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Opportunities for tidal range projects beyond energy generation: using Mersey barrage as a case study

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Opportunities for tidal range projects beyond energy generation: using Mersey barrage as a case study

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Abstract

Currently there is renewed interest in harnessing the vast tidal resource to combat the twin challenges of climate change and energy security. However, within the UK no tidal barrage proposals have passed the development stage, this is due to a combination of high cost and environmental concerns. This paper demonstrates how a framework, such as the North West Hydro Resource Model can be applied to tidal barrages, with the Mersey barrage as a case study. The model materialised in order to provide developers with a tool to successfully identify the capacity of hydropower schemes in a specific location. A key feature of the resource model is the understanding that there is no single barrier to the utilisation of small hydropower but several obstacles, which together impede development. Thus, this paper contributes in part to a fully holistic treatment of tidal barrages, recognising that apart from energy generation, other environmental, societal and economic opportunities arise and must be fully investigated for robust decision-making. This study demonstrates how considering the societal needs of the people and the necessity for compensatory habitats, for example, an organic architectural design has developed, which aims to enhance rather than detract from the Mersey.

Keywords

Renewable energy; Tidal power; tidal barrage; Mersey Estuary; Architectural concepts; Environmental concepts.

1 Introduction

Tidal range energy represents a vast and unexploited worldwide resource. The UK has the potential to generate large amounts of renewable energy from the tidal range (Burrows, et al., 2009), with a theoretical estimate in the region of 120 TWh/year (The Crown Estate, 2012). However, within the UK there are as yet no attempts to exploit the UK's large tidal range resource with tidal barrages. Nonetheless there has been a renewed interest in tidal energy in recent years in the face of current and anticipated issues of security of supply and the need to find local sources of renewable energy (Petley & Aggidis, 2016) (Uihlein & Magagna, 2016) (Hendry, 2017) (Rajgor, 2016). Moreover, the recent Paris agreement (United Nations, 2015) has put further emphasis on the substantial decarbonisation challenge that nations will face in the coming decades, while the UK will go through extensive political challenges as a result of the upcoming withdrawal from the European Union (PricewaterhouseCoopers, 2016). The resulting effect this will have on energy policy is yet unknown (Durham Energy Institute, 2017).

In recognition of the UK's unique position in terms of resource and as an island nation, there have been many proposals for tidal barrages and lagoons at various sites, generally on the west coast, going back several decades (Aggidis, 2010) (Aggidis & Feather, 2012) (Baker, 2006) (Waters & Aggidis, 2016) (Sustainable Development Commission, 2007). Table 1, outlines the status of several of these projects.

Location	**Mean Tidal Range (m)**	**Potential Output (TW h/yr)**	**Latest Reporting**
Severn	9.8	16.8	It was estimated that the Severn Barrage could alone generate 5% of UK electricity needs, however since 2011 when the project was shelved by the UK government there have been no new proposals (Melikoglu, 2018).
Solway	5.5	9.44	No tidal range energy schemes are publicly planned for the Solway however there is a number of reports of significant potential (Neill, et al., 2017)
Swansea Bay Lagoon	8.5	0.53	Tidal Lagoon Power Ltd have proposed a 320 MW tidal lagoon, which was awarded a Development Consent Order in 2015 (Tidal Lagoon Power Ltd, 2018). With the aim to begin construction in 2018.
Wyre	6.6	0.3	New Energy Wyre proposed at 160 MW tidal barrage across Wyre Estuary. As of November 2017 Atlantis Resources signed terms with the Duchy of Lancaster for an option for the long-term lease of the riverbed (Atlantis Resources, 2017).
Morecambe Bay	6.3	4.63	A barrage construction across Morecambe Bay is one of a larger scheme as part of Northern

			Tidal Power Gateways Ltd proposals, currently in review stage (Mott MacDonald, 2017).
Mersey	6.45	0.92	Peel Energy part of Peel Holding who own Port of Liverpool proposed in 2011 a 700 MW scheme, though progress stalled due to cost agreements implications (BBC, 2017).

