing solution options that will allow for the largest positive net gain in future tidal lagoons to be realised.

One of the key requirements for the industry's development is that influencers and developers work together to move forward through the planning and regulatory process ensuring that lagoons are developed efficiently and sustainably. The key challenges in the industry include a lack of clear and accessible guidance available for developers, in addition to lengthy regulator processing times.

The infancy of the industry means that to date there is no specific lagoon guidance and instead the industry relies on adapting guidance from other sectors. If lagoon-specific guidance were to be developed this would provide certainty of information to developers and indeed the influencers themselves, in addition to reducing regulatory process times. Clarity and consistency of specific guidance may also reduce the costs often associated with the requirements of a precautionary approach to development as suggested in the Ocean Energy Forum's Strategic Roadmap [13]. It is essential that any lagoon-specific guidance is set up prior to the first lagoon project; this ensures that the process is in place to support the industry through the development process.

Lack of industry experience and information is an issue, for developers and for influencers. Developers have no blueprint of plans to work with in development and influencers lack the evidence they need to ensure compliance with legislative regimes and environmental directives. This issue will improve with time and thorough monitoring will allow for updated and enhanced regulatory guidance and smoother developer deployments. It will also provide opportunities in terms of exportable skills, experience and information as the world's first movers in the tidal lagoon industry.

5. Conclusions & recommendations

The study presents a first identification and analysis of the regulator and developer views on the environmental impacts of tidal lagoons. Aligning the views of the influencers and developers on this topic is vital to allow for a smooth transition of tidal lagoons from current planning to future development. This study provides a starting point to realising this sector aim.

Both influencers and developers are ultimately working towards 'Good Environmental Status' as one of the priority outcomes for tidal lagoons, and so this provides a foundation of a common goal to strive for. It is important to keep in mind that other outcomes are also of high priority and that the primary goals of a lagoon are ultimately to produce low carbon electricity at a cost competitive rate. In addition, whilst lagoons will have a number of local environmental impacts, it is essential not to forget the overarching global benefit of their potential contribution towards tackling climate change through the displacement of fossil fuels.

Environmental impacts of a lagoon will have complex implications to the intertidal, marine and terrestrial ecosystem in which it is developed [33,36]. The impacts in this study look at the known and known unknown impacts, since the unknown unknowns will only be apparent once a tidal lagoon is operational. 'Sediment Regime Alterations' and 'Changing Hydrodynamics' are at the forefront of influencers' and developers' minds as the key impacts of tidal lagoons. Whilst there is some differences in the priorities given to 'Water Quality' and 'Restricted Passage and Migration' by influencers and developers, both impacts are considered to be of high priority by the industry as a whole.

A number of key benefits of tidal lagoons were highlighted by influencers and developers. Influencers' key benefits provided beneficiaries spanning the ecosystem, society and individuals whilst developers focused mainly on the benefits to the local area and its people. It is expected that this result is due to the strong local connections the developers have with the local project areas. Effective management of environmental benefits and impacts of a lagoon could result in an overall positive impact on the environment (net gain), that goes over and above regulatory requirements.

The industry is focusing largely on avoiding or compensating impacts through engineering design, technology and compensation measures. There is a short-fall in the focus being placed on restoring and reducing environmental impacts through operation and maintenance strategies and an underestimation of the potential scope of contribution that compensation and catchment based solution measures could provide. In addition, one of the biggest hurdles currently being presented to the industry is the lack of clear and accessible regulator guidance providing a focused connection point between influencers and developers.

The three key recommendations from this paper are as follows:

- Lagoon-specific regulatory guidance or policy should be developed providing clear and accessible information to both influencers and developers to ensure a smooth development of the sector and reduction in regulatory process times.
- Further research should be undertaken into reducing and restoring environmental impacts through the use of operation and maintenance strategies.
- There needs to be further acknowledgement in the lagoon industry of solution options that go over and above regulatory requirements to provide environmental and economic enhancement to achieve overall project net gain. In particular this should be further investigated within the compensation and catchment based solution options.

These recommendations provide a starting point for research that works towards marrying the views of the influencers and developers on the environmental interactions of tidal lagoons. The study provides a snapshot of what is at the forefront of the minds' of key industry participants, highlighting the relevant information that will aid in the industry's development moving forward. Further work building on this study as a platform will contribute towards a smoother transition from lagoon regulatory planning at present to the world's first tidal lagoon development in the future.

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References

[1] United Nations, Paris Agreement - Status of Ratification. Framework Convention on Climate Change [cited 2016 Nov 28]. Available from:, 2016 http://unfccc.int/2860.php.
[2] Department of Energy & Climate Change (DECC), UK Renewable Energy Roadmap Update 2013, Available from:, 2013 https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/255182/UK_Renewable_Energy_Roadmap_-_5_November_-_FINAL_DOCUMENT_FOR_PUBLICATIO___.pdf.
[3] Parlimentary Business, Parliment Publication [cited 2016 Nov 10]. Available from:, 2016 https://www.parliament.uk/business/committees/committees-a-z/commons-select/energy-and-climate-change-committee/news-parliament-2015/heat-transport-report-published-16-17/.
[4] K. Mackinnon, H.C. Smith, F. Moore, Optimising Tidal Lagoons: Environmental Interactions. Engineering & Technology Reference, Available from:, 2016 https://energyhub.theiet.org/users/56863-kathryn-mackinnon/posts/18658-tidal-lagoon-environmental-interactions-regulator-perspective-solution-options-and-industry-challenges.
[5] Sustainable Development Comission, Turning the Tide: Tidal Power in the UK, Available from:, 2007 http://www.sd-commission.org.uk/data/files/publications/Tidal_Power_in_the_UK_Oct07.pdf.
[6] The Crown Estate, UK wave and Tidal Key Resource Areas Project, Available from:, 2012 http://www.thecrownestate.co.uk/media/5476/uk-wave-and-tidal-key-resource-areas-project.pdf.
[7] Department of Energy & Climate Change (DECC), Digest of UK Energy Statistics (DUKES): Chapter 5: Electricity, Available from:, 2016 https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/552059/Chapter_5_web.pdf.
[8] Tidal Lagoon Power Ltd, Tidal Lagoon Power: Key Statistics [cited 2016 Jan 1]. Available from:, 2016 http://www.tidallagoonpower.com/about/key-statistics/.
[9] S.P. Neill, M.R. Hashemi, M.J. Lewis, Tidal energy leasing and tidal phasing, Renew. Energy 85 (2016) 580–587, https://doi.org/10.1016/j.renene.2015.07.016. Available from:.
[10] Tidal Lagoon Power Ltd, Swansea Bay Lagoon Project - Planning [cited 2016 Jul 20]. Available from:, 2015 http://www.tidallagoonswanseabay.com/planning/planning-process/61/.
[11] C. Hendry, The Role of Tidal Lagoons Final Report [cited 2017 Feb 7]. Available from:, 2016 https://hendryreview.files.wordpress.com/2016/08/hendry-review-final-report-english-version.pdf.
[12] T. Hooper, M. Austen, Tidal barrages in the UK: ecological and social impacts, potential mitigation, and tools to support barrage planning, Renew. Sustain Energy Rev. 23 (2013 Jul) 289–298 [cited 2015 Jun 27] Available from: http://www.sciencedirect.com/science/article/pii/S1364032113001500.
[13] Ocean Energy Forum, Ocean Energy Strategic Roadmap 2016, Building Ocean Energy for Europe, 2016.
[14] T. a. Adcock, S. Draper, T. Nishino, Tidal power generation - a review of hydrodynamic modelling, Proc Inst Mech Eng Part a J Power Energy 0 (0) (2015) 1–17. Available from: http://pia.sagepub.com/lookup/doi/10.1177/0957650915570349.
[15] A. Angeloudis, R. Ahmadian, R. a. Falconer, B. Bockelmann-Evans, Numerical model simulations for optimisation of tidal lagoon schemes, Appl. Energy 165 (2016) 522–536. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0306261915016529.

[16] J. Xia, R. a. Falconer, B. Lin, Impact of different tidal renewable energy projects on the hydrodynamic processes in the Severn Estuary, UK, Ocean. Model 32 (1–2) (2010) 86–104, https://doi.org/10.1016/j.ocemod.2009.11.002. Available from:.

[17] J. Xia, R. a. Falconer, B. Lin, Hydrodynamic impact of a tidal barrage in the Severn Estuary, UK, Renew. Energy 35 (7) (2010) 1455–1468, https://doi.org/10.1016/j.renene.2009.12.009. Available from:.

[18] R. Ahmadian, R. a. Falconer, Bockelmann-Evans B, Comparison of hydro-environmental impacts for ebb-only and two-way generation for a Severn Barrage, Comput. Geosci. 71 (C) (2014) 11–19, https://doi.org/10.1016/j.cageo.2014.05.006. Available from:.

[19] I. Fairley, R. Ahmadian, R. a. Falconer, M.R. Willis, I. Masters, The effects of a severn barrage on wave conditions in the Bristol channel, Renew. Energy 68 (2014) 428–442, https://doi.org/10.1016/j.renene.2014.02.023. Available from:.

[20] M.J. Lewis, S.P. Neill, a J. Elliott, Interannual variability of two offshore sand banks in a region of extreme tidal range, J. Coast Res. 31 (2014) (June):1–12.

[21] J.S. Pethick, RK a Morris, D.H. Evans, Nature conservation implications of a Severn tidal barrage - a preliminary assessment of geomorphological change, J. Nat. Conserv. 17 (4) (2009) 183–198, https://doi.org/10.1016/j.jnc.2009.04.001. Available from:.

[22] M. Kadiri, R. Ahmadian, B. Bockelmann-Evans, W. Rauen, R. Falconer, A review of the potential water quality impacts of tidal renewable energy systems, Renew. Sustain Energy Rev. 16 (1) (2012 Jan) 329–341 [cited 2015 Feb 20] Available from: http://www.sciencedirect.com/science/article/pii/S1364032111004072.

[23] M. Kadiri, R. Ahmadian, B. Bockelmann-Evans, R. a. Falconer, D. Kay, An assessment of the impacts of a tidal renewable energy scheme on the eutrophication potential of the Severn Estuary, UK, Comput. Geosci. 71 (2014) 3–140, https://doi.org/10.1016/j.cageo.2014.07.018. Available from:.

[24] Vincent de Laleu, La Rance Tidal Power Plant. 40 Year Operation Feedback - Lessons Learnt, in: BHA Annual Conference. Liverpool, 2009. Available from: http://www.british-hydro.org/downloads/LaRance-BHA-Oct 2009.pdf.

[25] M. Schneeberger, Sihwa tidal - turbines and generators for the world's largest tidal power plant, in: Andritz Hydro Brisitsh Hydropower Associateion 2008, 2009. Bristol, UK.

[26] typeform. Typeform: Online Survey Tool. [cited 2016 Oct 31]. Available from: https://www.typeform.com/.

[27] P. Bazeley, K. Jackson, Qualitative Data Analysis with NVivo. Second, SAGE publications, 2013.

[28] H. Bernard, G. Ryan, Analyzing Qulaitative Data: Systematic Approaches, SAGE, Thousand Oaks, CA, 2010.

[29] G. Gibbs, C. Taylor, How and what to Code, Online QDA Website University of Huddersfield, 2010 [cited 2016 Nov 10]. Available from: http://onlineqda.hud.ac.uk/Intro_QDA/how_what_to_code.php.

[30] K. Punch, Introduction to Social Research: Quantitative and Qualitative Approaches, second ed., London Sage, 2005.

[31] Wyre Tidal. Wyre Tidal Energy: The Team. [cited 2016 Nov 21]. Available from: http://www.wyretidalenergy.com/the-team/.

[32] P.S. Moschella, M. Abbiati, P. Åberg, L. Airoldi, J.M. Anderson, F. Bacchiocchi, et al., Low-crested coastal defence structures as artificial habitats for marine life: using ecological criteria in design, Coast Eng. 52 (10–11) (2005 Nov) 1053–1071 [cited 2015 Oct 9] Available from: http://www.sciencedirect.com/science/article/pii/S0378383905001146.

[33] Park N. Sihwa Tidal Power Plant: a Success of Environment and Energy Policy in Korea. In: Korea University. Available from: http://www.eer.wustl.edu/McDonnellMayWorkshop/Presentation_files/Saturday/Saturday/Park.pdf.

[34] eftec, Economic Valuation of the Effect of the Shortlisted Tidal Options on the Ecosystem Services of the Severn Estuary, 2010. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/51157/11._Ecosystems_Valuation_-_Technical_Report.pdf.

[35] JNCC. JNCC Severn Estuary SPA description. [cited 2016 Nov 21]. Available from: http://jncc.defra.gov.uk/default.aspx?page=2066.

[36] Shaw T. La Rance Tidal Power Barrage, Ecological Observations Relevant to a Severn Barrage Project.

[37] Industrial Doctoral Centre for Offshore Renewable Energy (IDCORE), 2016 [cited 2016 Oct 11]. Available from: http://www.idcore.ac.uk/.

[38] European Commission, Marine Strategy Framework Directive (MSFD) Good Environmental Status, 2016 [cited 2016 Aug 15]. Available from: http://ec.europa.eu/environment/marine/good-environmental-status/index_en.htm.

Appendix 3: International Conference on Ocean Energy (ICOE) Poster

Optimising Tidal Lagoon Development: Environment & Economics

Kathryn Elliott[1]*, Helen Smith[2], Fran Moore[3], Iraklis Lazakis[4], Harry Van Der Weijde[5]
*Email: ElliottK@bv.com [1]IDCORE, [2]University of Exeter, [3]Black & Veatch, [4]University of Strathclyde, [5]University of Edinburgh

Introduction

There is potential for tidal lagoons to contribute significantly to the global energy mix. Despite there being six tidal lagoons in the UK planning pipeline, deployment has been prevented or delayed to date largely due to cost or regulatory environmental concerns.

Targeted questionnaires were sent to regulatory, policy and conservation organisations. The responses represent their view on the key environmental impacts, opportunities and outcomes of future tidal lagoon developments.

Highlighting areas of regulatory priority will allow focused solutions to be developed. These will enhance the overall net environmental status of tidal lagoons making their deployment more straight forward in the future.

The **main objectives** of the research are to determine the public sector and NGO's view on:

- The most desired future outcomes of tidal lagoon developments
- Their key environmental impacts and opportunities
- The priority impacts that industry should focus on finding solutions for

Method

One of the first steps to optimising the net environmental and economic status of tidal lagoon developments is to identify key environmental impacts and benefits, Figure 1. An impact and benefit register was developed based on literature review. The impacts and benefits obtained from this register were then used to develop a short online questionnaire for NGO's and public sector organisations.

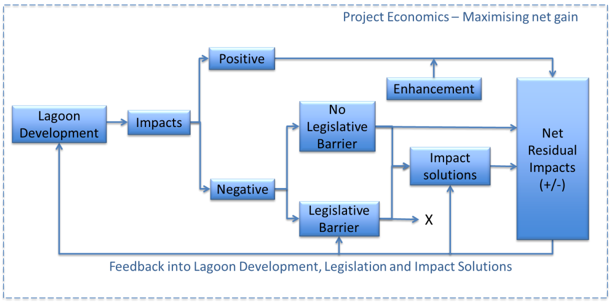


Figure 1: Research conceptual model: Optimising tidal lagoon developments

The online survey tool 'Typeform' was used to develop the questionnaire. A combination of closed and open questions were used. Information was provided to participants throughout to allow for informed decisions. Respondents were chosen based on relevance of their current roles and organisations. Surveys were emailed to participants with follow up phone calls undertaken where necessary. Figure 2 forms the basis of the questionnaire to determine participants secondary and primary impacts.

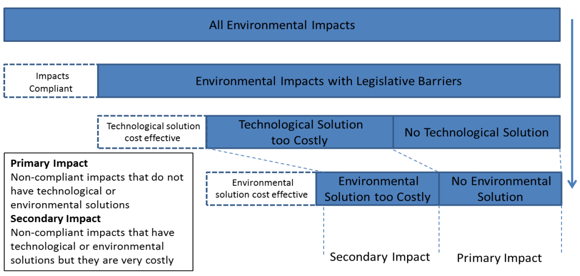


Figure 2:Schematic to show the basis of the questionnaire

Respondent Statistics

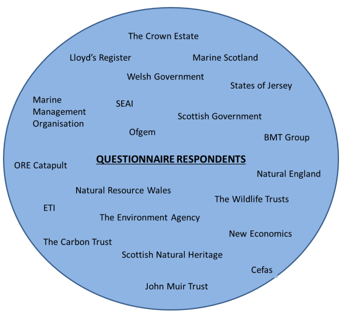


Figure 3: Circle of Respondents

- 47 individuals invited to participate
- 24 individuals responded (51% response rate)
- 21 different organisations participated (regulatory, conservation or policy), Figure 3.
- Respondents from a variety of backgrounds; 67% from either policy or environmental roles
- Examples of respondent's roles include: Directors, Leads, Advisors and Decision makers within marine policy, conservation or planning positions.

Main Results

Respondents believed 'Good Environmental Status' and 'Cost Competitiveness' to be the most desired outcomes of future tidal lagoon developments, see Figure 4 below.

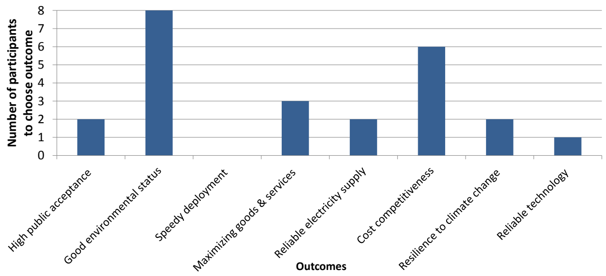


Figure 4: Most desirable outcome of tidal lagoon developments selected by participants

Sediment regime alterations, restricted passage and migration and changing hydrodynamics were selected by respondents to be the top three most significant environmental impacts, see Figure 5.. Blade interaction, benthic habitat loss and water level change were also deemed to be important to participants. Environmental impacts are likely to be inter-linked and have various knock-on effects.

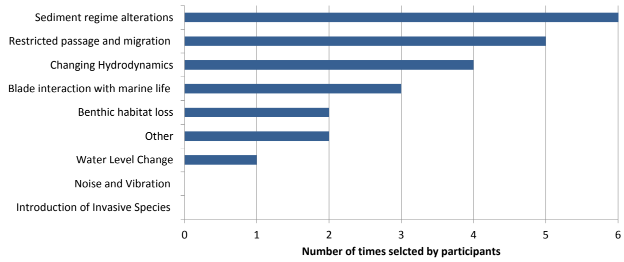


Figure 5: Participant's most significant environmental impacts

Tidal lagoons can provide numerous opportunities and benefits. It is thought that these can be provided 'naturally' from the development itself and by providing solutions to address negative impacts that go over and above legislative requirements. Participants identified key benefits to be flood defence, recreation, enhancing biodiversity and habitat creation, Table 1.

Table 1: Key benefits a tidal lagoon can provide

Benefits of Tidal Lagoon Developments	*Times Mentioned*
Multiple use opportunity	2
Area regeneration/ Socio-economic benefits	2
Local economy boost	1
Export opportunities	2
Flood defense/control	7
Coastal erosion protection	4
Leisure & Recreation	7
Research/Development/Education	3
Local Supply Chain	2
Local Employment	2
Countries Image	1
New or enhanced habitat	2
Energy baseload potential	1
Renewable Energy acceptance/shift	2
Tourism	2
Aquaculture	2
Community share opportunities	1

Benefits of Addressing Impacts	*Times Mentioned*
Coastal Defense	1
Project Consent gaining/Going ahead	3
Habitat protection/creation & Biodiversity	5
Create a Tourist Attraction	1
Sustainable Energy	2
Maintained spawning	1
Higher Cost Certainty/ Lower cost	3
Resilience to climate change	1
Improved Coastal Management	1
Higher public acceptance	1
Increased or sustained economic activity	2

Participants were asked where developers should be focusing their efforts to enhance the environmental status of tidal lagoons. There was a varied response but a key theme throughout was on **site selection** and avoiding impacts to designated or otherwise sensitive areas.

Conclusions

The key findings are as follows:

- The most desired future outcomes of tidal lagoon developments, according to respondents are 'Good Environmental Status' and 'Cost Competitiveness'
- Sediment regime, changing hydrodynamics and restricted passage and migration were noted as significant potential environmental impacts. Environmental impacts are interlinked and a holistic approach to solutions would need to be taken
- The key 'natural' benefits noted by participants include flood defence, leisure and recreation, with further opportunities lying within addressing impacts over and above legislative requirements.
- Participants suggested site selection be the first option to enhance future tidal lagoon environmental status, by avoiding environmentally sensitive or designated locations.

The next steps are to glean the view of tidal range developers on the subject to provide a comparison, in addition to developing targeted solutions to priority environmental impacts.

Industrial Doctoral Centre for Offshore Renewable Energy

International Conference on Ocean Energy (ICOE) 2016 – Edinburgh – 23-25 February 2016

Appendix 4: All Energy Conference Presentation

Conference: All Energy 2016
Location: Glasgow
Date: 04-05/05/2016

Speaker: Kathryn Mackinnon, Research Engineer

Optimising Tidal Lagoon Developments: An Environmental Focus

Idcore
Industrial Doctoral Centre for Offshore Renewable Energy

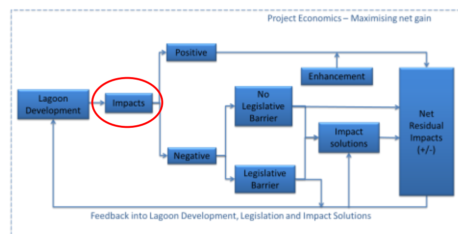
THE UNIVERSITY of EDINBURGH · UNIVERSITY OF EXETER · University of Strathclyde Glasgow

AGENDA

RESEARCH OVERVIEW

THE RESEARCH PROJECT

Optimising Tidal Lagoon Developments: An Environmental Focus

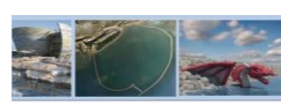


METHODS

IDENTIFYING IMPACTS & BENEFITS

Register

- Impact and opportunities register
- Based on literature review
- Referenced with added information



Questionnaire Aims

Gain the regulatory industry's view on tidal lagoons and:

1. Key Environmental Impacts
2. Priority benefits
3. Future Outcomes
4. Developer Focus

Picture source: Tidal Lagoon Swansea bay. Online. Accessed 20/04/2016. URL: http://www.tidallagoonswanseabay.com/

RESULTS

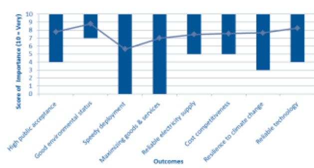
STATISTICS

- 47 Invited
- 24 Participated
- 51% response rate
- 21 organisations
- 67% from Policy or Environmental Roles
- Example Roles:

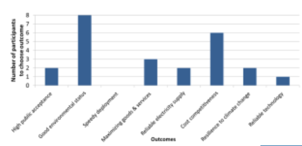
Head, Director or Advisors of Policy, Marine Specialists, Consents Advisors, Case Managers, Planning Officers

OUTCOMES

Please rate the following in terms of their importance for future tidal lagoons developments

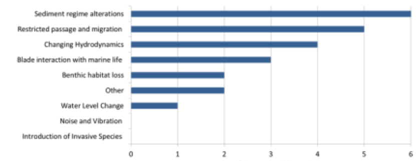


Which outcome do you believe is the MOST important for future tidal lagoon developments?



NEGATIVE IMPACTS

What do you consider to be the most significant environmental impact of tidal lagoon developments?



Top 3:
1. Sediment regime
2. Restricted Migration
3. Changing Hydrodynamics

BENEFITS

Other than low carbon energy and the direct economic benefits, what are the priority opportunities of a lagoon?