Table 1: UK tidal range schemes and proposals

The aim of this paper was to investigate the potential contributions of tidal range energy beyond the energy generation possibilities, looking specifically from an architectural perspective. For the purposes of providing a case study we aim to address the viability of the most recent Mersey tidal barrage proposal which was initiated by Peel Energy and the Northwest Development Agency (NWDA) in 2006. The Mersey Tidal Power Feasibility Study: Stage 3 was released in 2011 and documented the extensive studies that had been carried out into the potential barrage including; ideal location, type of turbines to be used and the effect on the environment (Peel Energy, 2010). The Mersey is of particular interest to the authors due to the proximity to our homes and work places and the recently elected Liverpool Mayor Steve Rotheram has stated that it is one of his “major priorities” for the city, reinvigorating interest in the project, which stalled in 2011 (Liverpool Echo, 2018).

2 The Mersey Barrage

The Mersey Estuary has one of the largest tidal ranges in the UK, making it a highly suitable location for a tidal energy generation scheme. There have been a number of different barrage proposals suggested for the Mersey; in 1988 Marinetech North West initially investigated the potential of tidal power in the Mersey estuary in collaboration with the Department of Energy and the United Kingdom Atomic Energy Authority. A few years later in 1992 the Mersey Barrage Company continued this research and carried out further studies between 1988 and 1992 (Mersey Barrage Corporation, 1992). The results of these studies were published in two sets of conference notes by the Institute of Civil Engineers. More recently, Peel Holdings, as part of the Atlantic Gateway proposal, carried out an extensive feasibility study into a tidal barrage across the Mersey. As well as the main feasibility report a series of 9 technical reports were produced. All the reports concluded that a Mersey tidal barrage would be a very successful and sustainable scheme with a lifespan of 120 years. However, the project stalled due to the high capital costs compared to other forms of renewable energy. It was suggested that a number of things could take place to encourage initial capital investment, such as coupling the barrage with another infrastructure project and offering research and education into hydropower to begin changing the public perception of tidal power. Community consultations also raised concerns about the visual impact of the scheme, environment and wildlife, particularly bird and fish populations. Finding a way to minimise these impacts as well as providing compensatory habitats would be essential before the project could go ahead.

2.1 Location and Wider Context

In line with the Peel Holdings report, as well as the earlier reports by the Mersey Barrage Corporation (Mersey Barrage Corporation, 1992), the planned location for the barrage will be between Liverpool Festival Gardens and Port Sunlight River Park. Sitting to the south of the city centre this location affects residential areas on either side of the river. On the south bank the affluent rural community of Port Sunlight and on the north, the very mixed demographic of Dingle. However, the waterfront parks on both sides act as a buffer to the residents and create green gateways to the development. In 2000, the NWDA proposed that a series of regional parks in the North West of England could unify the river Mersey waterfront. The Mersey Waterfront Regional Park (MWRP) Strategic Framework identifies 14 unique "windows to the waterfront" and describes a development plan for each (Mersey Basin Campaign, 2007). Our site at the Liverpool Festival Gardens has been identified as "riverlands" and is the only area of urban greenspace to meet the riverfront. The MWRP envisions land form art work, events space and better connections from St Michael's the station to the river will help to animate the area. The development of each window aims to:

1. Consider the influence of the estuary and coast
2. Create a stronger sense of identity
3. Ensure connectivity
4. Incorporation existing assets.

The proposition of establishing a tidal barrage in this location does not counteract any of these ambitions for the "riverlands" window. A development like this will help the area to achieve these goals. The influence of the estuary and coast in this area has already been proven highly suitable for a tidal barrage. A piece of architectural infrastructure of this scale will be identifiable not only locally, but globally as it will be unique in the world. The barrage itself will form a new green connection, from Liverpool to the Wirral expanding on the park assets either side.

In addition, the barrage scheme is sited within the wider regional development plan known as the Atlantic Gateway. The Atlantic Gateway scheme proposes to better connect Liverpool City Region, Cheshire, and Greater Manchester by means of a business investment plan and a network of parklands. The scheme aims to attract investment in high growth sectors such as logistics and science & innovation and accelerate economic growth by delivering major infrastructure projects.

Our proposal to combine a tidal barrage with a green river crossing presents a fantastic opportunity to bookend the Atlantic Gateway with a large-scale infrastructure project that responds to both the business plan as well as the parklands framework. In addition to a tidal barrage, we propose a world centre for hydropower research that will be a global leader in science and innovation. Finally, we propose a monorail system that connects to the existing rail networks and creates a new commuter link between

Liverpool and the Wirral, with the aim of reducing the pressure on the road network in line with the Atlantic Gateway.

2.2 Prior Art

Tidal range power is generated from a head difference between two bodies of water (Prandle, 1984). To create this difference an impoundment dam is used to separate the two areas and as the tide flows in or out, the dam blocks the flow of the tide and creates a head difference. When the head difference has reached an optimum level, the water passes through the turbines placed within the dam (Charlier & Finkl, 2009). With two tidal cycles per day, this head difference is created four times each day (as the tide comes in and out). Thus, energy can be generated in either direction, known as flood and ebb modes and in both directions, known as dual mode.

Generating electricity using tidal barrages is mature and reliable (O'Rourke, et al., 2010) and has been utilised most effectively in France and South Korea (Waters & Aggidis, 2016), which is described below.

2.2.1 La Rance Tidal Barrage, France

The oldest barrage in the world was constructed at La Rance in France (Figure 1), and began operating in 1966 (Cottillon, 1978). The barrage is 720 m long, which encloses a surface area of 22 km^2 of the estuary. Twenty-four 5.35 m diameter reversible 10 MW Alstom Hydro bulb turbines are operating with a typical hydrostatic head of 5 m. The flow of water amounts to some 24000 m^3/s. The mode of operation of the La Rance tidal power facility uses a combination of two-way generation and pumped storage. The station was linked to France's National grid allowing the rising of the reservoirs level by pumping, thus at high tide the overfilling raises the head by some meters (Charlier & Finkl, 2009). Pumping from the sea to the basin is carried out at certain tides to enhance generation on the ebb. La Rance demonstrates well the feasibility of tidal barrages and has provided some useful information on how they can be operated, it has a very good track record and provides a useful road link across the estuary. Since the plant has been in operation the average output is 68 MW and currently generates around 480 GWh per year (O'Rourke, et al., 2010).

Figure 1: Photograph of La Rance tidal barrage from above (de Laleu, 2009)

2.2.2 Lake Sihwa Tidal Barrage, South Korea

Sihwa is an artificial lake that was created with the construction of a dam in 1994 (Bae, et al., 2010). The lake was used to secure agricultural water for the region but over time had become stagnant and contaminated by the nearby industrial metropolis (Park, 2007). It was decided to open the reservoir to the sea and not only utilise the tidal capacity to generate power but improve the quality of water in the lake and bring back wildlife. The positive effect on the ecosystem is carried through to the operation of the turbines which only generate energy from the flood tide to allow water to circulate freely. A man-made island was constructed by use of a coffer damn into which foundations were laid for an eco-park. Sihwa has 10 turbines and has a maximum output of 254 MW (Schneeberger, 2008) generating an estimated 550 GWh annually in the flood direction only (Borthwick, 2016).

Sihwa provides an interesting case study of how a tidal barrage has been used to mitigate an environmental problem caused by a prior mismanaged and poorly planned dam infrastructure. Planning and construction management is increasingly considering environmental and socio-economic benefits of coastal structures to minimise or mitigate ecological impacts (John, et al., 2015) right from the conception stage (Naylor, et al., 2011).

2.2.3 Site Specification and Engineering Options

There have been a number of studies assessing the potential energy generation from a tidal barrage on the Mersey estuary using a variety of different models, barrage parameters and operational modes. The Department of Energy carried out a study in 1984 (Department of Energy and UKAEA, 1984), followed by Mersey Barrage Company in 1992 (Mersey Barrage Corporation, 1992), the 'Joule' Project by the University of Liverpool and Proudman Oceanographic Laboratories in 2009 (Burrows, et al., 2009) and the Peel Energy Limited and Northwest Regional Development Agency feasibility study in 2011 (Libaux, 2011). A recent study at Lancaster University (Aggidis & Benzon, 2013) reviewed the predicted energy outputs of the studies described in Table 2 using the latest double regulated turbine technology from Andritz Hydro (Aggidis & Feather, 2012) and improved bathymetric data. Results highlighted that, for operating modes of ebb generation with and without additional pumping, these turbines increased predicted annual energy output by around 20 %.