If your impact is addressed what benefits can be gained?

Benefits of Tidal Lagoon Developments	*Times Mentioned*
Multiple use opportunity	2
Area regeneration/ Socio-economic benefits	2
Local economy boost	1
Export opportunities	2
Flood defense/control	7
Coastal erosion protection	4
Leisure & Recreation	7
Research/Development/Education	3
Local Supply Chain	2
Local Employment	2
Countries Image	1
New or enhanced habitat	2
Energy baseload potential	1
Renewable Energy acceptance/shift	2
Tourism	2
Aquaculture	2
Community share opportunities	1

Benefits of Addressing Impacts	*Times Mentioned*
Coastal Defense	1
Project Consent gaining/Going ahead	3
Habitat protection/creation & Biodiversity	5
Create a Tourist Attraction	1
Sustainable Energy	2
Maintained spawning	1
Higher Cost Certainty/ Lower cost	3
Resilience to climate change	1
Improved Coastal Management	1
Higher public acceptance	1
Increased or sustained economic activity	2

DEVELOPER FOCUS

Where should developers be focusing their efforts to enhance the environmental status of tidal lagoons?

"Site selection" "Choice of location" "Cost effective environmental mitigation"

"Improved modelling" "Site selection should be key" "Focus on benefits outweighing the risks"

"Benthic habitats and fish nurseries" "Location and design" "Reduce impact on designated features"

"Build up of sediment" "Avoiding designated sites" "Co-existence of activities"

"Footprint of the lagoon and habitat loss" "Engagement with NGO's"

Key theme:

Site selection and avoiding impacts to designated or otherwise sensitive areas

NEXT STEPS

13

NEXT STEPS

- Interview Developers
- Rank Impacts – top 20% causing 80% of the problem
- Value Benefits and Impacts – compare with responses
- Cost Benefit Analysis
- Impact Uncertainty Analysis
- Strategies to reduce uncertainty
- Investigation into Solutions

Government Review depending !

NEXT STEPS

14

CONCLUSIONS

15

CONCLUSIONS

- 'Good Environmental Status' and 'Cost competitiveness' important outcomes
- Top three impacts : changing sediment regime, restricted passage and migration and changing hydrodynamics
- Key 'natural' benefits include flood defence, leisure and recreation,
- Further opportunities within addressing impacts
- Developer focus on site selection
- Future of lagoons depends on government review

RESULTS

16

QUESTIONS

Thank you for listening

17

Building a world of difference.®

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QUESTIONNAIRE STRATEGY

- Targeted questionnaire
- Regulatory, policy, conservation and think-tank organisations
- Short online survey
- 'Typeform' software
- Closed and open questions

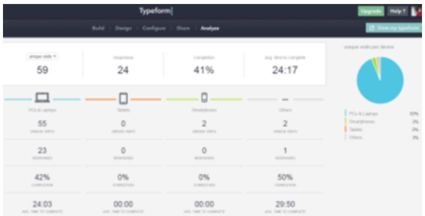
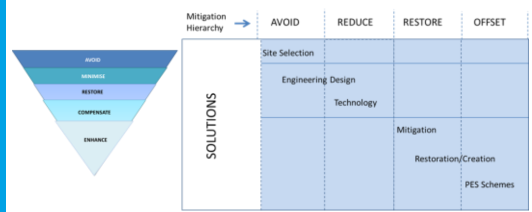


Figure: Screenshot of the typeform questionnaire analysis

METHODS

IMPACT SOLUTIONS



NEXT STEPS

Appendix 5: Industry Engagement Questionnaire Sheet

Questionnaire Information Sheet: De-risking Tidal Lagoons: An Environmental Focus

Please respond to this 20-minute questionnaire to be entered into a £50 amazon voucher raffle

Questionnaire link: https://lagoonresearch.typeform.com/to/HQ1szq

Who is inviting me?

The questionnaire forms part of an Engineering Doctorate (EngD) with the Industrial Doctoral Centre for Offshore Renewable Energy (IDCORE) and sponsoring company Black & Veatch. The research is being carried out by **EngD Student Kathryn Elliott** with the following supervisors:

Lead Industrial	Fran Moore	(Black & Veatch)
Lead Academic	Helen Smith	(University of Exeter)
Co-Academic	Iraklis Lazakis	(University of Strathclyde)
Co-Academic	Harry Van De Weijde	(University of Edinburgh)

What is the purpose of the research?

Tidal lagoons are an attractive renewable energy option but have been prevented or delayed to date, largely due to cost and environmental concerns. Six tidal lagoons are proposed in the UK, each in various stages of planning. Swansea Bay Tidal Lagoon is the most advanced having received planning consent in June 2015. It is therefore more important than ever to further understand if and how the net environmental and economic benefits of tidal lagoon developments in the UK can be maximised, in order to prevent future delays and abortive development investment.

The doctoral research aims to identify the key environmental impacts of tidal lagoon developments and how best to avoid, mitigate or offset these. Strategies such as innovation in technology, environmental measures and project decision making will be explored, and then assessed for cost effectiveness and suitability. I will use the information you provide in this questionnaire to identify those environmental risks that should be prioritised for attention; either because there are currently no technological or environmental solutions to these risks, or the solutions available are too costly to implement. See Figure 1 below. In addressing these priority risks, this research will then inform strategies to optimize the economic and environmental net benefits of tidal lagoon development in the UK.

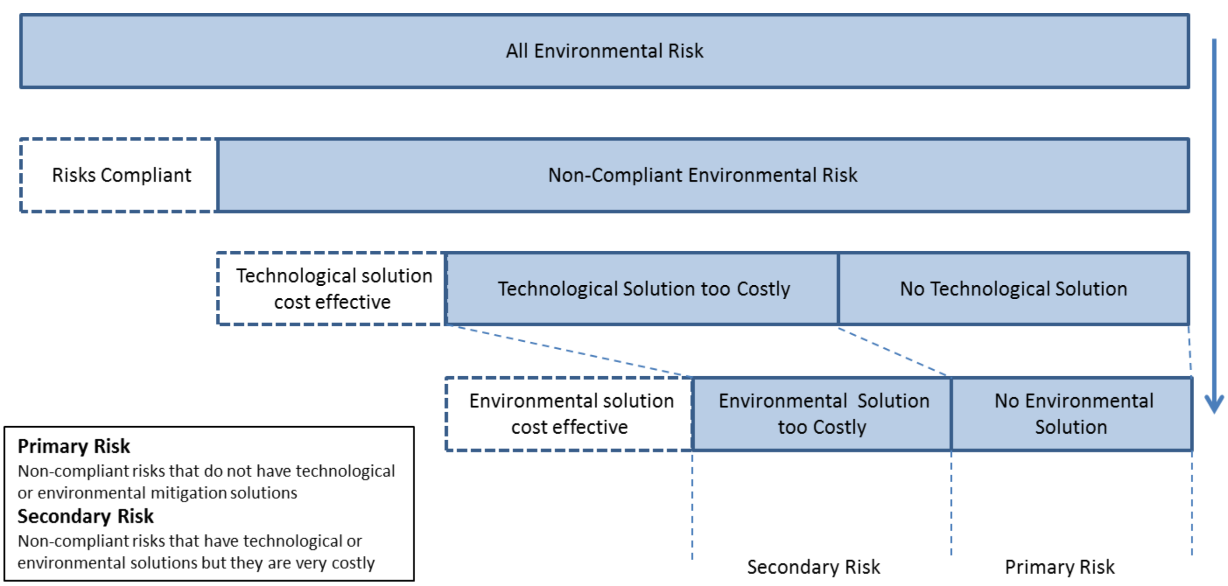


Figure 1: Process of identifying primary and secondary environmental risks

What is the purpose of the questionnaire?

The questionnaire aims to glean participant's views on what the key environmental risks are, and the implications these may have upon lagoon technology, finance, socio-economics, the wider environment and most importantly legislative compliance. It aims to identify which risks are currently not addressed via risk mitigation measures or avoidance strategies. Mitigation and avoidance strategies both technological (engineering design, turbine selection, operation strategies) and environmental (site placement, habitat creation and offsetting) will be considered. It hopes to draw out what you believe to be the most important future environmental risks associated with tidal lagoon development in the UK. The responses will be used to validate a risk register and inform prioritisation of the environmental risks.

Why have I been invited to participate?

The questionnaire seeks the input of regulators, statutory advisors and policy makers, due to your relevant and detailed experience and knowledge. This knowledge does not necessarily have to be specific to tidal lagoons. Please answer the questions in relation to your current role as opposed to any personal opinion on tidal lagoons. You do not have to answer all of the questions. The research will be shared with developers, in order to steer them as to where they should be working the most to reduce the environmental risks of tidal lagoon developments. Your input into the research through participation in the online questionnaire would be valued, if you would prefer a telephone interview please indicate so in the questionnaire.

What are the benefits of taking part?

The questionnaire provides an opportunity for you to have your say on where tidal lagoon developers should be focusing their efforts in reducing environmental risks. This will ultimately help industry to focus risk management in key areas, to allow future tidal lagoons to be more economically and environmentally viable, thereby reducing the delays currently seen in their deployment.

It is hoped that this work will feedback into lagoon technology design and potentially into tidal lagoon specific planning. It is therefore an opportunity to inform this process using knowledge based on your current role. Most importantly, you will be automatically entered into a **raffle to win a £50 amazon voucher.**

How much of my time is needed?

The questions are a mix of both closed and open questions. The closed questions aim to keep question responses clear and to shorten the length of time to participate in the questionnaire. Multiple-choice questions are included to provide the participant with background information for an informed decision. Open-ended questions invite the participant to elaborate on important points to provide further understanding and explanation, these are not compulsory. Some questions are similar but presented in different forms to get a different type of response. The response time will depend on the length of detail you wish to go into, however it is generally expected that the questionnaire will take **no longer than 20 minutes** to complete.

How do I participate?

The questionnaire is conducted online through a survey tool named 'typeform', this allows you to simply click the LINK taking you straight to the questionnaire. Your responses will be logged for analysis automatically.

What do I need to know?

- The questionnaire is 25 questions long, please scroll down to Q25 before submitting
- You do not have to answer all of the questions, just answer the ones you can
- The questionnaire is your opinion, there are no wrong answers
- If the questionnaire stops (will not let you scroll further) it is because input is required to proceed

What if I have a question? Contact details

If you have any questions regarding the questionnaire or the research project, please do not hesitate to get in touch.

Kathryn Elliott Tel: +44 (0) 1737856319 Mob: +44 (0) 7533893874 Email: ElliottK@bv.com

Thank You in Advance

Appendix 6: Industry Engagement Interview Sheet

Interview Information Sheet: Optimising Tidal Lagoons: Environment & Economics

Who wants to talk to me?

The interviews form part of an Engineering Doctorate (EngD) with the Industrial Doctoral Centre for Offshore Renewable Energy (IDCORE) and sponsoring company Black & Veatch. The research, and in turn the interviews, are being carried out by **EngD Student Kathryn Elliott** (E: ElliottK@bv.com, T: 07533893874) with the following supervisors:

Lead Industrial	Francesca Moore	Black & Veatch
Lead Academic	Helen Smith	University of Exeter
Co-Academic	Iraklis Lazakis	University of Strathclyde
Co-Academic	Harry Van Der Weijde	University of Edinburgh

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Tidal lagoons are an attractive renewable energy option but have been prevented or delayed to date, largely due to cost and environmental concerns. At least six tidal lagoons are proposed in the UK, each in various stages of development and planning. Swansea Bay Tidal Lagoon is the most advanced having received planning consent in June 2015. It is therefore more important than ever to further understand if and how the net environmental and economic benefits of tidal lagoon developments in the UK can be maximised, in order to prevent future delays and abortive development investment.

The doctoral research aims to firstly identify the key environmental impacts of tidal lagoon developments and then determine how best to avoid, mitigate or offset these. Strategies such as innovation in technology, environmental measures and project decision making will be explored, and then assessed for cost, effectiveness and suitability. Tidal lagoons can provide numerous opportunities and benefits. It is thought that these can be provided 'naturally' from the development itself and by providing solutions to address negative impacts that go over and above legislative requirements. Figure 1 below shows the research conceptual model for optimising tidal lagoon developments.

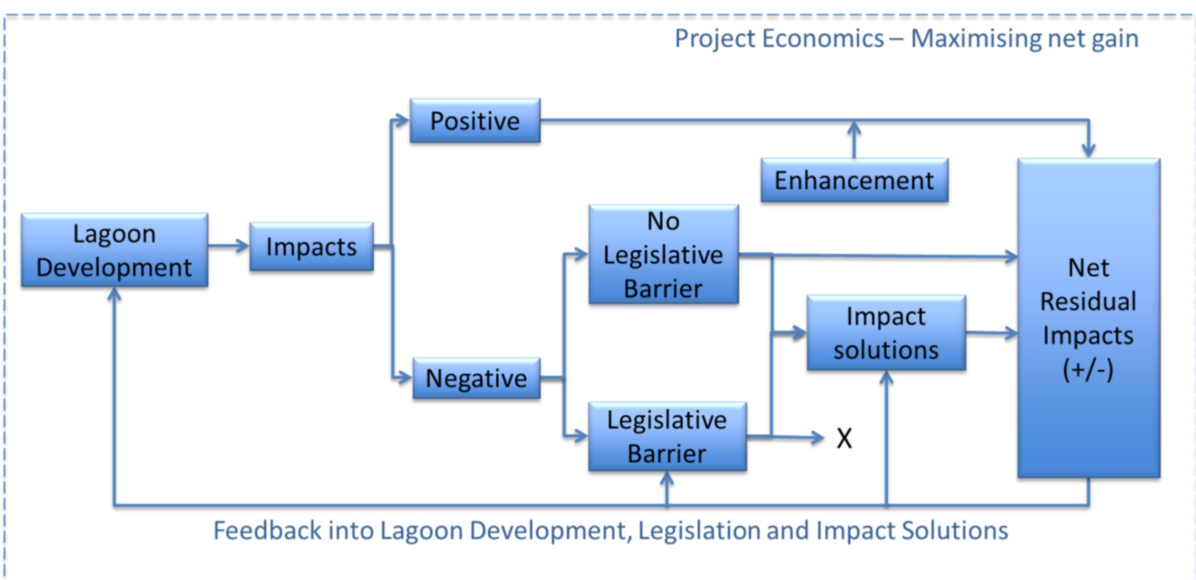


Figure 1: EngD Conceptual Model: Optimising Tidal Lagoon Developments

What work has been done to date?
A total of six months research has been conducted out of the total three-year doctorate program. The initial stages of this research aim to identify the key impacts, opportunities and anticipated outcomes of tidal lagoon developments. An impact and opportunities register was created based on literature review. The information from this register was used in an online questionnaire for regulatory, policy and conservation organisations. The aim of this was to determine the public sector and NGO's view on tidal lagoon development environmental impacts. With 21 participating organisations, 24 responses from individuals in relevant roles within these organisations and a 51% overall response rate we are satisfied that this view has now been represented.

Why am I being interviewed?
Although some information on key impacts and opportunities can be gleaned from literature review, the most up to date, accurate and realistic information will be gained through industry engagement. This is particularly important due to the relative infancy of the industry in the UK and lack of operational evidence. It is hoped that a range of views will be collected from both industry and regulatory/public bodies. The responses from your interview will be used to focus and inform the next steps of the doctoral research, to ensure the research is in line with industry requirements.

What are the benefits of taking part?
The interviews provide an opportunity for you to have your say on where you believe the difficulties lie within the environmental consenting process for tidal lagoon developments, and the challenges in addressing their environmental impacts. It also allows you to guide the direction of the doctoral research to be in line with industry requirements. It is hoped that later research will result in recommendations for impact management, lagoon technology design and tidal lagoon planning. It is therefore an opportunity to inform this process at an early stage using knowledge based on your current role in the industry. Following the interview process, if requested, the general results from consultation with the public sector and NGO's on the environmental impacts of tidal lagoon developments will be provided.

What consents will I be asked to give?

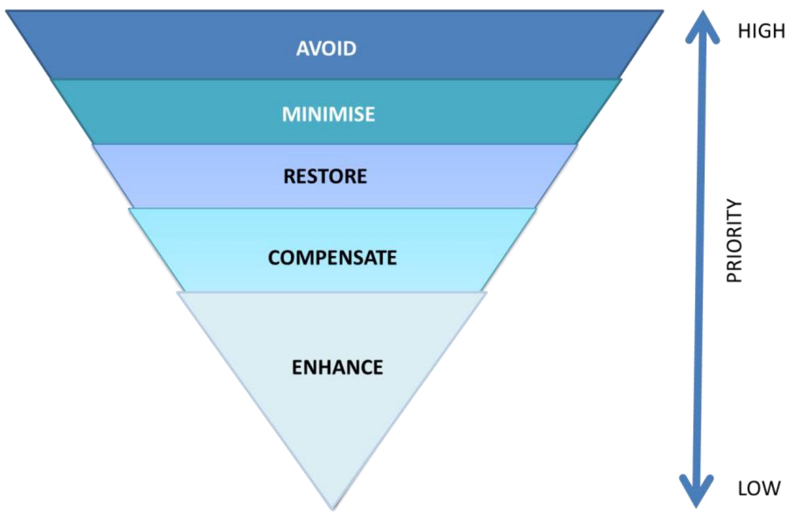
- You will be asked if the interview can be recorded. This is to ensure that your responses are represented as accurately as possible and to reduce the time needed for note taking.
- The study is for an Engineering Doctorate; your responses will be used to complete this academic qualification. This includes discussing any results with supervisors, at a final viva, and with your permission within publications and at scientific conferences. You will be asked if you would like your responses not to be linked to your organisation.
- You will be asked for permission to use excerpts of your responses in EngD work, and potentially in scientific publication and/or conferences.

We will always ask your permission to use your responses out-with the EngD qualification, for example, in scientific publication or at academic conferences. You can get in touch with Kathryn Elliott at any time if you have any questions about the research, use of your responses or to withdraw your participation in the research.

What questions are you going to ask me?

Below is an example list of the questions that you will be asked. The interview might not follow these rigidly but they do provide an example of what you are likely to be asked. Any unclear questions will be explained further in the interview.

1. What would you say is the single most desired outcome of future tidal lagoon developments? And why?
2. What do you consider to be the top three most significant environmental impacts of tidal lagoon developments? Why these three?
3. If you had to select one of these to be THE most important impact, which one would it be?
4. What are the likely knock-on implications of this impact?
5. What category is likely to be most affected by these implications? Socio-economics, environment, lagoon finance or lagoon technology/engineering
6. In what way could your key environmental impact undermine the consenting process?
7. Could it threaten compliance to a specific legislation? Which one?
8. With respect to environment impacts, have you found any aspects of the regulatory process challenging to date? Which parts? How could it be improved?
9. Based on the mitigation hierarchy (Figure 2 below), let's talk through potential solutions to address your top key impacts.



10. Are any of the solutions you mentioned deemed too expensive to implement?
11. Where should research be undertaken in terms of potential solutions to environmental impacts? Where does the research fall short?
12. What are the key environmental benefits that a tidal lagoon can provide 'naturally'?
13. What additional benefits can be gained by addressing any environmental impacts of tidal lagoons? What desired outcomes are any benefits likely to contribute towards?

Thank You in Advance

Appendix 7: Literature Review List of Included Papers

1	Ahr, B., Farris, M., & Lowe, C. G. (2015). Habitat selection and utilization of white croaker (Genyonemus lineatus) in the Los Angeles and Long Beach Harbors and the development of predictive habitat use models. *Marine Environmental Research*, *108*. http://doi.org/10.1016/j.marenvres.2015.04.005
2	Anthony, K. R. N., Marshall, P. A., Abdulla, A., Beeden, R., Bergh, C., Black, R., … Wear, S. (2015). Operationalizing resilience for adaptive coral reef management under global environmental change. *Global Change Biology*, *21*(1). http://doi.org/10.1111/gcb.12700
3	Bas, A., Jacob, C., Hay, J., Pioch, S., & Thorin, S. (2016). Improving marine biodiversity offsetting: A proposed methodology for better assessing losses and gains. *Journal of Environmental Management*, *175*, 46–59. http://doi.org/10.1016/j.jenvman.2016.03.027
4	Bitner-Gregersen, E. M., Bhattacharya, S. K., Chatjigeorgiou, I. K., Eames, I., Ellermann, K., Ewans, K., … Waseda, T. (2014). Recent developments of ocean environmental description with focus on uncertainties. *Ocean Engineering*, *86*, 26–46. http://doi.org/10.1016/j.oceaneng.2014.03.002
5	Blau, J., & Green, L. (2015). Assessing the impact of a new approach to ocean management: Evidence to date from five ocean plans. *Marine Policy*, *56*, 1–8. http://doi.org/10.1016/j.marpol.2015.02.004
6	Brandt, M. J., Höschle, C., Diederichs, A., Betke, K., Matuschek, R., Witte, S., & Nehls, G. (2013). Far-reaching effects of a seal scarer on harbour porpoises, Phocoena phocoena. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *23*(2). http://doi.org/10.1002/aqc.2311
7	Brondizio, E. S., Vogt, N. D., Mansur, A. V., Anthony, E. J., Costa, S., & Hetrick, S. (2016). A conceptual framework for analyzing deltas as coupled social–ecological systems: an example from the Amazon River Delta. *Sustainability Science*, *11*(4). http://doi.org/10.1007/s11625-016-0368-2
8	Brown, C. J. (2016). Social, economic and environmental effects of closing commercial fisheries to enhance recreational fishing. *Marine Policy*, *73*. http://doi.org/10.1016/j.marpol.2016.08.010
9	Burgass, M. J., Halpern, B. S., Nicholson, E., & Milner-Gulland, E. J. (2017). Navigating uncertainty in environmental composite indicators. *Ecological Indicators*, *75*, 268–278. http://doi.org/10.1016/j.ecolind.2016.12.034
10	Bush, D., Neal, W., Young, R., & Pilkey, O. (1999). Utilization of geoindicators for rapid assessment of coastal-hazard risk and mitigation. *Ocean & Coastal Management*. Retrieved from http://www.sciencedirect.com/science/article/pii/S0964569199000277
11	Carrillo-Guerrero, Y. K., Flessa, K., Hinojosa-Huerta, O., & López-Hoffman, L. (2013). From accident to management: The Cienega de Santa Clara ecosystem. *Ecological Engineering*, *59*. http://doi.org/10.1016/j.ecoleng.2013.03.003
12	Cochard, R. (2017). Chapter 12 – Coastal Water Pollution and Its Potential Mitigation by Vegetated Wetlands: An Overview of Issues in Southeast Asia. In *Redefining Diversity and Dynamics of Natural Resources Management in Asia, Volume 1* (pp. 189–230). http://doi.org/10.1016/B978-0-12-805454-3.00012-8
13	Copping, A., Smith, C., Hanna, L., Battey, H., Whiting, J., Reed, M., … Massaua, M. (2013). Tethys: Developing a commons for understanding environmental effects of ocean renewable energy. *International Journal of Marine Energy*, *3*, 41–51. http://doi.org/10.1016/j.ijome.2013.11.004
14	Costanza, R., Pérez-Maqueo, O., & Martinez, M. (2008). The value of coastal wetlands for hurricane protection. *The Human Environment*. Retrieved from http://www.bioone.org/doi/abs/10.1579/0044-7447(2008)37[241:TVOCWF]2.0.CO;2
15	Dabrowski, J., Peall, S., & Reinecke, A. (2002). Runoff-related pesticide input into the Lourens River, South Africa: basic data for exposure assessment and risk mitigation at the catchment scale. *Water, Air, and Soil*. Retrieved from http://link.springer.com/article/10.1023/A:1014705931212
16	Dafforn, K. A., Mayer-Pinto, M., Morris, R. L., & Waltham, N. J. (2015). Application of management tools to integrate ecological principles with the design of marine infrastructure. *Journal of Environmental Management*, *158*. http://doi.org/10.1016/j.jenvman.2015.05.001
17	Davis, A. R., Broad, A., Gullett, W., Reveley, J., Steele, C., & Schofield, C. (2016). Anchors away? The impacts of anchor scour by ocean-going vessels and potential response options. *Marine Policy*, *73*, 1–7. http://doi.org/10.1016/j.marpol.2016.07.021
18	Debenay, J.-P., Marchand, C., Molnar, N., Aschenbroich, A., & Meziane, T. (2015). Foraminiferal assemblages as bioindicators to assess potential pollution in mangroves used as a natural biofilter for shrimp farm effluents (New Caledonia). *Marine Pollution Bulletin*, *93*(1–2). http://doi.org/10.1016/j.marpolbul.2015.02.009
19	Del-Pilar-Ruso, Y., Martinez-Garcia, E., Giménez-Casalduero, F., Loya-Fernández, A., Ferrero-Vicente, L. M., Marco-Méndez, C., … Sánchez-Lizaso, J. L. (2015). Benthic community recovery from brine impact after the implementation of mitigation measures. *Water Research*, *70*, 325–336. http://doi.org/10.1016/j.watres.2014.11.036
20	Deng, Z. D., Carlson, T. J., Fu, T., Ren, H., Martinez, J. J., Myers, J. R., … Copping, A. E. (2013). Design and implementation of a Marine animal alert system to support Marine renewable energy. *Marine Technology Society Journal*, *47*(4). http://doi.org/10.4031/MTSJ.47.4.2
21	Dolman, S. J., & Jasny, M. (2015). Evolution of marine noise pollution management. *Aquatic Mammals*, *41*(4). http://doi.org/10.1578/AM.41.4.2015.357
22	Erftemeijer, P., & Lewis, R. (2006). Environmental impacts of dredging on seagrasses: a review. *Marine Pollution Bulletin*. Retrieved from http://www.sciencedirect.com/science/article/pii/S0025326X06003778
23	Ferrario, F., Beck, M. W., Storlazzi, C. D., Micheli, F., Shepard, C. C., & Airoldi, L. (2014). The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nature Communications*, *5*. http://doi.org/10.1038/ncomms4794
24	Friess, D. A., Phelps, J., Garmendia, E., & Gómez-Baggethun, E. (2015). Payments for Ecosystem Services (PES) in the face of external biophysical stressors. *Global Environmental Change*, *30*. http://doi.org/10.1016/j.gloenvcha.2014.10.013
25	Frihy, O. (2001). The necessity of environmental impact assessment (EIA) in implementing coastal projects: lessons learned from the Egyptian Mediterranean Coast. *Ocean & Coastal Management*. Retrieved from http://www.sciencedirect.com/science/article/pii/S096456910100062X
26	Frost, T. K., Myrhaug, J. L., Ditlevsen, M. K., & Rye, H. (2014). Environmental monitoring and modeling of drilling discharges at a location with vulnerable seabed fauna: Comparison between field measurements and model simulations. In *Society of Petroleum Engineers - SPE International Conference on Health, Safety and Environment 2014: The Journey Continues* (Vol. 1).

27	Gavrilescu, M., Demnerová, K., Aamand, J., Agathos, S., & Fava, F. (2015). Emerging pollutants in the environment: Present and future challenges in biomonitoring, ecological risks and bioremediation. *New Biotechnology*, *32*(1). http://doi.org/10.1016/j.nbt.2014.01.001
28	Gonçalves, S. C., & Marques, J. C. (2017). Assessement and management of environmental quality conditions in marine sandy beaches for its sustainable use—Virtues of the population based approach. *Ecological Indicators*, *74*, 140–146. http://doi.org/10.1016/j.ecolind.2016.11.024
29	Goodsir, F., Bloomfield, H. J., Judd, A. D., Kral, F., Robinson, L. A., & Knights, A. M. (2015). A spatially resolved pressure-based approach to evaluate combined effects of human activities and management in marine ecosystems. *ICES Journal of Marine Science*, *72*(8). http://doi.org/10.1093/icesjms/fsv080
30	Halpern, B., McLeod, K., & Rosenberg, A. (2008). Managing for cumulative impacts in ecosystem-based management through ocean zoning. *Ocean & Coastal*. Retrieved from http://www.sciencedirect.com/science/article/pii/S0964569107000798
31	Hendrick, V. J., Hutchison, Z. L., & Last, K. S. (2016). Sediment burial intolerance of marine macroinvertebrates. *PLoS ONE*, *11*(2). http://doi.org/10.1371/journal.pone.0149114
32	Hooper, T., & Austen, M. (2013). Tidal barrages in the UK: Ecological and social impacts, potential mitigation, and tools to support barrage planning. *Renewable and Sustainable Energy Reviews*, *23*, 289–298. http://doi.org/10.1016/j.rser.2013.03.001
33	Houser, D. (2006). A method for modeling marine mammal movement and behavior for environmental impact assessment. *IEEE Journal of Oceanic Engineering*. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1645245
34	Idllalène, S., & Van Cauwenbergh, N. (2016). Improving legal grounds to reduce vulnerability to coastal flooding in Morocco – A plea for an integrated approach to adaptation and mitigation. *Ocean & Coastal Management*, *120*, 189–197. http://doi.org/10.1016/j.ocecoaman.2015.11.012
35	Islam, T., Ryan, J., Islam, T., & Ryan, J. (2016). Chapter 9 – Mitigation Strategies for Natural Hazards. In *Hazard Mitigation in Emergency Management* (pp. 275–314). http://doi.org/10.1016/B978-0-12-420134-7.00009-6
36	Jefferson, T., Hung, S., & Würsig, B. (2009). Protecting small cetaceans from coastal development: Impact assessment and mitigation experience in Hong Kong. *Marine Policy*. Retrieved from http://www.sciencedirect.com/science/article/pii/S0308597X08001255
37	Kirby, M., & Law, R. (2010). Accidental spills at sea–Risk, impact, mitigation and the need for co-ordinated post-incident monitoring. *Marine Pollution Bulletin*. Retrieved from http://www.sciencedirect.com/science/article/pii/S0025326X10001050
38	Knights, A. M., Piet, G. J., Jongbloed, R. H., Tamis, J. E., White, L., Akoglu, E., … Robinson, L. A. (2015). An exposure-effect approach for evaluating ecosystem-wide risks from human activities. *ICES Journal of Marine Science*, *72*(3). http://doi.org/10.1093/icesjms/fsu245
39	Kostow, K. (2009). Factors that contribute to the ecological risks of salmon and steelhead hatchery programs and some mitigating strategies. *Reviews in Fish Biology and Fisheries*. Retrieved from http://link.springer.com/article/10.1007/s11160-008-9087-9
40	Kyriazi, Z., Lejano, R., Maes, F., & Degraer, S. (2015). Bargaining a net gain compensation agreement between a marine renewable energy developer and a marine protected area manager. *Marine Policy*, *60*. http://doi.org/10.1016/j.marpol.2015.06.005
41	Lofrano, G., Libralato, G., Minetto, D., de Gisi, S., Todaro, F., Conte, B., … Notarnicola, M. (2016). In situ remediation of contaminated marinesediment: an overview. *Environmental Science and Pollution Research*. http://doi.org/10.1007/s11356-016-8281-x
42	Ludwig, S., Kreimeyer, R., & Knoll, M. (2016). *Comparison of PAM systems for acoustic monitoring and further risk mitigation application*. *Advances in Experimental Medicine and Biology* (Vol. 875). http://doi.org/10.1007/978-1-4939-2981-8_79
43	Luo, S., Cai, F., Liu, H., Lei, G., Qi, H., & Su, X. (2015). Adaptive measures adopted for risk reduction of coastal erosion in the People's Republic of China. *Ocean and Coastal Management*, *103*. http://doi.org/10.1016/j.ocecoaman.2014.08.008
44	Mahmood, K. (1987). Reservoir sedimentation: impact, extent, and mitigation. Technical paper. Retrieved from http://www.osti.gov/scitech/biblio/5564758
45	Marsooli, R., Orton, P. M., Georgas, N., & Blumberg, A. F. (2016). Three-dimensional hydrodynamic modeling of coastal flood mitigation by wetlands. *Coastal Engineering*, *111*, 83–94. http://doi.org/10.1016/j.coastaleng.2016.01.012
46	Mayo-Ramsay, J. (2010). Environmental, legal and social implications of ocean urea fertilization: Sulu sea example. *Marine Policy*, *34*(5), 831–835. http://doi.org/10.1016/j.marpol.2010.01.004
47	Moshtagh, B., & Hawboldt, K. (2015). Production of biodispersants for oil spill remediation in Harsh environment using glycerol from the conversion of fish oil to biodiesel. In *2014 Oceans - St. John's, OCEANS 2014*. http://doi.org/10.1109/OCEANS.2014.7003019
48	Murray, A., & Peeler, E. (2005). A framework for understanding the potential for emerging diseases in aquaculture. *Preventive Veterinary Medicine*. Retrieved from http://www.sciencedirect.com/science/article/pii/S0167587704002120
49	Pei, W., Zhu, Y. Y., Zeng, L., Liu, S. X., Wang, X. J., & An, Z. J. (2013). *The remote sensing identification of marine oil spill based on oil fingerprinting*. *Communications in Computer and Information Science* (Vol. 398 PART I). http://doi.org/10.1007/978-3-642-45025-9_74
50	Petersen, J., & Malm, T. (2006). Offshore windmill farms: threats to or possibilities for the marine environment. *AMBIO: A Journal of the Human Environment*. Retrieved from http://www.bioone.org/doi/abs/10.1579/0044-7447(2006)35[75:OWFTTO]2.0.CO;2
51	Peterson, C., & Bishop, M. (2005). Assessing the environmental impacts of beach nourishment. *Bioscience*. Retrieved from http://bioscience.oxfordjournals.org/content/55/10/887.short
52	Poustie, M. S., Brown, R. R., & Deletic, A. (2014). Receptivity to sustainable urban water management in the South West Pacific. *Journal of Water and Climate Change*, *5*(2). http://doi.org/10.2166/wcc.2013.242
53	Price, C., Black, K. D., Hargrave, B. T., & Morris, J. A. (2014). Marine cage culture and the environment: Effects on water quality and primary production. *Aquaculture Environment Interactions*, *6*(2). http://doi.org/10.3354/aei00122

54	Ruckelshaus, M., Doney, S. C., Galindo, H. M., Barry, J. P., Chan, F., Duffy, J. E., … Talley, L. D. (2013). Securing ocean benefits for society in the face of climate change. *Marine Policy*, *40*(1). http://doi.org/10.1016/j.marpol.2013.01.009
55	Saussaye, L., Hamdoun, H., Leleyter, L., van Veen, E., Coggan, J., Rollinson, G., … Baraud, F. (2016). Trace element mobility in a polluted marine sediment after stabilisation with hydraulic binders. *Marine Pollution Bulletin*, *110*(1). http://doi.org/10.1016/j.marpolbul.2016.06.035
56	Schramm, M. P., Bevelhimer, M. S., & DeRolph, C. R. (2016). A synthesis of environmental and recreational mitigation requirements at hydropower projects in the United States. *Environmental Science & Policy*, *61*, 87–96. http://doi.org/10.1016/j.envsci.2016.03.019
57	Schulz, R. (2004). Field studies on exposure, effects, and risk mitigation of aquatic nonpoint-source insecticide pollution. *Journal of Environmental Quality*. Retrieved from https://dl.sciencesocieties.org/publications/jeq/articles/33/2/419?highlight=&search-result=1
58	Sheavly, S., & Register, K. (2007). Marine debris & plastics: environmental concerns, sources, impacts and solutions. *Journal of Polymers and the Environment*. Retrieved from http://link.springer.com/article/10.1007/s10924-007-0074-3
59	Soomere, T., Delpeche-Ellmann, N. C., Torsvik, T., & Viikmäe, B. (2015). *Towards a new generation of techniques for the environmental management of maritime activities*. *Environmental Security of the European Cross-Border Energy Supply Infrastructure*. http://doi.org/10.1007/978-94-017-9538-8_8
60	Srinivas, H., & Nakagawa, Y. (2008). Environmental implications for disaster preparedness: lessons learnt from the Indian Ocean Tsunami. *Journal of Environmental Management*. Retrieved from http://www.sciencedirect.com/science/article/pii/S0301479707001430
61	Stigner, M. G., Beyer, H. L., Klein, C. J., Fuller, R. A., & Carvalho, S. (2016). Reconciling recreational use and conservation values in a coastal protected area. *Journal of Applied Ecology*, *53*(4). http://doi.org/10.1111/1365-2664.12662
62	Suzdalev, S., Gulbinskas, S., Sivkov, V., & Bukanova, T. (2014). Solutions for effective oil spill management in the south-eastern part of the Baltic sea. *Baltica*, *27*. http://doi.org/10.5200/baltica.2014.27.09
63	Tallis, H., Kennedy, C. M., Ruckelshaus, M., Goldstein, J., & Kiesecker, J. M. (2015). Mitigation for one & all: An integrated framework for mitigation of development impacts on biodiversity and ecosystem services. *Environmental Impact Assessment Review*, *55*, 21–34. http://doi.org/10.1016/j.eiar.2015.06.005
64	Teichert, N., Borja, A., Chust, G., Uriarte, A., & Lepage, M. (2016). Restoring fish ecological quality in estuaries: Implication of interactive and cumulative effects among anthropogenic stressors. *Science of the Total Environment*, *542*. http://doi.org/10.1016/j.scitotenv.2015.10.068
65	Thomas, I. A., Jordan, P., Mellander, P.-E., Fenton, O., Shine, O., Ó hUallacháin, D., … Murphy, P. N. C. (2016). Improving the identification of hydrologically sensitive areas using LiDAR DEMs for the delineation and mitigation of critical source areas of diffuse pollution. *Science of The Total Environment*, *556*, 276–290. http://doi.org/10.1016/j.scitotenv.2016.02.183
66	Torres, L. G., Smith, T. D., Sutton, P., Macdiarmid, A., Bannister, J., & Miyashita, T. (2013). From exploitation to conservation: Habitat models using whaling data predict distribution patterns and threat exposure of an endangered whale. *Diversity and Distributions*, *19*(9). http://doi.org/10.1111/ddi.12069
67	Touili, N., Baztan, J., Vanderlinden, J.-P., Kane, I. O., Diaz-Simal, P., & Pietrantoni, L. (2014). Public perception of engineering-based coastal flooding and erosion risk mitigation options: Lessons from three European coastal settings. *Coastal Engineering*, *87*, 205–209. http://doi.org/10.1016/j.coastaleng.2014.01.004
68	Tri, N., Adger, W., & Kelly, P. (1998). Natural resource management in mitigating climate impacts: the example of mangrove restoration in Vietnam. *Global Environmental Change*. Retrieved from http://www.sciencedirect.com/science/article/pii/S095937809700023X
69	Verfuss, U. K., Sparling, C. E., Arnot, C., Judd, A., & Coyle, M. (2016). *Review of offshore wind farm impact monitoring and mitigation with regard to marine mammals*. *Advances in Experimental Medicine and Biology* (Vol. 875). http://doi.org/10.1007/978-1-4939-2981-8_147
70	Waggitt, J. J., Cazenave, P. W., Torres, R., Williamson, B. J., & Scott, B. E. (2016). Predictable hydrodynamic conditions explain temporal variations in the density of benthic foraging seabirds in a tidal stream environment. *ICES Journal of Marine Science*, *73*(10). http://doi.org/10.1093/icesjms/fsw100
71	Weber, T. C., & Allen, W. L. (2010). Beyond on-site mitigation: An integrated, multi-scale approach to environmental mitigation and stewardship for transportation projects. *Landscape and Urban Planning*, *96*(4), 240–256. http://doi.org/10.1016/j.landurbplan.2010.04.003
72	Weilgart, L. (2007). The impacts of anthropogenic ocean noise on cetaceans and implications for management. *Canadian Journal of Zoology*. Retrieved from http://www.nrcresearchpress.com/doi/abs/10.1139/z07-101
73	Wilson, J., & Elliott, M. (2009). The habitat-creation potential of offshore wind farms. *Wind Energy*. Retrieved from http://onlinelibrary.wiley.com/doi/10.1002/we.324/full
74	Yáñez-Arancibia, A., Day, J. W., & Reyes, E. (2013). Understanding the coastal ecosystem-based management approach in the gulf of Mexico. *Journal of Coastal Research*, *63*(SPL.ISSUE). http://doi.org/10.2112/SI63-018.1
75	Yates, K. L., Schoeman, D. S., & Klein, C. J. (2015). Ocean zoning for conservation, fisheries and marine renewable energy: Assessing trade-offs and co-location opportunities. *Journal of Environmental Management*, *152*. http://doi.org/10.1016/j.jenvman.2015.01.045
76	Zanuttigh, B., Angelelli, E., Bellotti, G., Romano, A., Krontira, Y., Troianos, D., … Broszeit, S. (2015). Boosting blue growth in a mild sea: Analysis of the synergies produced by a multi-purpose offshore installation in the Northern Adriatic, Italy. *Sustainability (Switzerland)*, *7*(6). http://doi.org/10.3390/su7066804
77	Zuliani, T., Mladenovič, A., Ščančar, J., & Milačič, R. (2016). Chemical characterisation of dredged sediments in relation to their potential use in civil engineering. *Environmental Monitoring and Assessment*, *188*(4). http://doi.org/10.1007/s10661-016-5239-x

Appendix 8: International Conference on Coastal Engineering (ICCE) Poster

Addressing the Environmental Impacts of Tidal Lagoons

Scan to my profile

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Introduction

What are tidal lagoons?

Tidal lagoons harness the energy available in the rise and fall of the tides, by impounding water behind a walled structure. Typically tidal range energy consists of either tidal barrages or tidal lagoons. A tidal barrage extends the banks of a river or estuary, whilst a tidal lagoon forms a loop attached to one side of an estuary or is completely offshore. See sketch **Figure 1**.

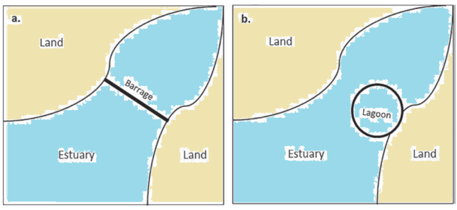


Figure 1: Basic sketch of the difference between tidal barrage (a) and tidal lagoon (b)

Why are we considering lagoons?

Tidal lagoons have the potential to contribute significantly to the global energy mix. They would provide a large source of renewable, predictable, continuous, base load supply of energy for 120 years. Recent proposals have suggested multi-benefit facilities that would provide environmental, social and economic benefits to the areas in which they are developed. They are often presented as environmentally friendly options compared to barrages, this does not mean their environmental impacts can be overlooked
.

Poster Objectives

The main reasons for lack of development of tidal lagoons to date have been high capital cost and regulatory environmental concerns. Further research is required on the key environmental impacts of lagoons and the expected 'cost' of their mitigation. The poster has the following objectives:

1. **Identify the key environmental impacts of tidal lagoons**
2. **Investigate solutions to those key environmental impacts**
3. **Consider ways in which solutions can be valued and compared**

1. What are the key impacts? (-/+)

Extensive industry engagement with both influential organisations (regulators) and tidal range project developers (developers) allowed the industry perspective on the most significant environmental impacts to be identified. The key negative environmental impacts are detailed in Figure 2. Both regulators and developers agree that '**Sediment Regime Changes**' and '**Changing hydrodynamics**' are key concerns.

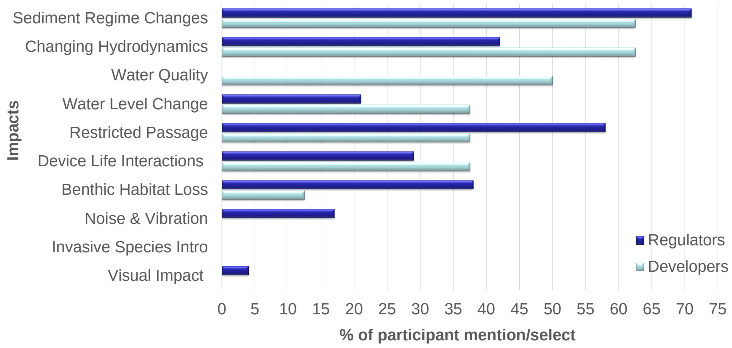


Figure 2 % participant selection of key environmental impacts when asked: "what are the most significant environmental impacts of tidal lagoons likely to be?"

Tidal lagoons have the potential to offer significant benefits to society, the wider environment and local economy, perhaps more so than any other large scale energy development. These benefits are often overlooked. The industry engagement asked developers what they believed to be the most beneficial impacts of lagoons to be, See Table 1. Developers focused mainly around '**Area Regeneration**', **'Local Economy Boost**' and **'Local Employment**' whereas regulators were more interested in **'Flood Defense', 'Habitat biodiversity** and '**Leisure and Recreation'.**

Table 1 : Benefits identified by participants when asked "what do you believe the most significant beneficial impacts of lagoons will be?"

Benefits	% mention Regulators	% mention Developers	Δ Diff
Area Regeneration & Socio Economic Benefits	6	14	8
Coastal Erosion Protection	8	4	4
Community Share	2	4	2
Education & Research	5	7	2
Energy Base Load	3	4	1
Export Opportunities	3	4	1
Flood Defence & Control	16	9	7
Habitat Biodiversity	14	6	8
Leisure & Recreation	13	4	9
Local Economy Boost	3	9	6
Local Employment	3	11	8
Multiple Use	6	6	0
Renewable Energy Acceptance	6	0	6
Supply Chain	3	5	2
Tourism	6	7	1
Transport & Connectivity	0	5	5
UK Image	3	2	1

2. Are there solution options available?

Systematic literature review following the PRISMA guidelines was undertaken on 1114 documents to determine what transferable solution options from other industries could be applied to the key environmental impacts of tidal lagoons. Figure 3 below shows the global spread of expertise on the documented solutions found. Figure 4 shows what impacts the solutions are addressing and Table 2 how developed and applicable these are to lagoon application. A database of potential solutions was created as a result of the study including 77 relevant solution options. Over half of these are thought to be relevant and adaptable to lagoon application in the future (Figure 5 outlined Black Box)

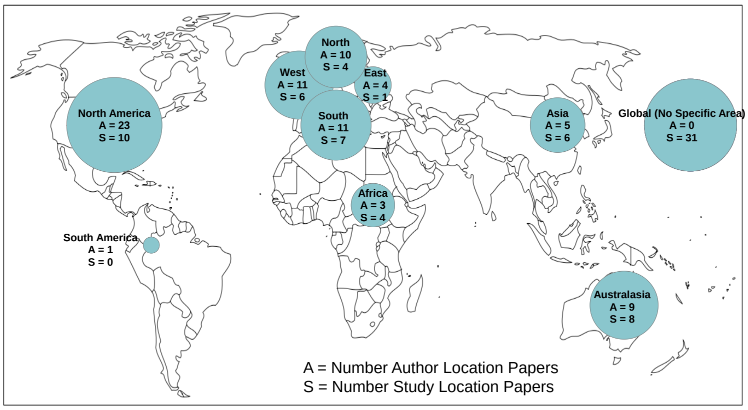
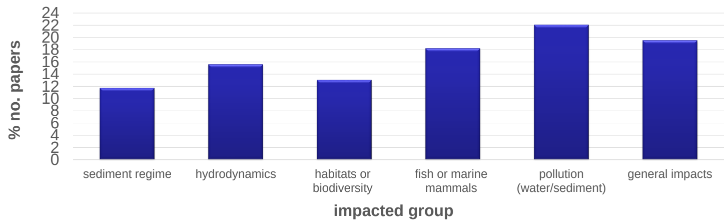


Figure 3 Number of papers per author affiliation location (A) and study area location (S). 31 papers of 77 (40%) had no **specific** area of study.