Study	Year	Capacity (MW)	Output (TWh/yr)	Physical and operational parameters	Source
Department of Energy	1984	621	1.32	27 × 7.6 m ⌀, 23 MW turbines, with 18 sluice gates. Ebb generation	(Peel Energy, 2011)
Mersey Barrage Company	1991	700	1.45	28 × 8 m ⌀, 25 MW turbines, with 47 channel sluices. Ebb generation	(Sustainable Development Commission, 2007)
University of Liverpool, Joule project	2009	621	1.07	27 × 7.6 m ⌀, 23 MW turbines, with 18 sluice gates. Ebb generation (	(Burrows, et al., 2009)
University of Liverpool, Joule project	2009	621	0.98	27 × 7.6 m ⌀, 23 MW turbines, with 18 sluice gates. Ebb and flood generation	(Burrows, et al., 2009)
University of Liverpool, Joule project	2009	1863	1.72	81 × 7.6 m ⌀, 23 MW turbines, without sluice gates. Ebb and flood generation	(Burrows, et al., 2009)
Mersey Tidal Power	2010	700	0.90	28 × 8 m ⌀, 25 MW turbines, with 18 sluice gates. Ebb generation with fixed starting head of 3.9 m	(Aggidis & Benzon, 2013)
Mersey Tidal Power	2011	700	0.92	28 × 8 m ⌀, 25 MW turbines, with 18 sluice gates. Flexible ebb generation with starting head optimised for maximum energy for 8 months and head limited to 3 m for 4 months of every year	(Peel Energy, 2011)

Table 2: Comparison of configuration and predicted energy outputs of previous Mersey barrage studies (Becker, et al., 2017)

3 Opportunities from Tidal Barrages

Any tidal barrage scheme is unique among power generation installations, in that it is an inherently multi-functional infrastructure offering such potential services as; flood mitigation (Prime, et al., 2018) , possible road and rail transport links (Faber Maunsell and Metoc, 2007), and significant amenity or leisure opportunities (Parson Brinckerhoff, 2008) . Thus, a fully holistic treatment of overall cost-benefit is imperative for robust decision-making. It is suggested that, to date, this position has been inadequately addressed in the formulation of energy strategy, especially in respect of barrages' potential strategic roles in flood defence and transportation planning (Aggidis, 2010). It follows, therefore, that apart from the direct appraisal of energy capture, other complementary investigations must be sufficiently advanced to enable proper input in decision-making in respect of these 'secondary' functions, as well as the various potentially adverse issues, such as sediment regime change (Kim, et al., 2017) (Kadiri, et al., 2012), impact on navigation and environmental modification (Kirby & Retière, 2009) (Xia, et al., 2010) (Hooper & Austen, 2013). As a high-level means of assessing natural and societal advantages and disadvantages of tidal barrages, impacts on ecosystems and associated societal benefits have been considered. The decision making process (Figure 2)**Error! Reference source not found.** has been adapted from the North West Hydro Resource Model developed at Lancaster University (Aggidis, et al., 2006).