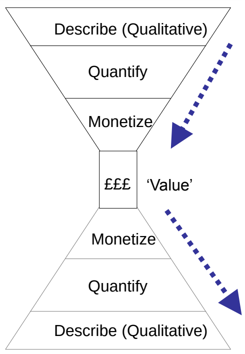
Solutions Matrix		Theoretical →				Applied
		1	2	3	4	5
Other Industry	1	0	2	0	1	0
↓	2	1	4	7	6	3
	3	2	2	7	8	5
	4	2	6	5	5	6
Lagoon Specific	5	0	0	2	2	1
					Total	77

Figure 4 (ABOVE): The key impacts addressed with the solutions found.

Table 2 (ADJACENT): Matrix of solution options in terms of their development to applied scale (1 to 5, 5= fully applied, 1=Theoretical) and adaption to be lagoon specific (1=Other Industry, 5=Lagoon or Barrage specific). Graded Colour Scale: No.Papers ≤2 Light Greens, 3-5 Medium Green, ≥5, Bright Greens.

3. How can solution options be 'valued' for comparison?

- Solutions can be selected using Multi-Criteria Decision Analysis (MCDA), using criteria such as solution cost, likely success, uncertainty, availability, applicability etc.
- Given that lagoons will have multi-use functions that could have social, environmental, and economic impacts a more holistic approach is recommended in the assessment of solution options
.
- Ecosystem Service Assessments (ESA) allow the qualitative information surrounding solutions to be captured and represented and better reflect the multi-disciplinary nature of lagoons.
- Once solutions have been qualitatively analysed, monetary values (£) can be placed on the ecosystem services where relevant and proportionate to do so in an Ecosystem Service Valuation (ESV)
- This 'value' put back into context of the qualitative assessment can be used to compare solution options.



Conclusions

Conclusions in the context of the original objectives:

1. Identify the key environmental impacts of tidal lagoons. Hydrodynamics and sediment regime changes
2. Investigate solutions to those key environmental impacts. There is a valuable resource of multiple solutions within other marine, coastal and river run industries that are relevant and adaptable to lagoon application
3. Consider ways in which solutions can be valued and compared. Solutions can be selected via MCDA, described and quantified in an ESA that will allow the social, environmental and economic multi-benefits of lagoons to be captured. A net present value can then be obtained through an ESV and used to compare solution options.

[1] K. Mackinnon, H.C.. Smith, F. Moore, Optimising Tidal Lagoons: Environmental Interactions, 2016. https://energyhub.theiet.org/users/56863-kathryn-mackinnon/posts/18658-tidal-lagoon-environmental-interactions-regulator-perspective-solution-options-and-industry-challenges.
[2] K. Mackinnon, H.C.M. Smith, F. Moore, A.H. van der Weijde, I. Lazakis, Environmental interactions of tidal lagoons: A comparison of industry perspectives, Renew. Energy. 119 (2018) 309–319. doi:10.1016/J.RENENE.2017.11.066.
[3] K. Mackinnon, H. Smith, F. Moore, I. Lazakis, H. Adrian, A systematic review of transferable solution options for the environmental impacts of tidal lagoons, Mar. Policy. Under review (2018).

International Conference on Coastal Engineering (ICCE) – Baltimore, Maryland – July 30th – August 03rd 2018

Appendix 9: ICCE Extended Abstract

A SOLUTIONS APPRAISAL TOOL TO ADDRESS THE ENVIRONMENTAL IMPACTS OF TIDAL LAGOONS

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1. EXTENDED ABSTRACT

The deployment of renewable energy is regarded as a strategy to combat climate change. There have been a number of global agreements aiming to mitigate climate change, the most recent of which was the 2015 Paris Agreement. Often overlooked is the vast amount of marine renewable energy available around the world's coastlines. In particular tidal range energy is a largely untapped resource which has benefits including reduced uncertainty through use of proven technology, a high level of predictability [1], the ability to phase shift energy to provide base load supply [2] and a long expected life span (100 years) [3]. The key barriers to development of tidal range energy have been environmental concerns and high capital cost [4], [5].

Tidal lagoons are often presented as environmentally friendly alternatives to tidal barrages [5], but this does not mean their environmental impacts can be overlooked. Recent developments in the UK lagoon industry such as the awarding of a Development Consent Order to Swansea Bay tidal lagoon [6], mean it is now more important than ever to consider the environmental impacts of tidal lagoons and what solutions are available to address them. This is challenging considering there are no operational tidal lagoons in the world yet. This study aims to:

1. Identify the key impacts through industry engagement
2. Find available solutions through systematic review
3. Select and analyze solutions using Multi Criteria Decision Analysis (MCDA), Cost Benefit Analysis (CBA) and Ecosystem Service Valuation (ESV).

1.1 What are the key impacts and benefits of tidal lagoons?

Extensive industry engagement with the UK tidal lagoon industry highlighted a number of key environmental impacts and benefits arising as a result of tidal lagoon deployment. This engagement included an online questionnaire to influential individuals in decision making roles within 21 different government, conservation, regulatory and practitioner organizations. In addition to this, semi-structured interviews were conducted with developers active in the lagoon industry, in which a total of eight developers participated. Using percentage mention, impact scoring and multiple choice selection along with coding of open ended questions and interview transcripts, the perspective of the UK tidal lagoon industry was outlined. The key environmental impacts of lagoons according to industry opinion are 'sediment regime alterations' and 'hydrodynamic changes', with key benefits including 'flood defense and control', 'leisure and recreation' and 'area regeneration'. More information on the methodology and results of this engagement can be found in reference 7. In addition, further information on categorization of impacts and a framework on the environmental impacts of tidal lagoons can be seen in reference 8.

1.2 What solutions are there to address the key impacts?

There are currently no man-made, energy generating, tidal lagoons in the world and as such there are no blueprint guidelines on solutions to address their environmental impacts. However, there is a vast quantity of literature available from other industries addressing similar impacts in the coastal, ocean and river environments.

A systematic review following the PRISMA (Preferred Reporting Items for Systematic Meta-Analysis) and Collaboration on Environmental Evidence Guidance was conducted. The purpose of this review was to investigate the extent and relevance of the existing research on solutions options which could be applied to address the environmental impacts likely to arise as a result of tidal lagoons.

An initial search uncovered a total of 1114 papers, 688 papers after duplicates removed, 129 papers after abstract screening and 77 papers after full text screening. The 77 papers included in final analysis included viable solution options, over half of which require only small shifts in their development stage or adaption to lagoon application to be realistic options for implementation in the future tidal lagoon industry [9].

1.3 How can solutions be selected and analyzed?

The key outcomes of the authors' previous research include a database of environmental impacts likely to arise as a result of tidal lagoons and a database of solution options. This inventory of information is only useful if it can analysed and applied so the next stage is to determine ways of selecting and analyzing different solution options.

In order to select combinations of solution options to be analysed a MCDA was used, this included criteria on: solution cost, solution stage of development, relevance to tidal lagoons, expected solution success, number of direct and indirect impacts it addresses and level of uncertainty. Using this method a combination of solution options were selected, with one solution for each key environmental impact. These solutions were then analyzed in terms of the wider environmental implications using a cost benefit analysis and ecosystem service assessment and valuation. Using guidance from the Green Book [10], solution combinations were assessed in terms of how their deployment would change the wider ecosystem service provision of tidal lagoons. This was compared to a baseline scenario of a lagoon with no environmental solution options implemented.

1.4 Conclusion

In conclusion the research aims to further the tidal lagoon industry into deployment by highlighting the key environmental impacts likely to arise, the potential extent and relevance of existing transferable solutions and how these can be selected and analysed. Figure 1 provides a summary of the methodology.

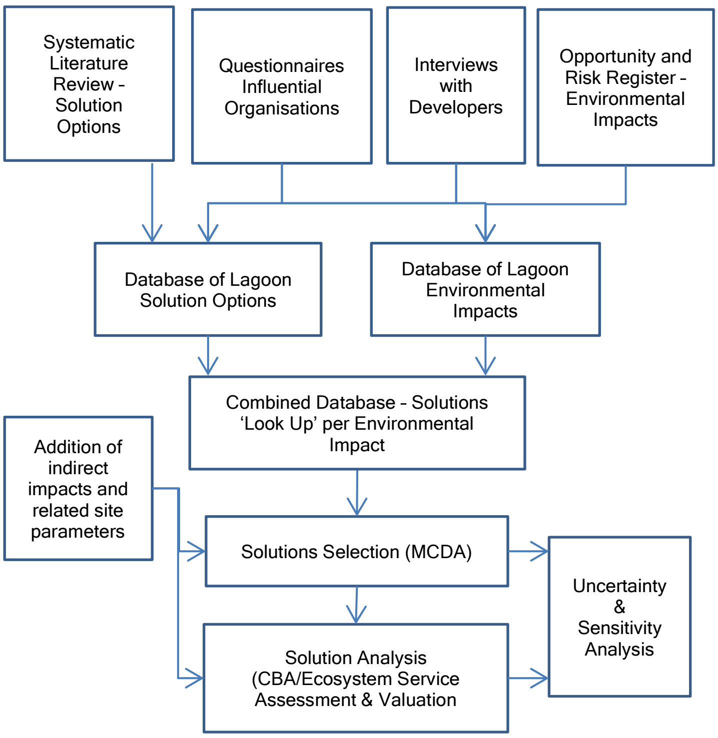

Figure 1 Schematic summary of methodology

References

[1] Tidal Lagoon Power Ltd, "Swansea Bay Lagoon ProjectL Project Benefits," 2015. [Online]. Available: http://www.tidallagoonswanseabay.com/the-project/project-benefits/54/. [Accessed: 29-Sep-2015].

[2] D. Mackay, *Sustainability without the hot air*. UIT Cambridge Ltd, 2009.

[3] Tidal Lagoon Power Ltd, "Tidal Lagoon Power: Key Statistics," 2016. [Online]. Available: http://www.tidallagoonpower.com/about/key-statistics/. [Accessed: 01-Jan-2016].

[4] F. Harvey, "Severn tidal power barrage plans slammed by MPs," *Guardian*, 2013. [Online]. Available: https://www.theguardian.com/business/2013/jun/10/severn-tidal-power-barrage-plans-mps. [Accessed: 19-Apr-2017].

[5] T. Hooper and M. Austen, "Tidal barrages in the UK: Ecological and social impacts, potential mitigation, and tools to support barrage planning," *Renew. Sustain. Energy Rev.*, vol. 23, pp. 289-298, Jul. 2013.

[6] Tidal Lagoon Power Ltd, "Swansea Bay Lagoon Project - Planning," 2015. [Online]. Available: http://www.tidallagoonswanseabay.com/planning/planning-process/61/. [Accessed: 20-Jul-2016].

[7] K. Mackinnon, H. C. M. Smith, F. Moore, A. H. van der Weijde, and I. Lazakis, "Environmental interactions of tidal lagoons: A comparison of industry perspectives," *Renew. Energy*, vol. 119, pp. 309-319, Apr. 2018.

[8] K. Mackinnon, H. C. . Smith, and F. Moore, "Optimising Tidal Lagoons: Environmental Interactions," 2016.

[9] K. Mackinnon, H. Smith, F. Moore, I. Lazakis, and A. H. van der Weijde, "A systematic review of the solution options for the environmental impacts of tidal lagoons," *Environ. Sci. Policy*, vol. (under rev, 2018.

[10] H.M treasury, "The Green Book: Appraisal and Evaluation in Central Government," no. July, pp. 57-58, 2011.

Appendix 10: ESA and ESV Research, Reference Map

Ecosystem Service Influenced		Baseline Benefit or Cost	Baseline (no solutions implemented)	Change as a result of - Group A						
				Flushing or sluicing	Dredging and utilising	Use of spatial zonation	Relocation or re-routed movement of vessels - traffic impact	Turbine selection with fish and marine mammals in mind	Use of temporal zonation	Scenario 1 OVERALL
Provisioning	1. Food a (aquaculture)	Benefit	Aquaculture production (++)			24,26,15,31,33			26,15,31, **38**	,,24,26,15,31,33,,,26,15,31, 38
	1b. Food (fish)	Benefit	Fish (++)							**39, 40, 60**
	2. Energy Generation	Benefit	Tidal Energy (++) - hindered by sediment, impact on fish and marine mammals etc	25,31,32,37	23,25,28,29,34,35,37			30, 43	26,15,31, **41, 42**	25,31,32,37,23,25,28,29,34,35,37,,,30, 43,26,15,31, 41, 42
Regulating	3. Air quality	Benefit	Displacement of fossil fuel PM10 (++)	25,31,32	23,25,28,29,34,35			30	26,15,31,**44,45,46, 47**	25,31,32,23,25,28,29,34,35,,,30,26,15, 31,44,45,46,47
	4. Climate change regulation emissions	Benefit	Displacement of fossil fuel CO2e (++)	25,31,32	23,25,28,29,34,35			30	26,15,31, **48, 49**	25,31,32,23,25,28,29,34,35,,,30,26,15, 31, 48, 49
	5. Climate change regulation sequestration	Cost	Overall habitat loss-hydrodynamic changes (--)	25,31,32	23,25,28,29,34,35	24,26,15,31,33	27		26,15,31, **50,51**	25,31,32,23,25,28,29,34,35,24,26,15,31,33,27,,26,15,31, 50,51
	6. Water regulation	Cost	Hydodynamic changes impact (--)	25,31,32	23,25,28,29,34,35					25,31,32,23,25,28,29,34,35,,,,
	7. Erosion/Sediment Control	Cost	Sediment regime changes (--)	25,31,32	23,25,28,29,34,35				**37, 52**	25,31,32,23,25,28,29,34,35,,,,37, 52
	8. Water purification	Cost	Potential pollution (-)	25,31,32	23,25,28,29,34,35	24,26,15,31,33	27			25,31,32,23,25,28,29,34,35,24,26,15,31,33,27,,
	9. Natural hazard protection (Flood Risk)	Benefit	Flood risk protection (++)	25,31,32	23,25,28,29,34,35				**53**	25,31,32,23,25,28,29,34,35,,,,53
Cultural Services	10. Social relations	Benefit	Boost of recreation societies (++)	25,31,32	23,25,28,29,34,35	24,26,15,31,33	27	30	26,15,31	25,31,32,23,25,28,29,34,35,24,26,15,31,33,27,30,26,15,31
	11. Asthetic values	Cost	Mostly negative (--)		23,25,28,29,34,35		27			,23,25,28,29,34,35,,27,,
	12. Cultural heritage values	Cost	Fish impact, pollution impact- fishing industry (--)			24,26,15,31,33	27	30		,,24,26,15,31,33,27,30,
	13. Recreation/ecotourism	Benefit	Tourism & recreation, marine mammal impact (++)			24,26,15,31,33	27		26,15,31, **54.55**	,,24,26,15,31,33,27,,26,15,31, 54.55
	134. Health benefits	Benefit	Increased pathways, increased swimming (++)			24,26,15,31,33	27		**56,57,58**	,,24,26,15,31,33,27,,56,57,58
	16. Heritage & Archeaology	Cost	Sediment regime changes (--)		23,25,28,29,34,35					,23,25,28,29,34,35,,,,

Ecosystem Service Influenced		Baseline Benefit or Cost	Baseline (no solutions implemented)	Change as a result of - Group B						
				Use of Geoindicators (sediment changes)	Ecosystem restoration to protect coastlines from erosion	Urea Fertilisation	Site selection close to natural water purification areas e.g. wetlands	Catchment land selection to reduce run off pollution	Keystone species and blue corridors	Scenario 2 OVERALL
Provisioning	**1. Food a (aquaculture)**	Benefit	Aquaculture production (++)			1,2,3 ,36		20,25		,,1,2,3 ,36,,20,25,
	1b. Food (fish)	Benefit	Fish (++)							60
	2. Energy Generation	Benefit	Tidal Energy (++) - hindered by sediment, impact on fish and marine mammals etc				18,19,21,22	20,25		,,,18,19,21,22,20,25,
Regulating	**3. Air quality**	Benefit	Displacement of fossil fuel PM10 (++)				18,19,21,22	20,25		,,,18,19,21,22,20,25,
	4. Climate change regulation emissions	Benefit	Displacement of fossil fuel CO2e (++)				18,19,21,22	20,25		,,,18,19,21,22,20,25,
	5. Climate change regulation sequestration	Cost	Overall habitat loss-hydrodynamic changes (--)		8,9,10,11,12,14,15,16	1,2,3				,8,9,10,11,12,14,15,16,1,2,3 ,,,
	6. Water regulation	Cost	Hydodynamic changes impact (--)					20,25		,,,,20,25,
	7. Erosion/Sediment Control	Cost	Sediment regime changes (--)	4,5,6,7,13,17	8,9,10,11,12,14,15,16		18,19,21,22			4,5,6,7,13,17,8,9,10,11,12,14,15,16,,18,19,21,22,,
	8. Water purification	Cost	Potential pollution (-)			1,2,3	18,19,21,22	20,25		,,1,2,3 ,18,19,21,22,20,25,
	9. Natural hazard protection (Flood Risk)	Benefit	Flood risk protection (++)		8,9,10,11,12,14,15,16		18,19,21,22			,8,9,10,11,12,14,15,16,,18,19,21,22,,
Cultural Services	**10. Social relations**	Benefit	Boost of recreation societies (++)			1,2,3		20,25		,,1,2,3 ,,20,25,
	11. Asthetic values	Cost	Mostly negative (--)			1,2,3		20,25		,, 1,2,3 ,,20,25,
	12. Cultural heritage values	Cost	Fish impact, pollution impact- fishing industry (--)			1,2,3	18,19,21,22	20,25	14	,,1,2,3 ,18,19,21,22,20,25,14
	13. Recreation/ecotourism	Benefit	Tourism & recreation, marine mammal impact (++)			1,2,3		20,25	14	,,1,2,3 ,,20,25,14
	134. Health benefits	Benefit	Increased pathways, increased swimming (++)					20,25		,,,,20,25,
	16. Heritage & Archeaology	Cost	Sediment regime changes (--)	4,5,6,7,13,17						4,5,6,7,13,17,,,,,,
Actual Cost	**17. Solution CAPEX**	Cost	Zero	4,5,6,7,13,17	8,9,10,11,12,14,15,16	1,2,3	18,19,21,22	20,25	14	4,5,6,7,13,17,8,9,10,11,12,14,15,16,1,2,3 ,18,19,21,22,20,25,14
	18. Solution OPEX	Cost	Zero	4,5,6,7,13,17		1,2,3				4,5,6,7,13,17,,1,2,3 ,,,

Ref 1	Mayo-Ramsay, J. (2010). Environmental, legal and social implications of ocean urea fertilization: Sulu sea example. *Marine Policy*, *34*(5), 831–835. http://doi.org/10.1016/j.marpol.2010.01.004
Ref 2	Williamson P, Wallace D, Law C, Boyd P, Collos Y, Croot P, et al. Ocean fertilization for geoengineering: A Review of effectiveness, environmental impacts and emerging governance. Proccess Saf Environ Prot [Internet]. 2012;90(6):475–88. Available from: http://www.homepages.ed.ac.uk/shs/Hurricanes/Ocean fertilization for geoengineering A review of effectiveness, environmental impacts and emerging governance.htm?np=y
Ref 3	Glibert PM, Azanza R, Burford M, Furuya K, Abal E, Al-Azri A, et al. Ocean urea fertilization for carbon credits poses high ecological risks. Mar Pollut Bull [Internet]. 2008 [cited 2017 Sep 8];56:1049–56. Available from: http://www.whoi.edu/fileserver.do?id=45403&pt=2&p=28251
Ref 4	Bush D, Neal W, Young R, Pilkey O. Utilization of geoindicators for rapid assessment of coastal-hazard risk and mitigation. Ocean Coast Manag [Internet]. 1999 [cited 2017 Jan 18]; Available from: http://www.sciencedirect.com/science/article/pii/S0964569199000277
Ref 5	Berger AR. Assessing rapid environmental change using geoindicators. Environ Geol [Internet]. 1997 Jul 28 [cited 2017 Sep 8];32(1):36–44. Available from: http://link.springer.com/10.1007/s002540050191
Ref 6	Souza PE, Nicolodi JL, Souza PE, Nicolodi JL. Coastal Vulnerability Assessment using geoindicators: case study of Rio Grande do Sul coastline. Brazilian J Oceanogr [Internet]. 2016 Sep [cited 2017 Sep 8];64(3):309–22. Available from: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1679-87592016000300309&lng=en&tlng=en
Ref 7	Queiroz De Lima E, Farias Do Amaral R. Use of geoindicators in vulnerability mapping for the coastal erosion of a sandy beach. J Integr Coast Zo Manag [Internet]. 2015 [cited 2017 Sep 14];15(4):545–57. Available from: http://www.aprh.pt/rgci/pdf/rgci-502_Lima.pdf
Ref 8	Ruckelshaus M, Doney SC, Galindo HM, Barry JP, Chan F, Duffy JE, et al. Securing ocean benefits for society in the face of climate change. Mar Policy. 2013;40(1).
Ref 9	Yáñez-Arancibia A, Day JW, Reyes E. Understanding the coastal ecosystem-based management approach in the gulf of Mexico. J Coast Res. 2013;63(SPL.ISSUE).
Ref 10	Marsooli R, Orton PM, Georgas N, Blumberg AF. Three-dimensional hydrodynamic modeling of coastal flood mitigation by wetlands. Coast Eng. 2016;111:83–94.
Ref 11	Tri N, Adger W, Kelly P. Natural resource management in mitigating climate impacts: the example of mangrove restoration in Vietnam. Glob Environ Chang [Internet]. 1998 [cited 2017 Jan 18]; Available from: http://www.sciencedirect.com/science/article/pii/S095937809700023X
Ref 12	Srinivas H, Nakagawa Y. Environmental implications for disaster preparedness: lessons learnt from the Indian Ocean Tsunami. J Environ Manage [Internet]. 2008 [cited 2017 Jan 18]; Available from: http://www.sciencedirect.com/science/article/pii/S0301479707001430
Ref 13	Burgass MJ, Halpern BS, Nicholson E, Milner-Gulland EJ. Navigating uncertainty in environmental composite indicators. Ecol Indic. 2017;75:268–78.
Ref 14	Weber TC, Allen WL. Beyond on-site mitigation: An integrated, multi-scale approach to environmental mitigation and stewardship for transportation projects. Landsc Urban Plan. 2010;96(4):240–56.
Ref 15	Islam T, Ryan J, Islam T, Ryan J. Chapter 9 – Mitigation Strategies for Natural Hazards. In: Hazard Mitigation in Emergency Management. 2016. p. 275–314.
Ref 16	Luo S, Cai F, Liu H, Lei G, Qi H, Su X. Adaptive measures adopted for risk reduction of coastal erosion in the People's Republic of China. Ocean Coast Manag. 2015;103.
Ref 17	Gonçalves SC, Marques JC. Assessement and management of environmental quality conditions in marine sandy beaches for its sustainable use—Virtues of the population based approach. Ecol Indic. 2017;74:140–6.
Ref 18	Carrillo-Guerrero YK, Flessa K, Hinojosa-Huerta O, López-Hoffman L. From accident to management: The Cienega de Santa Clara ecosystem. Ecol Eng. 2013;59.
Ref 19	Debenay J-P, Marchand C, Molnar N, Aschenbroich A, Meziane T. Foraminiferal assemblages as bioindicators to assess potential pollution in mangroves used as a natural biofilter for shrimp farm effluents (New Caledonia). Mar Pollut Bull. 2015;93(1–2).
Ref 20	Dabrowski J, Peall S, Reinecke A. Runoff-related pesticide input into the Lourens River, South Africa: basic data for exposure assessment and risk mitigation at the catchment scale. Water, Air, Soil [Internet]. 2002 [cited 2017 Jan 16]; Available from: http://link.springer.com/article/10.1023/A:1014705931212
Ref 21	Schulz R. Field studies on exposure, effects, and risk mitigation of aquatic nonpoint-source insecticide pollution. J Environ Qual [Internet]. 2004 [cited 2017 Jan 16]; Available from: https://dl.sciencesocieties.org/publications/jeq/articles/33/2/419?highlight=&search-result=1
Ref 22	Knights AM, Piet GJ, Jongbloed RH, Tamis JE, White L, Akoglu E, et al. An exposure-effect approach for evaluating ecosystem-wide risks from human activities. ICES J Mar Sci. 2015;72(3).
Ref 23	Peterson C, Bishop M. Assessing the environmental impacts of beach nourishment. Bioscience [Internet]. 2005 [cited 2017 Jan 18]; Available from: http://bioscience.oxfordjournals.org/content/55/10/887.short

Ref 24	Weilgart L. The impacts of anthropogenic ocean noise on cetaceans and implications for management. Can J Zool [Internet]. 2007 [cited 2017 Jan 18]; Available from: http://www.nrcresearchpress.com/doi/abs/10.1139/z07-101
Ref 25	Mahmood K. Reservoir sedimentation: impact, extent, and mitigation. Technical paper. 1987 [cited 2017 Jan 18]; Available from: http://www.osti.gov/scitech/biblio/5564758
Ref 26	Yates KL, Schoeman DS, Klein CJ. Ocean zoning for conservation, fisheries and marine renewable energy: Assessing trade-offs and co-location opportunities. J Environ Manage. 2015;152.
Ref 27	Soomere T, Delpeche-Ellmann NC, Torsvik T, Viikmäe B. Towards a new generation of techniques for the environmental management of maritime activities. Environmental Security of the European Cross-Border Energy Supply Infrastructure. 2015.
Ref 28	Frihy O. The necessity of environmental impact assessment (EIA) in implementing coastal projects: lessons learned from the Egyptian Mediterranean Coast. Ocean Coast Manag [Internet]. 2001 [cited 2017 Jan 16]; Available from: http://www.sciencedirect.com/science/article/pii/S096456910100062X
Ref 29	Touili N, Baztan J, Vanderlinden J-P, Kane IO, Diaz-Simal P, Pietrantoni L. Public perception of engineering-based coastal flooding and erosion risk mitigation options: Lessons from three European coastal settings. Coast Eng. 2014;87:205–9.
Ref 30	Hooper T, Austen M. Tidal barrages in the UK: Ecological and social impacts, potential mitigation, and tools to support barrage planning. Renew Sustain Energy Rev. 2013;23:289–98.
Ref 31	Schramm MP, Bevelhimer MS, DeRolph CR. A synthesis of environmental and recreational mitigation requirements at hydropower projects in the United States. Environ Sci Policy. 2016;61:87–96.
Ref 32	Erftemeijer P, Lewis R. Environmental impacts of dredging on seagrasses: a review. Mar Pollut Bull [Internet]. 2006 [cited 2017 Jan 16]; Available from: http://www.sciencedirect.com/science/article/pii/S0025326X06003778
Ref 33	Stigner MG, Beyer HL, Klein CJ, Fuller RA, Carvalho S. Reconciling recreational use and conservation values in a coastal protected area. J Appl Ecol. 2016;53(4).
Ref 34	Zuliani T, Mladenovič A, Ščančar J, Milačič R. Chemical characterisation of dredged sediments in relation to their potential use in civil engineering. Environ Monit Assess. 2016;188(4).
Ref 35	Brown CJ. Social, economic and environmental effects of closing commercial fisheries to enhance recreational fishing. Mar Policy. 2016;73.
Ref 36	Jones ISF. Contrasting micro- And macro-nutrient nourishment of the ocean. Mar Ecol Prog Ser [Internet]. 2011 [cited 2017 Oct 3];425:281–96. Available from: http://www.int-res.com/articles/meps_oa/m425p281.pdf
Ref 37	Kondolf GM, Gao Y, Annandale GW, Morris GL, Jiang E, Zhang J, et al. Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. Earth's Futur [Internet]. 2014 May 1 [cited 2017 Oct 10];2(5):256–80. Available from: http://doi.wiley.com/10.1002/2013EF000184
Ref 38	T. Ellis, R. Gardiner, M. Gubbins, A. Reese, D. Smith, and C. Weymouth, "Aquaculture statistics for the UK, with a focus on England and Wales 2012."
Ref 39	Marine Management Organisation, "UK Sea Fisheries Statistics 2016," 2016.
Ref 40	Natural Resources Wales, "Location and boundaries Key Characteristics," 2016.
Ref 41	Tidal Lagoon Power Ltd, "Tidal Lagoon Power: Key Statistics," 2016. [Online]. Available: http://www.tidallagoonpower.com/about/key-statistics/. [Accessed: 01-Jan-2016].
Ref 42	"Lagoon cost 'same as Hinkley' - Wave and Tidal | reNEWS - Renewable Energy News," *ReNews*, 2018. [Online]. Available: http://renews.biz/103387/lagoon-cost-same-as-hinkley/. [Accessed: 22-Feb-2018].
Ref 43	Tidal Lagoon Swansea Bay plc, "Selection of turbine technology to minimise impacts on fish 1.0 Introduction," 2015.
Ref 44	UK Government, "Trends Air Emissions 2015 Excel Data." 2015.
Ref 45	G. Kerai, "Annex 1: Background and methods for experimental pollution removal estimates - Office for National Statistics," *Office for National Statistics*, 2016. [Online]. Available: https://www.ons.gov.uk/economy/environmentalaccounts/methodologies/annex1backgroundandmethodsforexperimentalpollutionremovalestimates. [Accessed: 23-Feb-2018].
Ref 46	"The costs of reducing PM 10 and NO 2 emissions and concentrations in the UK: Part 1: PM 10," 2001.
Ref 47	"Defra National Statistics Release: Emissions of air pollutants in the UK."
Ref 48	UK Government, "Valuation of energy use and greenhouse gas emissions for appraisal - Data Tables 1-19 supporting the toolkit and the guidance." 2018.

Ref 49	E. and I. S. Department of Business, “VALUATION OF ENERGY USE AND GREENHOUSE GAS (GHG) EMISSIONS,” 2018.
Ref 50	Department of Energy and Climate Change, “RECORD OF THE HABITATS REGULATIONS ASSESSMENT UNDERTAKEN UNDER REGULATION 61 OF THE CONSERVATION OF HABITATS AND SPECIES REGULATIONS 2010 (AS AMENDED). & ASSESSMENT OF THE PROJECT UNDER ARTICLE 4.7 DEROGATION FOR THE WATER FRAMEWORK DIRECTIVE. Project Title: Tidal Lagoon Swansea Bay,” 2015.
Ref 51	Natural England, “Carbon storage by habitat: Review of the evidence of the impacts of management decisions and condition of carbon stores and sources - NERR043,” 2012.
Ref 52	Tidal Lagoon Swansea Bay, “Tidal Lagoon Swansea Bay Habitats Regulations Assessment Updated Screening Report Tidal Lagoon Swansea Bay plc,” 2014.
Ref 53	Tidal Lagoon Power, “Ecosystem Enhancement Programme (EEP),” 2016.
Ref 54	C. Hendry, “THE ROLE OF TIDAL LAGOONS FINAL REPORT,” 2016.
Ref 55	M. Munday and C. Jones, “Turning Tide: the economic significance of the Tidal Lagoon Swansea Bay,” 2013.
Ref 56	World Health Orgnisation Europe, “Health Economic Assessment Tool (HEAT) for walking and cycling.” [Online]. Available: http://www.heatwalkingcycling.org/#homepage. [Accessed: 23-Feb-2018].
Ref 57	Q. Di, Y. Wang, A. Zanobetti, Y. Wang, P. Koutrakis, C. Choirat, F. Dominici, and J. D. Schwartz, “Air Pollution and Mortality in the Medicare Population,” *N. Engl. J. Med.*, vol. 376, no. 26, pp. 2513–2522, Jun. 2017.
Ref 58	P. Kelly, S. Kahlmeier, T. Götschi, N. Orsini, J. Richards, N. Roberts, P. Scarborough, and C. Foster, “Systematic review and meta-analysis of reduction in all-cause mortality from walking and cycling and shape of dose response relationship,” *Int. J. Behav. Nutr. Phys. Act.*, vol. 11, no. 1, p. 132, Dec. 2014.
Ref 59	E. Bayraktarov, M. I. Saunders, S. Abdullah, M. Mills, J. Beher, H. P. Possingham, P. J. Mumby, and C. E. Lovelock, “The cost and feasibility of marine coastal restoration,” *Ecol. Appl.*, vol. 26, no. 4, pp. 1055–1074, Jun. 2016.
Ref 60	Tegen Mor Fisheries Consultants, Swansea Bay Fishing Industry Research Study, 2015.

Appendix 11: ESV explanation of monetary values methods

ESV Methods Further Detail

For the exact values and calculations please see the ESA and ESV spreadsheet. This section walks through the process and assumptions made to obtain the values presented in Table 20 in the ecosystem service valuation section (Chapter 5) of the thesis. It has not been added to the main text of the document to avoid emphasis being placed on the monetary values in the research and light taken away from the assessment, description and story of the changes. It is here for further information should anyone wish to see the methods in more detail. If this were to be applied in practice, the assumptions would need to be supported by more robust data or expert opinion. The process in this research is for example only and makes high level assumptions in order to demonstrate how it could be done based on a theoretical lagoon scenario and solution implementation selected in previous sections of the research.

Food (Aquaculture)

The baseline assumption for this ecosystem service is that aquaculture production at the lagoon is expected to be of equivalent value per year as an average Welsh aquaculture enterprise. Once this was calculated assumptions were then made on how this production would change given implementation of solution group A and solution group B.

The landed tonnage of fish in Wales per year was found using government data [1], this included government information on the number of aquaculture enterprises and the value in pounds per tonne of fish landed. From this the tonnage per aquaculture enterprise was obtained and the estimated average value of this. This provided a baseline average value per enterprise per year.

The assumptions at this stage include a consistent tonnage per year for 50 years and a consistent price; although a discount rate has been applied it is likely that aquaculture values will go up and down out with the discount period fluctuation. It also assumes that the lagoon will be as productive and of the same scale as the average Welsh aquaculture site.

It was assumed that none of the solutions in Group A will impact the aquaculture production present at the baseline.

It is assumed that the only solution in Group B to influence aquaculture production is urea fertilisation. Studies found show that ocean fertilisation can increase productivity by 33% for a short period of time [2–5]. Assuming ocean fertilisation is applied twice a year, productivity is increased by 33% in the months in which it is applied. It is known that urea fertilisation is not sustainable. As such this research assumes this positive in production will become a zero after 25 years.

All the values were set over a 50-year time scale applying a discount factor to gain net present values. The full calculations for this ecosystem service can be found on the yellow '1.Food (a)' tab in the ESA and ESV spreadsheet.

Food (Fishing)

The biggest assumption in this section is that the baseline lagoon will have an overall benefit on fish production. The basis for this assumption in this research is on literature studying the fishing industry in Swansea Bay [6]. This is a topical and debated assumption and if this were to be applied in practice this assumption in particular would need reviewing based on site specific surveys and local knowledge. Working with this assumption it is then considered how the implementation of solution groups A and B will influence this ecosystem service.

The value of fish caught in Swansea bay was found [7] alongside reports specifically on the fishing industry and site characteristics in Swansea bay [6,8]. These allowed a baseline tonne per year of fish at Swansea bay and its value to be obtained for the baseline. It was assumed that in Group A the use of spatial and temporal zonation, turbine selection with fish and marine mammals will allow for preservation of the fish population and therefore the ecosystem service provided. It was assumed that relocation and re-routed movement of vessel traffic might result in a negative impact on the fishing industry, but that it is likely that fishing will occur elsewhere in stead and so not influence the overall baseline.

The solutions in group B are thought to cause no change to the baseline, except for urea fertilisation. Based on previous calculations in Food (A) and urea causing an increase in production of 33% [2–5], assuming that 10% is lost at each tropic level the increase to fish populations will be 23% per year. Again, this benefit is assumed to deplete rapidly after 25 years, leading to little benefit over the 50 year valuation time line.

All the values were set over a 50-year time scale applying a discount factor to gain net present values. The full calculations for this ecosystem service can be found on the yellow '1.Food (b)' tab in the ESA and ESV spreadsheet.

Energy

One of the primary purposes of a baseline lagoon is to provide renewable energy. Based on the assumed energy generation estimates for Swansea Bay lagoon [9] and a cost per energy unit (GWh) [10] a value can be assumed in million pounds per year. The impact of solutions group A and group B were then considered in terms of how this ecosystem service would change with their implementation.

Group A

It is assumed that in Group A the following solutions will negatively impact the provision of energy in a lagoon: Flushing and sluicing, dredging, turbine selection and use of temporal zonation. All of these solutions are thought to reduce the amount of energy generated. Each of these has been described below in turn.

Flushing, sluicing and dredging are assumed to require a total of 44 days/year, this is based on data from the management of tidal barrages and reservoirs [11], it assumed that this would take place in the baseline lagoon but that approximately 10% would be for environmental reasons (4.4 days) [11]. Taking this into account the average energy pounds per is calculated based on the baseline information and 4.4 days' worth is reduced from the baseline for the solutions flushing, sluicing and dredging. It was found that the modern tidal turbines which are deemed to be 'fish friendly' are variable speed turbines and these are also more efficient in energy production than fixed sped turbines [12], therefore despite a negative impact being described, it has not been quantified for this research. The solution of temporal zonation is assumed to stop generation of power for big recreational events, for example open water swimming or triathlons, it was assumed for the purposes of this valuation that 3 big events per year would stop generation for 3 days. Using the calculation of the value of energy produced per day this was taken from the overall positive baseline for group A.

Group B

In group B it was described that site selection close to existing habitats for water quality improvement and catchment and land slope characteristics to reduce run off would also negatively impact energy generation. This is because perhaps the site better for environmental impacts would not be as productive for energy generation. It is likely that the tidal range will be the same and so the energy will also be the same, but the actual costs of development would be higher. How much higher is impossible to quantify without knowing the exact site-specific characteristics of where a baseline would be compared to an improved site for environmental impacts and therefore has not been valued in this research which is a high-level demonstration only.

All the values were set over a 50-year time scale applying a discount factor to gain net present values. The full calculations for this ecosystem service can be found on the yellow 'Energy' tab in the ESA and ESV spreadsheet.

Air Quality

It is assumed in this section that a tidal lagoon will displace fossil fuel energy generation therefore reducing the PM10 released into the environment and provide a benefit in terms of air quality. The baseline assumption is therefore a benefit of improved air quality (reduction in PM10 emissions). The total UK tonnes of PM10 emissions (tPM10) for fossil fuels in 2015 was found [13,14] in addition to the total GWh energy generation from fossil fuels in 2015 [15]; this allowed for a rough estimation of the PM10 emissions produced per GWh unit of energy in tPM10/GWh. Using the annual expected energy production of Swansea Bay Lagoon (GWh) [9] and the average tonne of PM10 released per GWh of energy we get the tonnes of PM10 avoided by a lagoon of the same size as Swansea Bay Lagoon per year. Using government data on the damage cost of PM10 emissions (£ per tonne) on an 'average urban area' [16] we get an idea of the damage cost avoided due to energy generation of a lagoon the same size and location as that of Swansea Bay lagoon. This value is the baseline benefit to air quality.

Given that this baseline value is underpinned by the energy produced by a lagoon (GWh) the solution groups A and B and their impact on this ecosystem service can be related to the impact they have on the energy production. Group A shows impact through 4.4 days of no energy generation due to sediment management (flushing and sluicing) and 3 days of no energy generation due to large recreational events. If no energy is generated, it is assumed that this will no longer displace fossil fuels, and therefore the damage cost avoided will no longer be as big of a benefit as it was in the baseline. Group B had no impact on energy generation and as a result will have no impact on the air quality ecosystem benefit provided in the baseline.

All the values were set over a 50-year time scale applying a discount factor to gain net present values. The full calculations for this ecosystem service can be found on the yellow 'Air Quality' tab in the ESA and ESV spreadsheet.

Carbon Regulation

Assuming that lagoons will replace natural gas energy use, the carbon dioxide equivalent per energy unit value per year was sourced for conventional gas (tCO_2e/kWh) [17]. Using the predicted energy generation of Swansea Bay lagoon per year (GWh) [9] we can then calculate the likely tonnes of carbon dioxide emissions displaced as a result of lagoon generation per year. Using carbon price predictions over 50 years (£/tCO_2e) [18] we can obtain a baseline value for the carbon regulation benefit of a lagoon of the same size of Swansea Bay.

Given that this baseline value is underpinned by the energy produced by a lagoon, and therefore the amount of gas energy generation displaced and subsequent tonnes of carbon dioxide avoided, the solution groups A and B and their impact on this ecosystem service are related directly to their impact on energy production. Group A shows impact of 7 days in total with no energy generation due to large recreational events and sediment management, therefore this reduces the baseline benefit of carbon regulation due to reducing the energy generation of a lagoon. Group B had no impact on energy generation and as a result will have no impact on the carbon regulation ecosystem benefit provided in the baseline.

The full calculations for this ecosystem service can be found on the yellow 'CR-CO2' tab in the ESA and ESV spreadsheet.

Carbon Sequestration

It was assumed that habitat under the footprint of a lagoon would be a mixture of sand dunes and intertidal/subtidal benthic ecology [19]. Using the Swansea Bay habitats regulation assessment it was assumed that 80% of habitat loss due to lagoon development would be intertidal or subtidal benthic habitat with 20% being sand dunes [19]. Using literature sourced figures for carbon sequestration per habitat type [20] and assuming that all of the habitat under the footprint of a lagoon will be lost and all of the carbon sequestration benefits also lost we can determine the negative loss of carbon sequestration in habitats for a baseline lagoon. Using predicted future carbon prices [18] gives us a monetary value for this.

Consideration of how the solution groups A and B will influence the footprint, habitat loss and therefore loss of carbon sequestration benefit followed. It was assumed that no solutions in group A will influence the carbon sequestration loss as a result of loss of habitat, as such the values remain the same as those in the baseline. Group B includes habitat restoration which is assumed will restore some of the lost habitats and therefore some of the carbon sequestration ecosystem service. This research assumes that ecosystem restoration solutions would restore sand dune habitat, allowing for it to obtain 100% of its former sequestration abilities (sand dunes making up 20% of the overall habitat lost in the footprint of a lagoon). The previous sequestration ability of sand dunes used to calculate the loss of carbon sequestration in the baseline is used again here, but it is assumed that sequestration in the first 40 years is greater as the habitat grows and reaches more equilibrium once the habitat is mature.

The full calculations for this ecosystem service can be found on the yellow 'CR-Sequestration' tab in the ESA and ESV spreadsheet.

Erosion & Sedimentation

The baseline assumption is that sedimentation within the lagoon will occur. Using a Tidal Lagoon Power report [19] the capital amount (initial) and maintenance amount (yearly requirement) of dredging (m^3) for Swansea bay was obtained, along with frequency required e.g. maintenance dredging not required for the first 10 years after construction, then needed every two years for the life time of the lagoon. The cost of dredging per volume (£/m^3) was obtained in literature based on sediment management in reservoirs [11]. This allowed for a negative value to be obtained which represented the cost of sediment change associated with a baseline lagoon.

Based on the author's opinion and associated literature it was expected that solutions of flushing and sluicing in Group A would reduce the need for maintenance dredging in a lagoon by 10% [11]. None of the other solutions within Group A are thought to have an impact on the dredging requirement. For solution group A 10% was reduced from the cost of a baseline lagoon. None of the solutions in Group B are thought to influence the erosion or sediment regime or the dredging requirement when compared to the baseline lagoon.

All the values were set over a 50-year time scale applying a discount factor to gain net present values. The full calculations for this ecosystem service can be found on the yellow 'Erosion and Sedimentation' tab in the ESA and ESV spreadsheet.

Water Quality

This ecosystem service was assessed using the Environment Agency's NWEBS tool which provides monetisation for marginal changes to water quality. It includes assessment of 6 ecological components: fish, invertebrates, plant communities, water clarity, flow of water and recreation. Recreation and fish were not assessed in this research in this section to avoid duplication with later assessment of recreation and fish. The NWEBS tool allows you to change the number of receptors and the quality of the changes to be input and these are changed depending on the solution group information.

In Group A it was assumed that 4 receptors would be influenced (all excluding recreation and fish) and that these are changed from poor to moderate. In Group B all 4 receptors are influenced again, these are assumed to change from poor to good. These ratings were chosen based on the findings from the ecosystem service assessment and author's opinion. If this were to be done in practice a more robust method which is supported by underlying data would be recommended. More information on the water appraisal guide and tool can be found at the environment agency's reference [21].

All values were set over a 50-year time scale. The full calculations for this ecosystem service can be found on the yellow 'Water quality' tab in the ESA and ESV spreadsheet and NWEBS ESV & ESA spreadsheet also on Zenodo [22].

Flood Protection

The ecosystem service assessment concluded that a baseline lagoon is likely to have an overall benefit in terms of flood protection. This is difficult to quantify and monetise without in-depth flood risk modelling or a specific site. This section of the research did not require a baseline as only the marginal change is required. In Group A it was expected that flushing, sluicing and dredging would all have additional positive impacts on the flood protection ecosystem service of a baseline, but that these are expected to be small and insignificant as many will already occur in the baseline and it would be difficult to separate out this benefit from the 'additional' or marginal as a result of solution implementation. In group B it is expected that adaption/restoration to protect coastlines from inundation will improve the flood protection ecosystem service when compared to the baseline.

In order to monetise this a big assumption has been made that any restoration activity undertaken by a lagoon to the coastline will be similar to that undertaken at Medmerry reserve. This was restoration of a 500ha area, which reduced the public spend of flood defence maintenance by approximately £300,000/year. The assumption in this research is that the restoration undertaken in Solution group B is the same as that in Medmerry reserve and therefore the benefits translate to £300,000/year.

All the values were set over a 50-year time scale applying a discount factor to gain net present values. The full calculations for this ecosystem service can be found on the yellow 'Flood Protection' tab in the ESA and ESV spreadsheet.

Recreation & Tourism

Based on a study on the economic impact of tidal lagoons which calculated the economic impact of visitors [23] a range of estimated visitor numbers and associated value of those visitors was provided

(70,000-100,000 visitors equates to £1.5m-£2.1m gross value added per annum respectively) [23]. Using recent research on visitors at tidal barrages and expected visitors for Swansea bay [24] a baseline conservative estimate of visitors to a tidal lagoon of similar size to Swansea bay, considering it will also be a world first is 70,000 visitors (£1.5m per annum).

In Group A it was assumed that spatial zonation, safer turbines and relocation of vessels will increase visitor numbers due to more opportunity for safe eco-tourism and sporting activities. The optimistic estimate for visitors from the literature was used for this group of solutions (100,000 visitors, £2.1m per annum). In Group B it was assumed that promotion of keystone species and building of green corridors may increase eco-tourism at the site and provide benefit marginally above the baseline but not as high as the benefits noted in Group A. As such it was assumed an average estimate of 95,000 visitors or £1.8m per annum. This assigning of value is very simplistic and based on estimations in the literature provided. If this were to be done in practice it would require an in-depth assessment of recreation and tourism opportunity and would most likely be based on site specific data sets backed up by public engagement. The uncertainty surrounding the figures used in this section is high.