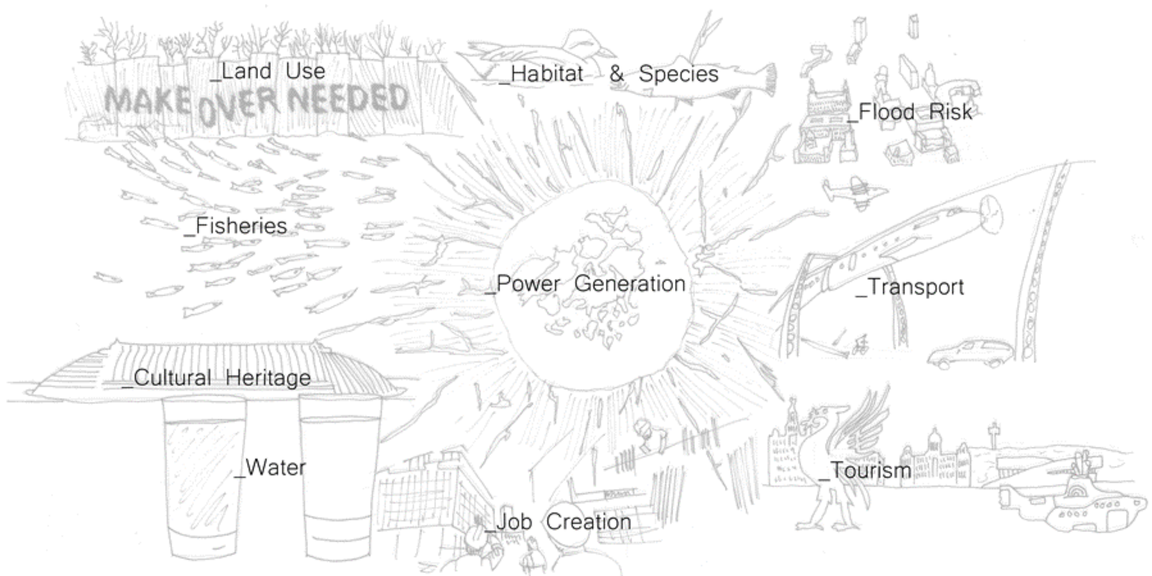

Figure 2: Design Manifesto - from the North West Hydro Resource Model

In previous studies an Ecosystems Services approach (Callaway, et al., 2017) has been used to appraise the benefits and costs of a large civil engineering project such as a tidal barrage. This can be defined as ‘a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way, and which recognises that people with their cultural and varied social needs, are an integral part of ecosystems’ (Secretariat of the Convention on Biological Diversity, 2004). The ecosystem services approach requires that all potential benefits from a development are weighed against anticipated costs taking the whole system into account. In line with this approach, the Ecosystem Services can be defined as such:

- Supporting services: geology and tidal currents, sediments and hydrodynamics
- Provisioning services: benthic ecology, fisheries and birds
- Cultural services: economy and tourism

The environmental implications of tidal barrage schemes remain one of the most significant obstacles for decision makers (Mackinnon, et al., 2018). Estuaries are often home to a number of unique habitats and species – particularly those with a very high tidal range, as this results in particularly harsh conditions that only some species can endure. As with hydropower dams, tidal barrages could have a major impact on local environments, with concerns raised over wider biodiversity objectives (World Commission on Dams, 2000). An Ecosystem Services approach would balance the negative environmental impact with the potential for flood protection services should global warming lead to the predicated sea level rise (IPCC, 2013), which would have an equally negative impact on habitats (Chen & Liu, 2017). It can be argued that further regulatory guidance or policy should be developed to provide a coherent framework to developers with specific regards to the environmental legislation. Indeed, recent interviews conducted have found that there is a disparity between the views of tidal project developers and other influencing stakeholders, such as government bodies, regulators, conservationists and practitioners, in terms of the compromise between environmental impacts and potential benefits (Mackinnon, et al., 2018).

The concept envisioned for the Mersey barrage will attempt to use the Ecosystem Services framework and the following subsections demonstrate how a number of key issues will be addressed as part of the design process. The Mersey barrage concept will attempt to create an iconic infrastructure project that promotes research and education into hydropower, while connecting communities over the River Mersey that will have not been connected by land before. To compensate for the negative ecological effects of the barrage, wildlife will be integrated into the core of the design, providing varied habitats to encourage positive increase in bio diversity on the Mersey Estuary. All the while the parasitic architectural typology will have a global impact turning existing water tower into a habited space that are powered by the water the towers are in proximity to.

3.1 Design Masterplan

The masterplan for the project (Figure 4), developed with the constraints imposed by several key issues, five of which are listed in Table 3, with their respective design strategy to accomplish them.