All the values were set over a 50-year time scale applying a discount factor to gain net present values. The full calculations for this ecosystem service can be found on the yellow 'Recreation & Tourism' tab in the ESA and ESV spreadsheet.

Appendix 12: Journal Publication: Marine Policy

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A systematic review of transferable solution options for the environmental impacts of tidal lagoons

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ABSTRACT

Tidal lagoons are presented as an environmentally friendly alternative to tidal barrages. This does not mean that their environmental impacts can be overlooked. A UK government review recommended a pilot scheme lagoon go ahead, with careful environmental monitoring. Despite recent government rejection of a lagoon scheme, it is still more important than ever to consider environmental solution options for any future lagoon developments. There are no operating lagoons in the world and so their environmental impacts are not fully understood. However, there is a vast quantity of literature available from other industries addressing similar impacts in the coastal, ocean and river environments. This systematic review follows the PRISMA and CEE guidance. Using this methodology the available literature covering relevant solution options from other industries that could be applied to future lagoon developments was quantified. This presents an investigation into solution options only, giving a quantitative analysis of what resources are available, how this compares to industry understanding, where the expertise lies globally, what impacts are being addressed and how applicable the solutions are for lagoon application. This paper analyses the extent and relevance of this available research on solutions as a resource for the nascent lagoon industry. Over half of the solutions found in this review require only small shifts in development for them to be realistic solution options for the lagoon industry in the future. This review opens the door on a vast and valuable resource and justifies the need for further investigation into solutions for the lagoon industry.

1. Introduction

Tidal range technology extracts energy from the tides by creating an artificial difference in water levels, or head. Higher water levels are constrained by barrage or lagoon walls and sluice gates; when these are opened, the flow of water drives turbines to generate electricity [1]. The key advantages of tidal range energy include a high level of predictability [2], the ability to phase shift energy to provide a continuous base load supply [3] and the long expected life span [4]. Despite these advantages there are concerns surrounding high capital cost and environmental impacts, and the Severn Barrage in the UK has been repeatedly rejected since 1920s for these reasons [5–7]. Whilst there are barrages in successful operation, such as the La Rance 240 MW barrage in Brittany, France and the Sihwa Barrage in South Korea, there have been numerous environmental issues associated with them, primarily sedimentation and water pollution issues [1]. Tidal lagoons are often presented as environmentally friendly alternatives to barrage developments [6,8,9], but this does not mean their environmental impacts can be overlooked.

A total of 145 countries signed the recent Paris Agreement for action on climate change [10]. As part of this the UK has ambitious carbon reduction targets of 80% reduction on 1990 levels by 2050 [11]. In addition, the UK is legally obliged to provide 20% of its energy needs from renewable sources by 2020 [12]. Drastic action is required to meet this, since under 'business as usual' conditions the UK will fail to reach this target in the next two years [13]. The UK has the greatest tidal energy resource in the world [7]. It is expected that a national fleet of lagoons could supply 8% of the UK's electricity [14].

The most recent developments in the lagoon sector have been in the UK, with Tidal Lagoon Power Ltd (TLP) proposing a fleet of lagoons for deployment and the government undertaking an extensive review into their feasibility. The focus of this paper is on the UK, because of these recent developments. Despite this focus, the analysis and key findings of the paper are relevant to any country wishing to develop a lagoon in the future. The government review recommended that a pilot scheme lagoon be deployed with careful environmental monitoring as a precursor for national lagoon development [9]. Whilst other sites and lagoons have been investigated, the most advanced project has been the

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Swansea Bay Tidal Lagoon from TLP [7,15,16]. The lagoon was awarded a Development Consent Order (DCO) in 2015, but was recently rejected by the UK government based on cost concerns [14,17]. Despite this set back, there are numerous lagoon projects in the pipeline in the UK and globally and there is a certain expectation placed on the first mover to set a precedent for an environmentally sustainable lagoon industry.

Progress has been made in identifying the environmental impacts of tidal lagoons such as the hydrodynamics [18–23], morphodynamics [24,25], water quality [26,27], ecological interactions and society [6], environmental knock on implications [1] and industry perspectives on the environmental impacts of lagoons [28]. Less well researched are the potential solution options for the identified and estimated environmental impacts. Whilst a few papers consider the operation of a tidal lagoon and its influence on the hydrodynamic regime [29,30], at the time of writing, no existing papers holistically investigate a variety of solution options to address numerous environmental impacts that are likely to arise from tidal lagoons. This is not surprising given that there are currently no operational, energy generating, man-made tidal lagoons in the world, and therefore no operational data on the environmental impacts of lagoons or lessons to be learnt on potential solution implementation options.

Recent industry engagement with the UK lagoon sector considered what the industry (developers, regulators, policy makers, consultants, conservation bodies, government bodies) believed to be the key impacts of lagoon developments and what the potential solution options could be [28]. The key findings of this research found that, from the industry's perspective, the most significant environmental impacts are: sediment regime changes, hydrodynamic change, impacts on habitats and biodiversity and impacts on marine mammals and fish [28]. The solution options presented by the industry in this research are mainly focused around engineering, site or technology design or compensation and catchment based measures [28]. This previous research will be built upon by considering and comparing the literature research available in comparison to this industry perspective referred to throughout this paper as the 'industry's perspective' or 'industry's understanding'.

Tidal lagoons are a new idea, but the key concepts making up this idea are not new. Other industries have applied similar technology and engineering concepts and as such have had similar environmental impacts. These other applications include use of walls to impound water in the coastal defence, dam, barrage and hydropower industries, and use of turbines to generate energy in river run, pumped storage and tidal stream applications. In addition, environmental impacts such as water and sediment pollution, fish and marine mammal impacts, marine spatial planning conflicts and loss of marine habitats and biodiversity are commonly addressed in maritime and river industries such as the offshore wind industry, shipping, port development, aquaculture, river catchment land management, and offshore oil and gas industries, to name only a few. It is expected that the nascent lagoon industry can draw from the experiences seen in these industries that have already successfully managed similar environmental impacts.

This systematic literature review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidance [31] alongside guidance from Collaboration on Environmental Evidence [32]. This methodology and reporting style is already established and recommended for research that uses systematic reviews to further knowledge in marine policy or ocean management sectors [33–35]. Using this methodology the extent and relevance of the available literature covering solution options from other ocean, coastal and river industries that could be applied to future lagoon developments is quantified.

This paper presents a quantitative investigation into the literature resources surrounding solution options only, it does not look in detail at the environmental impacts of tidal lagoons (only those being addressed by the solutions found) and it does not provide detailed qualitative analysis on the solutions options. The review gives a quantitative picture of what literature resources are currently available to the industry, how this compares to current industry understanding and perspective [28], where the clusters of expertise lie globally, what impacts are being addressed, where the solutions fit on a mitigation hierarchy and how well developed and applicable the solutions are in terms of their potential application to future lagoon development. This information determines whether the current research on solutions to environmental impacts from other industries is substantial and relevant enough to warrant further investigation by the lagoon sector into transferrable environmental policy and management options.

2. Methodology

2.1. Literature search

This review uses the PRISMA statement as a reporting style guide [31] alongside guidance from Collaboration on Environmental Evidence (CEE) [32] on systematic literature review methodology. This method was chosen based on its existing use and recent recommendation in the marine environmental sector [33–35]. Whilst the PRISMA methodology was used and followed in full, Sections 5 and 6 of the CEE were used as secondary supporting guidance to inform key parts of the methodology, such as conducting a literature search and screening documents for eligibility.

The literature search was performed on three databases: Google Scholar (https://scholar.google.co.uk/), SciVerse Scopus (https://www.scopus.com/home.uri) and Science Direct (http://www.sciencedirect.com/). Together, these form a comprehensive database of peer-reviewed research. The collected papers were between 1987 and the cut-off date of 04/04/2017. The following search terms in the title, abstract or keywords allowed the papers to be included in the initial literature search: 'Marine' or 'Ocean', 'Environmental impact' or 'Environmental risk' and 'Solution' or 'Mitigation'.

The search terms were entered into the search engines. The initial literature search brought up 1114 papers, 688 papers after duplicates removed, Fig. 1 shows a flow chart of paper selection, which is a standard PRISMA reporting guideline. Grey literature such as websites or documents outside traditional commercial or academic publishing, and non-English publications were excluded from the review at this point if found.

2.2. Selection criteria

The 688 papers from the initial search were screened in terms of their abstract contents. A total of 559 papers were excluded at this stage (Fig. 1) the exclusion criteria, with the number excluded for each reason are shown in Table 1. The remaining 129 paper abstracts included information on solutions which could be applied to the impacts likely to be presented by tidal lagoons in the future. As a general rule, if the abstract was unclear or any uncertainty surrounded its inclusion it was included for the next stage of screening.

The next stage was full text screening of the 129 papers selected from the abstract screening. The exclusion criteria here were the same as the abstract screening stage listed above, with the additional exclusion factor of books and any further grey literature found (Table 1). Books and 'grey literature' were excluded as any new, credible and innovative solutions are expected to be represented in the up-to-date, peer reviewed research papers. 'Grey literature' was defined in this study as any documents or websites that had not been peer reviewed or were not from a reputable company or organisation, expert judgement was used to exclude sources as 'Grey Literature'. A total of 52 papers were excluded at the full text screening stage of the review.

Following this final screening stage a total of 77 papers were included in the final data collection and quantitative analysis (Fig. 1). All the papers included had viable solution options presented in their full text that could be applied in the future to address the marine and

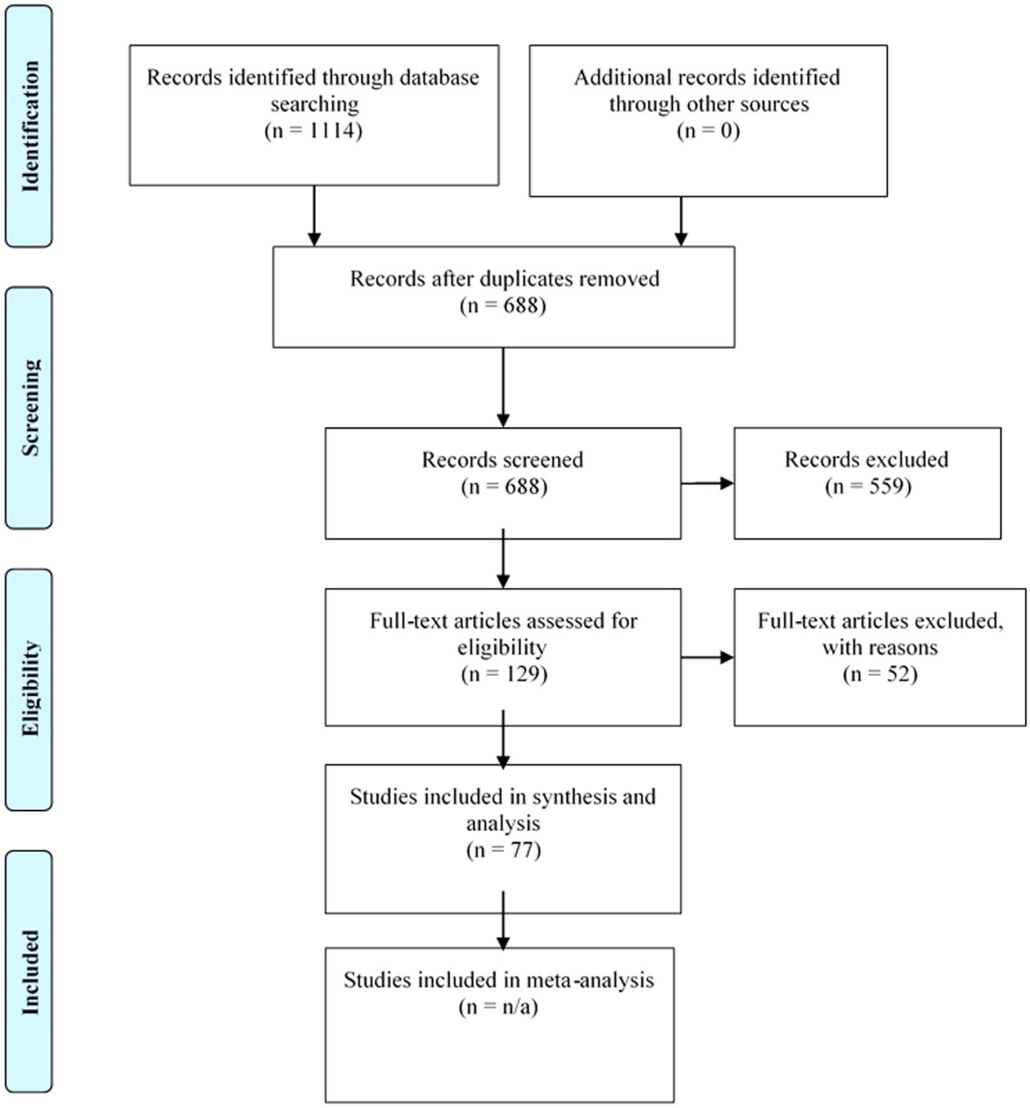

Fig. 1. Flow chart of the review paper selection process and the number of papers excluded at each stage. This follows the PRISMA statement guidelines on reporting review process [30].

coastal environmental impacts that may arise as a result of the implementation of tidal lagoons in the UK.

2.3. Data extraction

From the final 77 papers that remained after the screening process, information for analysis was extracted. The data extracted from the papers centred around two main themes: 1) characteristics of the paper; and 2) solution options presented for environmental impacts. The data extracted from the papers along with information on the purpose for extraction is detailed in Table 2.

The information extracted allowed a quantitative analysis of patterns, identification of knowledge gaps and further interpretation of the potential solution options that could be applied to the environmental impacts likely to arise in the future tidal lagoon industry. Applying expert judgement, the scaled scoring noted in Table 2 was used to determine the development stage and applicability of the solutions to lagoon application. Combining this with the other data extraction, a

Table 1
Paper exclusion criteria at abstract and full text screening stages with number excluded for each reason shown.

Exclusion Criteria	Abstract Screening	Full Text Screening
Impacts presented could not be related to lagoons	146	16
Impacts identified but no solution options given	143	11
Focus of the paper is not on environmental impacts	96	16
Focus of the paper on carbon emissions or climate change	67	1
Impacts are purely terrestrial/not relevant to lagoons	49	1
Paper is for global scale impacts	44	0
Impacts are of the environment on engineering	13	1
Not available/ Not Found	1	1
Books or grey literature publications	0	5

Table 2
Data extracted from the final 77 papers, further details and the reason or purpose for extraction.

Data Extracted	Details	Purpose
Publication year	Year first published	Provides timeframe information
Author location	Based on first author affiliation	Provides geographical location and indication of expertise location
Study location	If applicable (not all focus on a location)	Indication of application location and relevance of studies
Type of paper data	Review, model or analysis of existing data, direct observation, expert opinion	Provides indication of the quality and type of data available is it real world or theoretical
Paper Discipline	Environmental, engineering, social, economic, legal	Indication of from which disciplines solutions are arising
Study area type	Marine, coastal, river, other	Indication of relevance to coastal lagoon applications
Environmental Impact being addressed	e.g. fish and marine mammals, pollution (sediment/water), hydrodynamics, habitats and biodiversity, sediment regime	Indication of which impacts are well researched in terms of solution options
Description of solution option	Qualitative description	Provides understanding of the solution options available
Solution Type	Engineering, site of technology design, operation and maintenance, compensation or catchment based measures.	To determine at what stage solutions are most well researched, to identify any knowledge gaps
Mitigation hierarchy of solutions	Avoid, reduce, compensate/catchment based	To determine at what stage solutions are most well researched, to identify any knowledge gaps
1–5 Scale of solution development application[a]	1 = Theoretical 2 = Simulated or modelled 3 = Tested 4 = Applied at pilot scale 5 = Applied at large scale	Gives indication of how developed the solutions are
1–5 Scale of solution applicability to lagoons[a]	1 = Other Industry 2 = Other industry, easily adapted to lagoons 3 = Marine Industry, not easily adapted 4 = Marine industry, easily adapted 5 = Lagoon or barrage specific	Gives an indication as to how applicable the solutions are to application in the lagoon industry

[a] Scores assigned based on expert judgement

picture was built on the extent and relevance of the literature available and if the solution options presented from other industries could be valuable in the future lagoon industry.

3. Results

3.1. Analysis of included literature

The number of papers on solution options for environmental impacts increased significantly after 2012, with 70% of the included papers from 2012 onwards (Fig. 2). From the first paper in 1987 to 2011 there was an average of only 1 paper published per year. In comparison from 2012 to 2017 the average number of papers per year was 11. This suggests that this research field of beginning to address environmental impacts is relatively new and momentum is building on the subject of solution options.

The majority of papers are review papers (39%), followed by modelling or analysis of existing data (25%) with the remainder being direct observation studies (19%) and expert opinion (17%). The high number of review papers has allowed a greater net to be cast in terms of studies covered in this review (directly or via another review). Although it is a concern that the review papers will only provide theoretical ideas rather than concrete data, this is mitigated by the fact that a fifth of the papers included are direct observation papers, indicating that papers that have implemented and directly observed solution options to environmental impacts are present in the study.

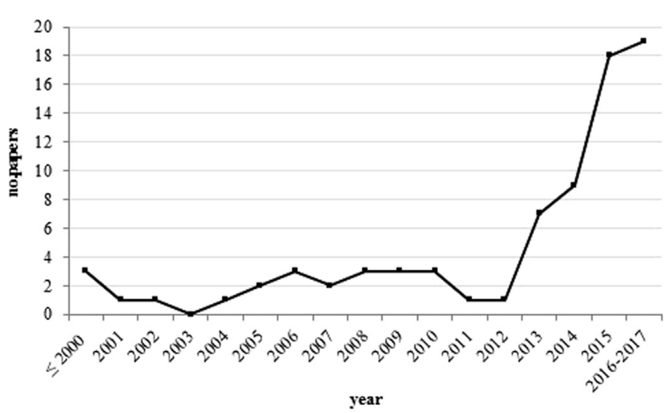

Fig. 2. Number of papers per year.

A large majority of papers on solution options (75%) are from an environmental discipline with the remaining quarter from either social (12%), engineering (9%), economic (3%) or legal (1%) disciplines. This is not surprising given the strong grounding in environmental disciplines required when considering solution options to environmental impacts. 87% of the papers included in the research are from either coastal or marine view points, this is not surprising given the aim of the study to find solutions for tidal lagoons using search terms ‘ocean’ and ‘marine’. However the remaining 13% of papers that met the criteria for inclusion were from river or other areas such as inland aquaculture farms or wetlands, showing that a wide variety of industries could contribute transferable solutions to the lagoon industry. This suggests that widening the search to include these parameters in the search terms may be beneficial in future literature reviews (Fig. 3).

Assuming that paper author affiliation and study area represents geographical areas of expertise, the main clusters of expertise on solution options to environmental impacts relevant to tidal lagoons lie within North America (30%), Western Europe (14%) and Southern Europe (14%) (Fig. 4). The author affiliations and number of papers mapped in Fig. 4 show a truly global perspective on the solution options to environmental impacts. A large proportion of the papers (40%, No. 31) had no specific area of study. The study area clusters align partly with the main author affiliation locations, with key clusters in Europe, North America and Australasia. Fig. 4 represents the review papers' global information gathering on solution options to the environmental impacts that tidal lagoons may present in the future. Despite the most progress on lagoon deployment being made in the UK, Fig. 4 suggests that there are lessons to be learnt globally from other industries on potential environmental impact solutions, in particular from the key clusters in North America, Europe and Australasia.

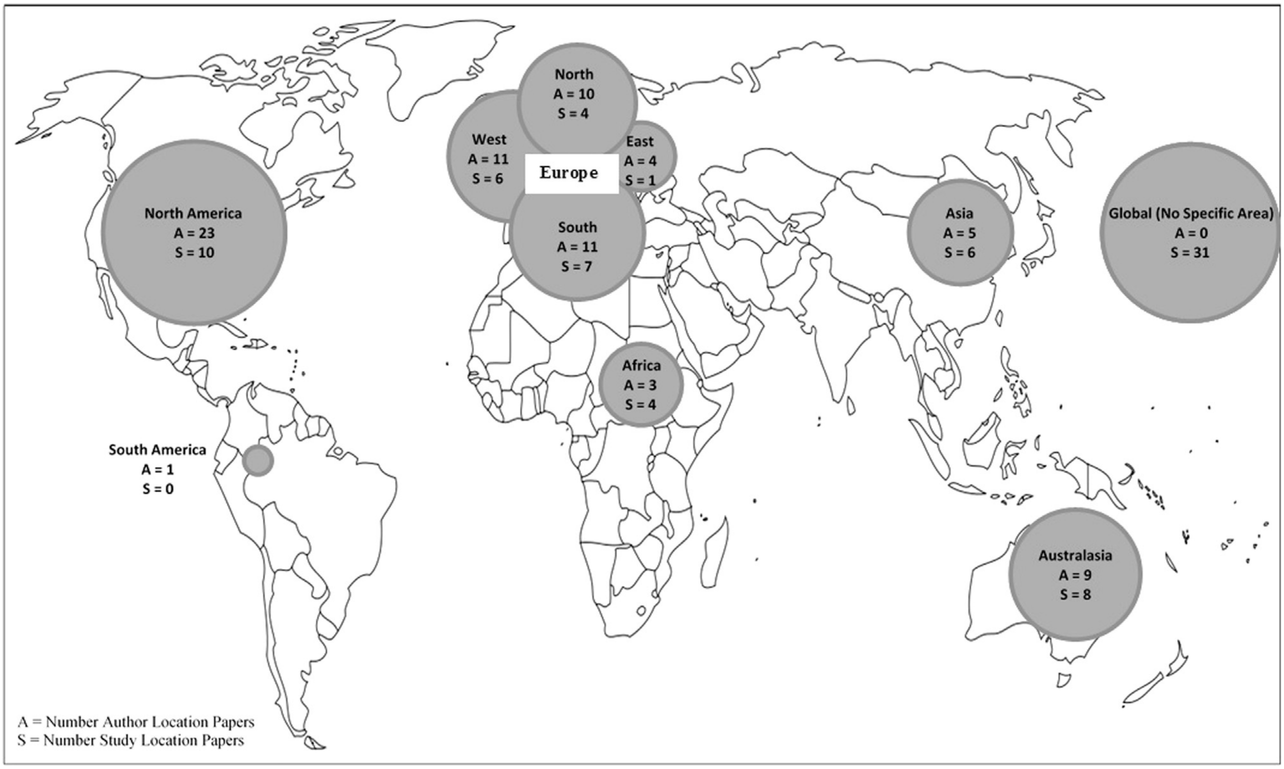

Fig. 3. Number of papers per author affiliation location (A) and study area location (S). 31 papers of 77 (40%) had no specific area of study. (Base Map Source: [91]).

3.2. Environmental impacts being addressed

The environmental impacts addressed in the included papers are varied and numerous. In order to provide an analysis each paper has been broadly categorised into one of the impacted groups as follows: Sediment regime, hydrodynamics, habitats and biodiversity, fish and marine mammals, pollution (water or sediment) and general impacts (more than 5 impacts considered in one paper). Fig. 4 shows the percentage number of papers against the impacted group which the papers addressed. The environmental impact categories were therefore defined based on what environmental impacts have been addressed by the solution options discovered in the literature review papers.

Almost a quarter (22%) of the papers consider solution options for the impact of either water pollution or pollution in the sediment. These impacts included marine water quality pollution from oil spills, increased vessel activity and associated pollution, pollution within entrapped or enclosed water bodies and marine litter due to increased tourism. They also included sedimentation pollution due to increased dredging activities and disturbance of contaminated sediments, entrapment of outflows and the pollution of sediment and benthic communities. The relatively high number of papers on these impacts could suggest that they have been common impacts in other marine, coastal and river industries and therefore may also be an issue for lagoons. All the papers present solution options for these impacts, so on the other hand the high number of papers could suggest that these impacts are well researched and therefore more easily addressed.

18% of the papers considered the impacts on fish and marine mammals, including noise pollution due to the construction of marine infrastructure, increased seismic marine surveys and vessel activity, blade interaction, barriers to migration and disruption to breeding grounds. A further 16% of papers considered changing hydrodynamics as the key environmental impact, 13% covered the impact on habitat or biodiversity loss, with 12% focusing on sediment regime changes including morphodynamics, bathymetry alterations, coastal sedimentation and/or erosion.

All the environmental impacts considered in the included papers are thought to be applicable to tidal lagoons in the future. The solutions presented in the literature to address these impacts could also potentially provide the foundation for solution options for the environmental impacts of tidal lagoons.

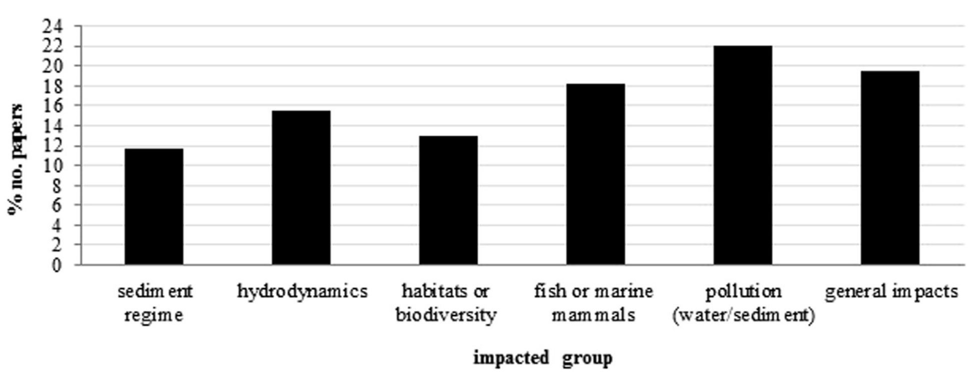

Fig. 4. Percentage number of papers addressing different environmental impacts.

Table 3
Selection of example solutions within each solution category.

Solution Category	Selection of Examples
Engineering, Site, Technology Design	Sensitive site selection, 'safe' exposure levels and distances from protected or otherwise sensitive areas [39] Site selection in terms of best potential for habitat creation within the structures themselves, site selection to promote habitat creation on the structure over that lost during installation [40] Using artificial reefs or installing marine structures with appropriate materials that will allow for an enhanced reef effect providing habitat [41] Building and designing of green infrastructure within the design plans such as providing green (or in lagoon case blue) corridors or hubs or targeting particular keystone or umbrella species in the design of structures [42] Use of multi-purpose offshore installations to reduce impacts and increase viability of blue growth projects [43] Advancements in turbine design to reduce collision risk, careful selection of turbines to suit not only energy generation but sensitive species in the area [6] Incorporation of bubble curtains, flashing lights, passive acoustic monitoring, fish ladders, spill gates, fish lifts, surface collector or guidance nets, hydro sound dampeners in the initial engineering design for the impacts on fish and marine mammals[44–46] Use of nearby land sloping characteristics in the initial design of a structure to predict and prevent the amount of run-off related water contamination or in the lagoon case pollution entrapment [47] Incorporation of engineering flooding options in the initial engineering plans such as use of beach nourishment or artificial sand dunes to avoid coastal erosion [48]. Better use of modelling, monitoring, incorporation of historic knowledge and advancements in new techniques, transfer of knowledge between industries, holistic view coupling of models to better understand and select sites, technology and engineering design [49–57].
Operation & Maintenance	Use of coastal geo-indicators and ecological indicators to provide rapid response to operation and maintenance plans [58, 59] Integration of ecosystem functioning and ecosystem based management into coastal management practices to reduce environmental impacts, using an ecosystem based approach [60, 61] Use of dredge and fill beach nourishment techniques to reduce erosion [62]. Could be dredged material from the lagoon. Control of sedimentation through sediment retention before entrance, sediment bypassing, control of hydrodynamic flow to reduce sediment accumulation, flushing or sluicing and managing existing deposits through sensitive dredging. Optimal dredging times and frequency. Potential end use of dredged sediments in civil engineering such as road subgrade layers. [63–66] Use of linkage framework to manage cumulative and overlapping ocean activities resulting in cumulative environmental impacts [67] Use of flora to filter pollutants or effluents [68] Spatial and temporal zonation and exclusion zones of activities to reduce environmental impacts [69–72] Energy generation operation to reduce hydrodynamic impacts [28]. Careful operations management of vessel activity, relocation of vessel movement to lower risk areas, careful monitoring of vessel speed limits, optimal vessel use in terms of time at sea and frequency of trips to reduce noise and water pollution and chance of collisions or oil/fuel spill [70,73]. In situ sediment pollution remediation techniques, including thin capping, solidification, sediment flushing, nanocompite reactive capping and bio reactive capping, Stabilisation of sediments using hydraulic binders [65,74] Visitor education on environmentally friendly practices in and around tourist attractions to reduce marine litter and pollution [75,76]
Compensation or Catchment Based Measures	Use of habitat creation through wetlands and vegetated ditches to reduce flooding or storm damage or to mitigate water pollution, improve water quality and compensate for loss elsewhere [77–81] Use of satellite remote sensing data to find and repair/compensate damage to ecology or habitat loss, mainly used for oil spills currently but could be applied to habitat loss [82] Use of geoengineering such as urea fertilisation to increase fish populations or using natural sediment transport systems to deposit sediment along the coastline to compensate for loss [83] Use of natural resources to increase flood defence level, such as mangrove restoration or afforestation [84] Use of Payment for Ecosystem Services (PES) schemes to conserve threatened ecosystems or to compensate over and above the value of ecosystem lost [85] Soft engineering approaches to provide compensation such as mangrove afforestation, coral reef transplants or introductions, marine reserves, planting of water filtering plants [86] Use of bioremediation methods like those seen in water pollution incidents [87] Incorporating net gain bargaining in development of marine energy, integrating ecosystem service impacts into decision making [88] Targeting certain impacts to improve status of certain species, some impacts more effectively mitigated than others [89] Predicting need for biodiversity offsetting for habitat or biodiversity loss using a projects Environmental Impact Assessment [90]

Note: These solutions are just to provide examples within each category. They are not a comprehensive list of solution options

3.3. Solution options and application for lagoons

Every one of the 77 included papers addressed a tidal lagoon-relevant environmental impact with a solution. Some of these solution options were the same, but nevertheless a database of literature on both the environmental impacts of lagoons and their potential solution options has been created through this systematic literature review. For analysis the solution options have been grouped into: 'Engineering, site or technology design', 'Operation and maintenance' and 'Compensation and catchment based measures'. Whilst it is impractical to list all of the solution options Table 3 provides examples of solutions within each of these categories and the accompanying database is published alongside this paper. Fig. 5 shows the spread of papers within these solution option categories.

Within the literature, 44% of the solution options fall under the 'Operation and maintenance' category. This includes, but is not limited to, temporal and spatial zonation of activities, sustainable dredging options and management of dredging material, advances in environmental monitoring, planning vessel activity and safety and operational timing and structure of energy generation. 30% of the solutions were within the 'engineering, site or technology design' category. This category refers to environmental awareness within site location, site design around sensitive locations, novel data or models to aid in site selection, integration of green infrastructure such as coral reefs, careful selection of building materials to promote target habitats, selection of technology to reduce impacts, wall design to reduce impacts and enhance potential environmental benefits. The lowest solution category reported in the literature is that of compensation or catchment based measures (25%). Within those solutions examples include habitat creation or restoration papers, payment for ecosystem services (PES)

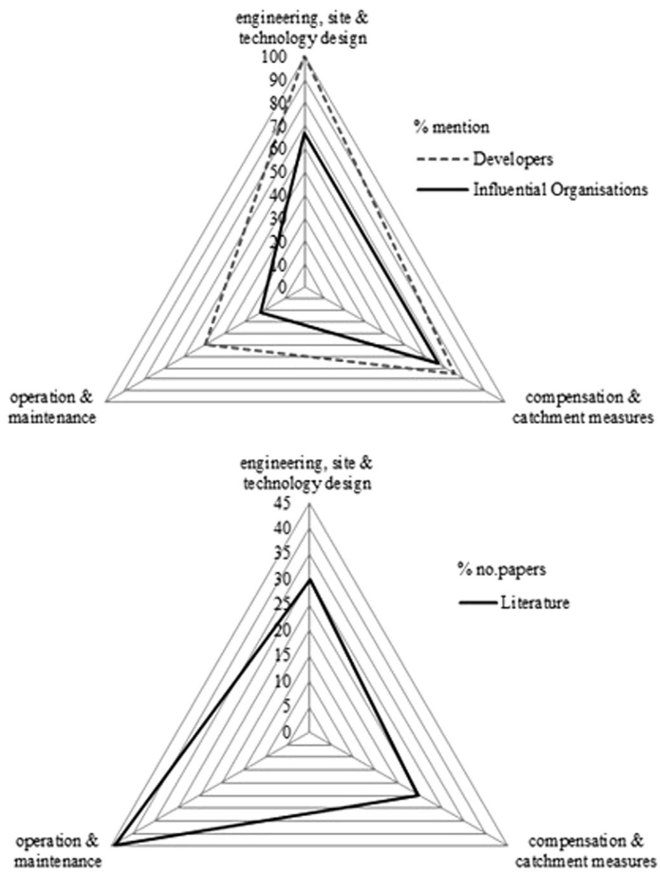

Fig. 5. Spread of solution options mentioned in a recent study on industry engagement for tidal lagoons (top) [27] and within this literature review study (bottom) over three basic categories.

schemes or other catchment based activities. Table 3 provides a more detailed list of solution examples.

A recent paper describing the lagoon industry perspective on solutions to environmental impacts sways more towards either engineering, site or technology design, or compensation and catchment based measures [28] (top triangle, Fig. 5). Neither developers nor influencing organisations mention operation and maintenance strategies most frequently. In comparison the literature found in this review on the potential solution options which could be applied to the impacts of tidal lagoons shows that the majority of papers are on operation and maintenance type solutions. Fig. 6 compares the industry's view on solutions [28] to the solution categories uncovered as part of this literature review. The results suggests that the gap in operation and maintenance understanding found in a recent paper on the industry's view of solutions [28] could be filled with the operation and maintenance solution options found within this literature review.

Traditionally solution options for environmental impacts follow the mitigation hierarchy [36,37]. This includes first avoiding environmental impacts, then reducing and finally compensating where necessary. Although the effectiveness of the mitigation is often questioned [38] it is still an established framework for addressing environmental impacts [39]. The solution options found in the literature review were categorised according to this basic mitigation hierarchy and compared to the text book version (Fig. 6). In reality the number of solution options found within this paper do not follow the theoretical hierarchy in that ‘avoiding’ solutions do not present in the majority of papers, with ‘reducing’ solutions next and ‘compensation’ least. The majority of solutions presented are to reduce environmental impacts, then to avoid and finally to compensate.

The 77 papers included in this review present a wide variety of solutions, some theoretical, others already applied in large-scale industries. Some of the solution application industries are similar to tidal lagoons, for example tidal barrages, others from less similar industries, like the natural hazard management sector. Each solution was ranked based on two scales, the first on level of development (theoretical or applied), and the second on relevance to lagoons (lagoon specific or other industry) (Fig. 7). The purpose of this was to determine how developed and relevant solutions presented in the literature might be to the future lagoon industry and therefore if it is a resource that should be further investigated and utilised in the future. The majority of solutions fall in the middle of being not quite lagoon-specific, but perhaps related to marine renewable energy and not fully applied, for example, applied at pilot scale or in testing. The bold black box in Fig. 7 shows that over half of the solution options presented need only minor shifts in either their development to applied scale or to be adapted to be lagoon-specific before they could potentially be implemented in the lagoon industry.

4. Discussion

The field of solution options for the environmental impacts likely to arise as a result of tidal lagoons is relatively new. The large growth in the number of papers over the last 5 years shows that the environmental industry is gaining momentum. This momentum is supported by the growth of the regulatory and legislative environmental sector and the increasing pressure for corporate environmental awareness and responsibility.

The lagoon industry is nascent, and environmental impacts are one of the key concerns for any future lagoon industry. With no operational man-made energy generating tidal lagoons in the world, there are no operational data on the environmental impacts of lagoons and no solution option guidelines to work by. Whilst tidal lagoons are a new

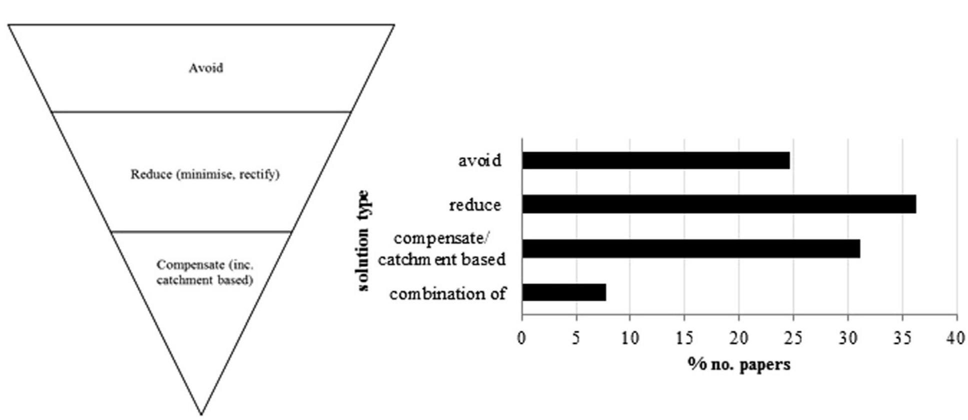

Fig. 6. Traditional mitigation hierarchy (left) compared to the solution options found within this systematic literature review (right).

Solutions Matrix		Theoretical →				Applied
		1	2	3	4	5
Other Industry	1	0	2	0	1	0
↓	2	1	4	7	6	3
	3	2	2	7	8	5
	4	2	6	5	5	6
Lagoon Specific	5	0	0	2	2	1
					Total	77

Fig. 7. Matrix of solution options in terms of their development to applied scale (1 to 5, 5 = fully applied, 1 = Theoretical) and adaption to be lagoon specific (1 = Other Industry, 5 = Lagoon or Barrage specific). Graded Colour Scale: No. Papers ≤2 Light Greens, 3–5 Medium Green, ≥5, Bright Greens.

concept, the technology and engineering feat they present is not new, and the individual engineering applications have been applied in other industries e.g. tidal barrages, dams, hydroelectric power stations, tidal stream turbines, breakwaters and coastal defence mechanisms. As such, the environmental impacts likely to arise from tidal lagoons are also likely to have already arisen and been addressed in other industries. This systematic review shows that there are wide-ranging solution options documented in the literature which have been either applied or suggested in other industries to address impacts similar to those which are likely to arise in the future lagoon industry. The review quantitatively analyses the literature to show the relevance and development stage of these solutions and if this resource warrants further investigation in the future.

The solution options have been analysed in terms of their potential to fill gaps, specifically the gaps in industry knowledge found in a recent paper [28], the cluster of expertise on solution options globally, the impacts which they seek to address and how well developed and adapted they are to a potential application in the lagoon industry.

4.1. Environmental Impacts

All the papers included in the review consider environmental impacts relevant to tidal lagoons. One of the key impacts addressed in this literature review is that of water or sediment pollution. The high level of research on this impact suggests that it is a common impact in other coastal and marine industries globally and therefore should be further investigated in terms of the lagoon industry. Water or sediment pollution was not within the top three environmental impacts suggested by the lagoon industry in recent industry engagement research [28]. It may not have been flagged by the industry as a key issue because there are a number of well-known solutions to address it.

The lagoon industry has indicated that one of the top three most significant impacts that tidal lagoons could present in the future is the impact on fish and marine mammals through restricted passage and migration [28]. This systematic review provides evidence that there are a relatively high number of papers within the body of knowledge that provide solutions to address this impact, and therefore the lagoon industry should use this knowledge to address the issue.

If it is assumed that the number of papers for an environmental impact relates to the level of research of solution options available for that impact, then the impacts with the lowest number of papers are the impacts with the least research on solution options available. These impacts may present a higher risk for the lagoon industry. The impacts with the lowest number of papers in the review, suggesting the lowest level of research on solution options are sediment regime changes, hydrodynamic change and impacts on habitats and biodiversity. These impacts were also highlighted by industry as being the most significant environmental impacts that lagoons could present in the future [28]. It can be inferred then that these impacts are likely to be key barriers in the development of the lagoon industry unless suitable solution options can be found, adapted and applied at lagoon scale.

Although the number of papers for these key impacts is lower than for other impacts, there are still some solutions presented, and therefore solutions available to address these key impacts. In addition the quantity of papers does not necessarily reflect on the quality or quantity of solution options presented. The solution options found in the literature should be used as a foundation or starting point for a drive and focus towards the development of applied, lagoon-specific solutions for these key environmental impacts.

4.2. Application of solutions

The literature presents a vast global knowledge base, spanning a variety of marine, coastal and river industries that could be drawn upon to address the potential environmental impacts that might arise from tidal lagoons in the future. The tidal lagoon industry has the benefit of hindsight and learning from other industries with similar environmental industries. It could and should utilise this.

The lagoon industry at present is very UK-orientated; the developers, regulators, policy makers, practitioners and consultants involved are largely based in the UK [28], however this review has shown there is relevant expertise from other industries worldwide. One of TLP's main goals is to boost the UK's supply chains, employment and economy [15], and this can still be achieved using a global outlook. This systematic review into solution options shows a global knowledge base of options available to address environmental impacts from other industries. There are clusters of expertise on impact solutions all over the world. The nascent lagoon industry should draw upon this global expertise. Using, adapting and implementing global knowledge within tidal lagoons will help address and progress global goals, such as that of addressing climate change. The recent advancements in the UK tidal lagoon industry therefore has global relevance. This audience also has solution options and knowledge to provide and the lagoon industry should capitalise on this opportunity.

The review shows that the majority of solution options arise from environmental disciplines. This is understandable given that a strong understanding of environmental impacts is essential to provide effective solution options. Environmental impacts are likely to have multi-disciplinary implications, such as on the economic, social, engineering and legal sectors. As such, it would be beneficial for the lagoon industry if these sectors were also involved in the designing of solution options for environmental impacts, providing a multidisciplinary approach to a multidisciplinary issue.

It was found that the majority of industry stakeholders focused on solution options related to engineering, site or technology design or compensation and catchment based measures [28]. A gap in the industry solution options was presented in the form of those relating to operation and maintenance strategies [28] (Fig. 6). In contrast, the literature presents the majority of solutions to be in the operation and maintenance category. The knowledge base within the literature could help fill gaps in the industry's understanding of solution options.

Combining both the industry understanding on solution options and the solution options found within the literature it seems that most bases are covered for addressing the environmental impacts of tidal lagoons. It is important for the lagoon industry to not only draw upon expert advice within the industry and from its stakeholders but also to refer and investigate further the available literature from other industries. In this way, the lagoon industry can find solution options from engineering, site and technology design, operation and maintenance and compensation and catchment based measures. This will reduce the number of gaps seen in the solution options available. Whilst most bases are covered in this way, the key question is now: are the solution options available actually developed enough and specific enough for applications in the lagoon industry?

Whilst the majority of papers included in this review are reviews themselves, 19% are direct observation. This suggests that some of the solution options being presented in the literature have also been applied and observed and therefore are not just theoretical ideas. Fig. 7 in the results gives a clearer picture of the number of solution options which are applied as opposed to theoretical and lagoon specific as opposed to from other industries. The majority of solution options presented in the literature are more advanced than purely theoretical but not quite applied yet on a large scale. Similarly the majority of solutions are in the marine or coastal industries but not yet specific for use in the lagoon industry. Over half of the solution options in the literature are on the brink of being realistic options for lagoon scenarios in the future. Work is required to shift them towards being applied at larger scales and adapting them for lagoon specific applications, but they are ready and waiting to be advanced.

The key message is that even though the lagoon industry is nascent and there is uncertainty surrounding its potential environmental impacts, the solution options do not have to be completely new, novel or innovative. The review suggests that with a relatively small amount of development, previously successful solutions applied to similar environmental impacts in related industries can be adapted to successfully address any environmental impacts that may arise in the future lagoon industry. This review shows that there is a valuable global literature resource representing solutions from other industries which should be further investigated for tidal lagoons.

5. Conclusion

There is pressure on the lagoon industry and in particular on Swansea Bay lagoon as a pilot scheme to ensure that any environmental impacts which may arise are addressed successfully. Swansea Bay lagoon needs to set the precedent on addressing its environmental impacts if the future UK and global lagoon industry is to flourish sustainably. With no operational tidal lagoon data available, there is no guidance on solution options for tidal lagoon environmental impacts. This review uses the PRISMA reporting guidelines methodology along with guidance from Collaboration on Environmental Evidence to consider a total of 1114 papers with a final 77 papers presenting solution options to the environmental impacts likely to arise as a result of tidal lagoon development.

The key environmental impacts according to industry engagement [28] are also shown in this review to have a reduced level of research available on solution options. These could present further concern for the industry and should be a focus for further research. Whilst this is a concern, the categories of solution options presented in the literature have also been shown to fill a gap in the current industry understanding.

The global spread of solution options gives the tidal lagoon sector a global audience and arena within which to both import and export knowledge and skills. The literature resource on solution options is vast and should be a valuable resource for the nascent lagoon industry. Other industries have applied similar engineering and technology concepts presenting and addressing the same environmental impacts which are expected of tidal lagoons. The lagoon industry can benefit from their hindsight and should capitalise on the opportunity to learn from their experience.

To conclude, this paper quantitatively analyses environmental management literature to identify the extent and relevance of this available research as a resource for the nascent lagoon industry. It opens the door on a vast and valuable research resource that the industry should be investigating. Over half of the solutions found in this review require only small shifts in their development for them to be realistic solution options for the lagoon industry in the future. This finding highlights and justifies the need for further investigation into transferable environmental management and policy options for application in the lagoon sector.

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References

[1] K. Elliott, H.C.M. Smith, F. Moore, A.H. van der Weijde, I. Lazakis, Environmental interactions of tidal lagoons: A comparison of industry perspectives, Renew. Energy. 119 (2018) 309–319. doi:10.1016/J.RENENE.2017.11.066.
[2] Tidal Lagoon Power Ltd, Swansea Bay Lagoon ProjectL Project Benefits, (2015). 〈http://www.tidallagoonswanseabay.com/the-project/project-benefits/54/〉 (Accessed 29 September 2015).
[3] D. Mackay, Sustainability Without the Hot Air, UIT Cambridge Ltd, 2009.
[4] Tidal Lagoon Power Ltd, Tidal Lagoon Power: Key Statistics, (2016). 〈http://www.tidallagoonpower.com/about/key-statistics/〉 (Accessed 1 January 2016).
[5] F. Harvey, Severn tidal power barrage plans slammed by MPs, Guardian. (2013). 〈https://www.theguardian.com/business/2013/jun/10/severn-tidal-power-barrage-plans-mps〉 (Accessed 19 April 2017).
[6] T. Hooper, M. Austen, Tidal barrages in the UK: Ecological and social impacts, potential mitigation, and tools to support barrage planning, Renew. Sustain. Energy Rev. 23 (2013) 289–298, https://doi.org/10.1016/j.rser.2013.03.001.
[7] S. Waters, G. Aggidis, A world first: Swansea Bay tidal lagoon in review, Renew. Sustain. Energy Rev. 56 (2016), https://doi.org/10.1016/j.rser.2015.12.011.
[8] Cebr, The Economic case for a tidal lagoon industry in the UK, 2014.
[9] C. Hendry, THE ROLE OF TIDAL LAGOONS FINAL REPORT, 2016. 〈https://hendryreview.files.wordpress.com/2016/08/hendry-review-final-report-english-version.pdf〉 (Accessed 7 February 2017).
[10] United Nations, Paris Agreement - Status of Ratification, Framew. Conv. Clim. Chang. (2016). 〈http://unfccc.int/2860.php〉 (Accessed 28 November 2016).
[11] Committee on Climate Change, UK climate action following the Paris Agreement, Paris, 2016. 〈https://www.theccc.org.uk/publication/uk-action-following-paris/uk-climate-action-following-the-paris-agreement-committee-on-climate-change-october-2016/〉.
[12] European Commission, Renewable Energy -What do we want to achieve, (n.d.). 〈http://ec.europa.eu/energy/en/topics/renewable-energy〉 (Accessed 19 April 2017).
[13] Parlimentary Business, Parliment Publ. (2016). 〈https://www.parliament.uk/business/committees/committees-a-z/commons-select/energy-and-climate-change-committee/news-parliament-2015/heat-transport-report-published-16-17/〉 (Accessed 10 November 2016).
[14] Tidal Lagoon Swansea Bay, Environmental Statement: Non-Technical Summary. The Proposed Tidal Lagoon Swansea Bay Order, 2014. 〈http://tidallagoon.opendebate.co.uk/files/TidalLagoon/DCO_Application/6.1_E.pdf〉.
[15] Tidal Lagoon Power Ltd, Swansea Bay Lagon Project Website, (2015). 〈http://www.tidallagoonswanseabay.com/〉 (Accessed 30 September 2015).
[16] Tidal Lagoon Power Ltd, Swansea Bay Lagoon Project - Planning, (2015). 〈http://www.tidallagoonswanseabay.com/planning/planning-process/〉61/ (Accessed 20 July 2016).
[17] S. Hinson, Briefing Paper Tidal Lagoons, 2018.
[18] T. a Adcock, S. Draper, T. Nishino, Tidal power generation – a review of hydrodynamic modelling, Proc. Inst. Mech. Eng. Part A J. Power Energy 0 (2015) 1–17, https://doi.org/10.1177/0957650915570349.
[19] R. Ahmadian, R. a Falconer, B. Bockelmann-Evans, Comparison of hydro-environmental impacts for ebb-only and two-way generation for a Severn Barrage, Comput. Geosci. 71 (2014) 11–19, https://doi.org/10.1016/j.cageo.2014.05.006.
[20] A. Angeloudis, R. Ahmadian, R. a Falconer, B. Bockelmann-Evans, Numerical model simulations for optimisation of tidal lagoon schemes, Appl. Energy. 165 (2016) 522–536, https://doi.org/10.1016/j.apenergy.2015.12.079.
[21] I. Fairley, R. Ahmadian, R. a Falconer, M.R. Willis, I. Masters, The effects of a Severn Barrage on wave conditions in the Bristol Channel, Renew. Energy 68 (2014) 428–442, https://doi.org/10.1016/j.renene.2014.02.023.
[22] J. Xia, R. a Falconer, B. Lin, Hydrodynamic impact of a tidal barrage in the Severn Estuary, UK, Renew, Energy. 35 (2010) 1455–1468, https://doi.org/10.1016/j.renene.2009.12.009.
[23] J. Xia, R. a Falconer, B. Lin, Impact of different tidal renewable energy projects on the hydrodynamic processes in the Severn Estuary, UK, Ocean Model. 32 (2010)

86–104, https://doi.org/10.1016/j.ocemod.2009.11.002.
[24] M.J. Lewis, S.P. Neill, a J. Elliott, Interannual variability of two offshore sand banks in a region of extreme tidal range, J. Coast. Res. 31 (2014) 1–12, https://doi.org/10.2112/JCOASTRES-D-14-00010.1.
[25] J.S. Pethick, R.K. a Morris, D.H. Evans, Nature conservation implications of a Severn tidal barrage – a preliminary assessment of geomorphological change, J. Nat. Conserv. 17 (2009) 183–198, https://doi.org/10.1016/j.jnc.2009.04.001.
[26] M. Kadiri, R. Ahmadian, B. Bockelmann-Evans, R. a Falconer, D. Kay, An assessment of the impacts of a tidal renewable energy scheme on the eutrophication potential of the Severn Estuary, UK, Comput. Geosci. 71 (2014) 3–140, https://doi.org/10.1016/j.cageo.2014.07.018.
[27] M. Kadiri, R. Ahmadian, B. Bockelmann-Evans, W. Rauen, R. Falconer, A review of the potential water quality impacts of tidal renewable energy systems, Renew. Sustain. Energy Rev. 16 (2012) 329–341, https://doi.org/10.1016/j.rser.2011.07.160.
[28] K. Elliott, H. Smith, F. Moore, I. Lazakis, H. Adriaan, A systematic review of transferable solution options for the environmental impacts of tidal lagoons, Mar. Policy. (2018).
[29] A. Angeloudis, R.A. Falconer, Sensitivity of tidal lagoon and barrage hydrodynamic impacts and energy outputs to operational characteristics, Renew. Energy. (2016), https://doi.org/10.1016/j.renene.2016.08.033.
[30] J. Xia, R. a Falconer, B. Lin, Impact of different operating modes for a Severn Barrage on the tidal power and flood inundation in the Severn Estuary, UK, Appl. Energy 87 (2010) 2374–2391, https://doi.org/10.1016/j.apenergy.2009.11.024.
[31] D. Moher, A. Liberati, J. Tetzlaff, D. Altman, The PRISMA Group, Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement, Ann. Intern. Med. 151 (2009), 〈http://annals.org/aim/article/744664/preferred-reporting-items-systematic-reviews-meta-analyses-prisma-statement?resultClick=3〉.
[32] Collaboration for Environmental Evidence, Guidelines and Standards for Evidence synthesis in Environmental Management., Version 5.0. (2018). 〈www.environmentalevidence.org/information-for-authors〉 (Accessed 11 April 2018).
[33] C. Liquete, C. Piroddi, et al., Current status and future prospects for the assessment of maine and coastal ecosystem services: a systematic review, PLoS One 8 (2013).
[34] B.C. O'Leary, H.R. Bayliss, N.R. Haddaway, Beyond PRISMA: systematic reviews to inform marine science and policy, Mar. Policy 62 (2015) 261–263, https://doi.org/10.1016/J.MARPOL.2015.09.026.
[35] P.C. Sierra-Correa, J.R. Cantera Kintz, Ecosystem-based adaptation for improving coastal planning for sea-level rise: a systematic review for mangrove coasts, Mar. Policy 51 (2015) 385–393, https://doi.org/10.1016/J.MARPOL.2014.09.013.
[36] C. Jacob, S. Pioch, S. Thorin, The effectiveness of the mitigation hierarchy in environmental impact studies on marine ecosystems: a case study in France, Environ. Impact Assess. Rev. 60 (2016) 83–98, https://doi.org/10.1016/j.eiar.2016.04.001.
[37] The Nature Conservancy, Achieving Conservation and Development. 10 principles for applying the mitigation hierarchy, 2015. 〈https://www.nature.org/ourinitiatives/applying-the-mitigation-hierarchy.pdf〉 (Accessed 16 April 2018).
[38] C. Jacob, S. Pioch, S. Thorin, The effectiveness of the mitigation hierarchy in environmental impact studies on marine ecosystems: A case study in France, Environ. Impact Assess. Rev. 60 (2016) 83–98, https://doi.org/10.1016/j.eiar.2016.04.001.
[39] L. Tso, THE GREEN BOOK Appraisal and Evaluation in Central Government Treasury Guidance, (n.d.).
[40] L. Weilgart, The impacts of anthropogenic ocean noise on cetaceans and implications for management, Can. J. Zool. (2007), 〈http://www.nrcresearchpress.com/doi/abs/10.1139/z07-101〉 (Accessed 18 January 2017).
[41] J. Wilson, M. Elliott, The habitat-creation potential of offshore wind farms, Wind Energy (2009), 〈http://onlinelibrary.wiley.com/doi/10.1002/we.324/full〉 (Accessed 16 January 2017).
[42] J. Petersen, T. Malm, Offshore windmill farms: threats to or possibilities for the marine environment, AMBIO: J. Hum. Environ (2006), 〈http://www.bioone.org/doi/abs/10.1579/0044-7447(2006)35〉 [75:OWFTTO]2.0.CO;2 (Accessed 16 January 2017).
[43] T.C. Weber, W.L. Allen, Beyond on-site mitigation: An integrated, multi-scale approach to environmental mitigation and stewardship for transportation projects, Landsc. Urban Plan. 96 (2010) 240–256, https://doi.org/10.1016/j.landurbplan.2010.04.003.
[44] B. Zanuttigh, E. Angelelli, G. Bellotti, A. Romano, Y. Krontira, D. Troianos, R. Suffredini, G. Franceschi, M. Cantù, L. Airoldi, F. Zagonari, A. Taramelli, F. Filipponi, C. Jimenez, M. Evriviadou, S. Broszeit, Boosting blue growth in a mild sea: analysis of the synergies produced by a multi-purpose offshore installation in the Northern Adriatic, Italy, Sustainability 7 (2015), https://doi.org/10.3390/su7066804.
[45] M.P. Schramm, M.S. Bevelhimer, C.R. DeRolph, A synthesis of environmental and recreational mitigation requirements at hydropower projects in the United States, Environ. Sci. Policy 61 (2016) 87–96, https://doi.org/10.1016/j.envsci.2016.03.019.
[46] S. Ludwig, R. Kreimeyer, M. Knoll, Comparison of PAM systems for acoustic monitoring and further risk mitigation application, Adv. Exp. Med. Biol. (2016), https://doi.org/10.1007/978-1-4939-2981-8_79.
[47] U.K. Verfuss, C.E. Sparling, C. Arnot, A. Judd, M. Coyle, Review of offshore wind farm impact monitoring and mitigation with regard to marine mammals, Adv. Exp. Med. Biol. (2016), https://doi.org/10.1007/978-1-4939-2981-8_147.
[48] J. Dabrowski, S. Peall, A. Reinecke, Runoff-related pesticide input into the Lourens River, South Africa: basic data for exposure assessment and risk mitigation at the catchment scale, Water, Air, Soil. (2002), 〈http://link.springer.com/article/10.1023/A:1014705931212〉 (Accessed 16 January 2017).
[49] N. Touili, J. Baztan, J.-P. Vanderlinden, I.O. Kane, P. Diaz-Simal, L. Pietrantoni, Public perception of engineering-based coastal flooding and erosion risk mitigation options: lessons from three European coastal settings, Coast. Eng. 87 (2014) 205–209, https://doi.org/10.1016/j.coastaleng.2014.01.004.
[50] D. Houser, A method for modeling marine mammal movement and behavior for environmental impact assessment, IEEE J. Ocean. Eng. (2006). 〈http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1645245〉 (Accessed 16 January 2017).
[51] V.J. Hendrick, Z.L. Hutchison, K.S. Last, Sediment burial intolerance of marine macroinvertebrates, PLoS One 11 (2016), https://doi.org/10.1371/journal.pone.0149114.
[52] I.A. Thomas, P. Jordan, P.-E. Mellander, O. Fenton, O. Shine, D.Ó. hUallacháin, R. Creamer, N.T. McDonald, P. Dunlop, P.N.C. Murphy, Improving the identification of hydrologically sensitive areas using LiDAR DEMs for the delineation and mitigation of critical source areas of diffuse pollution, Sci. Total Environ. 556 (2016) 276–290, https://doi.org/10.1016/j.scitotenv.2016.02.183.
[53] E.S. Brondizio, N.D. Vogt, A.V. Mansur, E.J. Anthony, S. Costa, S. Hetrick, A conceptual framework for analyzing deltas as coupled social–ecological systems: an example from the Amazon River Delta, Sustain, Science 11 (2016), https://doi.org/10.1007/s11625-016-0368-2.
[54] T.K. Frost, J.L. Myrhaug, M.K. Ditlevsen, H. Rye, Environmental monitoring and modeling of drilling discharges at a location with vulnerable seabed fauna: Comparison between field measurements and model simulations, in: Proceedings of SPE International Conference on Health, Safety, Security, Environment, and Social Responsibility, 2014 Journey Contin.,.
[55] E.M. Bitner-Gregersen, S.K. Bhattacharya, I.K. Chatjigeorgiou, I. Eames, K. Ellermann, K. Ewans, G. Hermanski, M.C. Johnson, N. Ma, C. Maisondieu, A. Nilva, I. Rychlik, T. Waseda, Recent developments of ocean environmental description with focus on uncertainties, Ocean Eng. 86 (2014) 26–46, https://doi.org/10.1016/j.oceaneng.2014.03.002.
[56] A. Copping, H. Battey, J. Brown-Saracino, M. Massaua, C. Smith, An international assessment of the environmental effects of marine energy development, Ocean Coast. Manag. 99 (2014), https://doi.org/10.1016/j.ocecoaman.2014.04.002.
[57] A. Copping, C. Smith, L. Hanna, H. Battey, J. Whiting, M. Reed, J. Brown-Saracino, P. Gilman, M. Massaua, Tethys: developing a commons for understanding environmental effects of ocean renewable energy, Int. J. Mar. Energy. 3 (2013) 41–51, https://doi.org/10.1016/j.ijome.2013.11.004.
[58] L.G. Torres, T.D. Smith, P. Sutton, A. Macdiarmid, J. Bannister, T. Miyashita, From exploitation to conservation: habitat models using whaling data predict distribution patterns and threat exposure of an endangered whale, Divers. Distrib. 19 (2013), https://doi.org/10.1111/ddi.12069.
[59] D. Bush, W. Neal, R. Young, O. Pilkey, Utilization of geoindicators for rapid assessment of coastal-hazard risk and mitigation, Ocean Coast. Manag. (1999), 〈http://www.sciencedirect.com/science/article/pii/S0964569199000277〉 (Accessed 18 January 2017).
[60] S.C. Gonçalves, J.C. Marques, Assessement and management of environmental quality conditions in marine sandy beaches for its sustainable use—virtues of the population based approach, Ecol. Indic. 74 (2017) 140–146, https://doi.org/10.1016/j.ecolind.2016.11.024.
[61] A. Yáñez-Arancibia, J.W. Day, E. Reyes, Understanding the coastal ecosystem-based management approach in the Gulf of Mexico, J. Coast. Res. 63 (2013), https://doi.org/10.2112/SI63-018.1.
[62] A.M. Knights, G.J. Piet, R.H. Jongbloed, J.E. Tamis, L. White, E. Akoglu, L. Boicenco, T. Churilova, O. Kryvenko, V. Fleming-Lehtinen, J.-M. Leppanen, B.S. Galil, F. Goodsir, M. Goren, P. Margonski, S. Moncheva, T. Oguz, K.N. Papadopoulou, O. Setälä, C.J. Smith, K. Stefanova, F. Timofte, L.A. Robinson, An exposure-effect approach for evaluating ecosystem-wide risks from human activities, ICES J. Mar. Sci. 72 (2015), https://doi.org/10.1093/icesjms/fsu245.
[63] C. Peterson, M. Bishop, Assessing the environmental impacts of beach nourishment, Bioscience (2005) (Accessed 18 January 2017), 〈http://bioscience.oxfordjournals.org/content/55/10/887.short〉.
[64] K. Mahmood, Reservoir sedimentation: impact, extent, and mitigation. Technical paper, (1987). 〈http://www.osti.gov/scitech/biblio/5564758〉 (Accessed 18 January 2017).
[65] O. Frihy, The necessity of environmental impact assessment (EIA) in implementing coastal projects: lessons learned from the Egyptian Mediterranean Coast, Ocean Coast. Manag (2001) (Accessed 16 January 2017), 〈http://www.sciencedirect.com/science/article/pii/S096456910100062X〉.
[66] L. Saussaye, H. Hamdoun, L. Leleyter, E. van Veen, J. Coggan, G. Rollinson, W. Maherzi, M. Boutouil, F. Baraud, Trace element mobility in a polluted marine sediment after stabilisation with hydraulic binders, Mar. Pollut. Bull. 110 (2016), https://doi.org/10.1016/j.marpolbul.2016.06.035.
[67] T. Zuliani, A. Mladenovič, J. Ščančar, R. Milačič, Chemical characterisation of dredged sediments in relation to their potential use in civil engineering, Environ. Monit. Assess. 188 (2016), https://doi.org/10.1007/s10661-016-5239-x.
[68] F. Goodsir, H.J. Bloomfield, A.D. Judd, F. Kral, L.A. Robinson, A.M. Knights, A spatially resolved pressure-based approach to evaluate combined effects of human activities and management in marine ecosystems, ICES J. Mar. Sci. 72 (2015), https://doi.org/10.1093/icesjms/fsv080.
[69] J.-P. Debenay, C. Marchand, N. Molnar, A. Aschenbroich, T. Meziane, Foraminiferal assemblages as bioindicators to assess potential pollution in mangroves used as a natural biofilter for shrimp farm effluents (New Caledonia), Mar. Pollut. Bull. 93 (2015), https://doi.org/10.1016/j.marpolbul.2015.02.009.
[70] K.L. Yates, D.S. Schoeman, C.J. Klein, Ocean zoning for conservation, fisheries and marine renewable energy: assessing trade-offs and co-location opportunities, J. Environ. Manag. 152 (2015), https://doi.org/10.1016/j.jenvman.2015.01.045.
[71] T. Jefferson, S. Hung, B. Würsig, Protecting small cetaceans from coastal development: Impact assessment and mitigation experience in Hong Kong, Mar. Policy

(2009), ⟨http://www.sciencedirect.com/science/article/pii/S0308597X08001255⟩ (Accessed 16 January 2017).

[72] M.G. Stigner, H.L. Beyer, C.J. Klein, R.A. Fuller, S. Carvalho, Reconciling recreational use and conservation values in a coastal protected area, J. Appl. Ecol. 53 (2016), https://doi.org/10.1111/1365-2664.12662.

[73] C.J. Brown, Social, economic and environmental effects of closing commercial fisheries to enhance recreational fishing, Mar. Policy 73 (2016), https://doi.org/10.1016/j.marpol.2016.08.010.

[74] T. Soomere, N.C. Delpeche-Ellmann, T. Torsvik, B. Viikmäe, Towards a new generation of techniques for the environmental management of maritime activities, Environmental Security of the European Cross-Border Energy Supply Infrastructure, 2015, https://doi.org/10.1007/978-94-017-9538-8_8.

[75] G. Lofrano, G. Libralato, D. Minetto, S. de Gisi, F. Todaro, B. Conte, D. Calabrò, L. Quatraro, M. Notarnicola, In situ remediation of contaminated marinesediment: an overview, Environ. Sci. Pollut. Res. (2016), https://doi.org/10.1007/s11356-016-8281-x.

[76] S. Sheavly, K. Register, Marine debris & plastics: environmental concerns, sources, impacts and solutions, J. Polym. Environ. (2007), ⟨http://link.springer.com/article/10.1007/s10924-007-0074-3⟩ (Accessed 16 January 2017).

[77] D. Sánchez-Quiles, A. Tovar-Sánchez, Are sunscreens a new environmental risk associated with coastal tourism? Environ. Int. 83 (2015) 158–170, https://doi.org/10.1016/j.envint.2015.06.007.

[78] R. Costanza, O. Pérez-Maqueo, M. Martinez, The value of coastal wetlands for hurricane protection, Hum. Environ. (2008), ⟨http://www.bioone.org/doi/abs/10.1579/0044-7447(2008)37⟩ [241:TVOCWF]2.0.CO;2 (Accessed 18 January 2017).

[79] R. Cochard, Chapter 12 – Coastal Water Pollution and Its Potential Mitigation by Vegetated Wetlands: An Overview of Issues in SoutheastAsia, in: Redefining Divers. Dyn. Nat. Resour. Manag. Asia, Vol. 1, 2017: pp. 189–230. doi:10.1016/B978-0-12-805454-3.00012-8.

[80] Y.K. Carrillo-Guerrero, K. Flessa, O. Hinojosa-Huerta, L. López-Hoffman, From accident to management: the Cienega de Santa Clara ecosystem, Ecol. Eng. 59 (2013), https://doi.org/10.1016/j.ecoleng.2013.03.003.

[81] R. Marsooli, P.M. Orton, N. Georgas, A.F. Blumberg, Three-dimensional hydrodynamic modeling of coastal flood mitigation by wetlands, Coast. Eng. 111 (2016) 83–94, https://doi.org/10.1016/j.coastaleng.2016.01.012.

[82] R. Schulz, Field studies on exposure, effects, and risk mitigation of aquatic non-point-source insecticide pollution, J. Environ. Qual. (2004), ⟨https://dl.sciencesocieties.org/publications/jeq/articles/33/2/419?highlight=&search-result=1⟩ (Accessed 16 January 2017).

[83] W. Pei, Y.Y. Zhu, L. Zeng, S.X. Liu, X.J. Wang, Z.J. An, The remote sensing identification of marine oil spill based on oil fingerprinting, 2013 doi: 10.1007/978-3-642-45025-9_74.

[84] J. Mayo-Ramsay, Environmental, legal and social implications of ocean urea fertilization: Sulu sea example, Mar. Policy 34 (2010) 831–835, https://doi.org/10.1016/j.marpol.2010.01.004.

[85] N. Tri, W. Adger, P. Kelly, Natural resource management in mitigating climate impacts: the example of mangrove restoration in Vietnam, Glob. Environ. Chang (1998), ⟨http://www.sciencedirect.com/science/article/pii/S095937809700023X⟩ Accessed 18 January 2017.

[86] D.A. Friess, J. Phelps, E. Garmendia, E. Gómez-Baggethun, Payments for Ecosystem Services (PES) in the face of external biophysical stressors, Glob. Environ. Chang. 30 (2015), https://doi.org/10.1016/j.gloenvcha.2014.10.013.

[87] S. Luo, F. Cai, H. Liu, G. Lei, H. Qi, X. Su, Adaptive measures adopted for risk reduction of coastal erosion in the People's Republic of China, Ocean Coast. Manag. 103 (2015), https://doi.org/10.1016/j.ocecoaman.2014.08.008.

[88] M. Gavrilescu, K. Demnerová, J. Aamand, S. Agathos, F. Fava, Emerging pollutants in the environment: Present and future challenges in biomonitoring, ecological risks and bioremediation, N. Biotechnol. 32 (2015), https://doi.org/10.1016/j.nbt.2014.01.001.

[89] H. Tallis, C.M. Kennedy, M. Ruckelshaus, J. Goldstein, J.M. Kiesecker, Mitigation for one & all: An integrated framework for mitigation of development impacts on biodiversity and ecosystem services, Environ. Impact Assess. Rev. 55 (2015) 21–34, https://doi.org/10.1016/j.eiar.2015.06.005.

[90] N. Teichert, A. Borja, G. Chust, A. Uriarte, M. Lepage, Restoring fish ecological quality in estuaries: Implication of interactive and cumulative effects among anthropogenic stressors, Sci. Total Environ. 542 (2016), https://doi.org/10.1016/j.scitotenv.2015.10.068.

[91] A. Bas, C. Jacob, J. Hay, S. Pioch, S. Thorin, Improving marine biodiversity offsetting: a proposed methodology for better assessing losses and gains, J. Environ. Manag. 175 (2016) 46–59, https://doi.org/10.1016/j.jenvman.2016.03.027.