Key Issues	Key Strategies
Scale	Reclaiming land from the Mersey tackles both the scale and issue of building on water, Figure demonstrates the scale of the project by showing the length of the barrage in terms of 10 Liverpool Anglican Cathedrals
Building on Water	Nodes will be created along the barrage to break up the journey
Elegance	Using sweeping curvilinear forms to contradict the traditional straight line of a dam
Environment	Create a diverse range of habitats
Interaction	Floating elements and gardens to maintain contact with the water

Table 3: Design Masterplan key issues and strategies

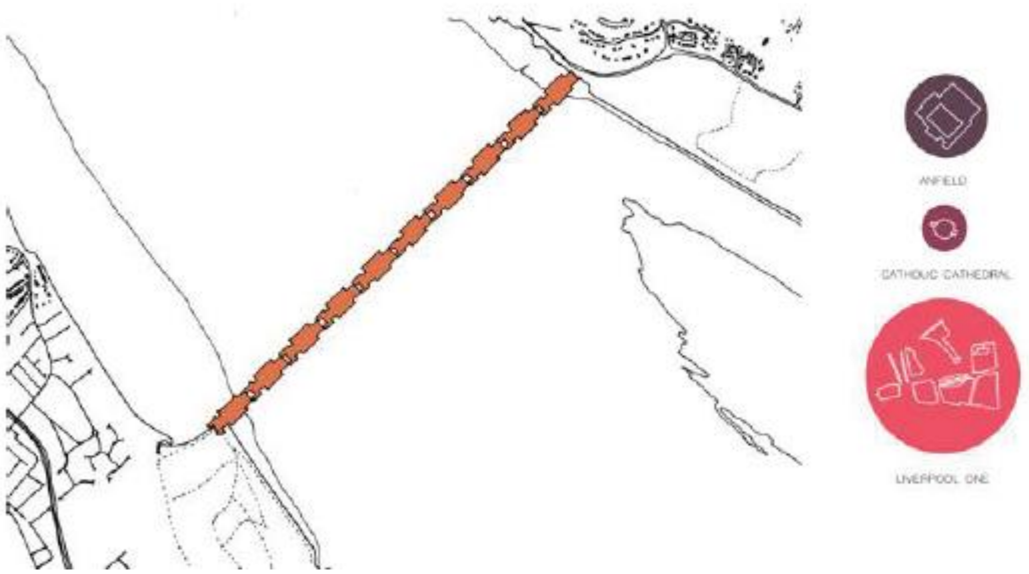

Figure 3: Scale diagram with 10 Anglican Cathedrals highlighted in orange

Further engineering constraints are the twenty-eight 8 m diameter turbines placed in a housing and the positioning of commercial and industrial size locks in the river, which could not be changed without considerable deductions to their functionality. Other existing factors such as the Site of Special Scientific interest on the Wirral bank of the river has influenced the design from a wildlife perspective (Wirral Council, 2018). As well as providing a green link between two recreational parks the Mersey barrage presents an opportunity for commuters travelling to and from Liverpool City centre. As such, it is important that the masterplan includes a light rail link that connects to existing transport networks. This, as well as a new waterfront housing development generate revenue to pay for the scheme.

The design of the barrage has been carefully considered and demonstrates how an engineering project can evolve from a simple dam into a sweeping curve. Pulling green space from the northern point of Liverpool Festival Gardens, and the southern point of Port Sunlight River Park into the river. The two parks become thinner, turning into paths as they near the centre.

Buildings for habitation and recreation have been situated at the most dramatic location in the middle of the Mersey. The series of towers that support the buildings surround a landscaped island. Some grow directly out the island to provide access at ground level. Others emerge from the water and are accessed via elevated pathways. Either side of the central island the riverbed is dug away to form trenches in which the sluice gates casing and turbine casing sit. Landscaping to the top of these accommodates pedestrians', cyclists and wildlife. Beyond these the shipping locks and artificial mudflats sit to the south approaching Port Sunlight and the reclaimed festival gardens and fish ladder to the north, adjoining Liverpool. Continuous elements such as paths for pedestrians and cyclists and the Monorail link tie the whole scheme together as well as to the context and transportation networks. The following subsections cover these in greater detail.

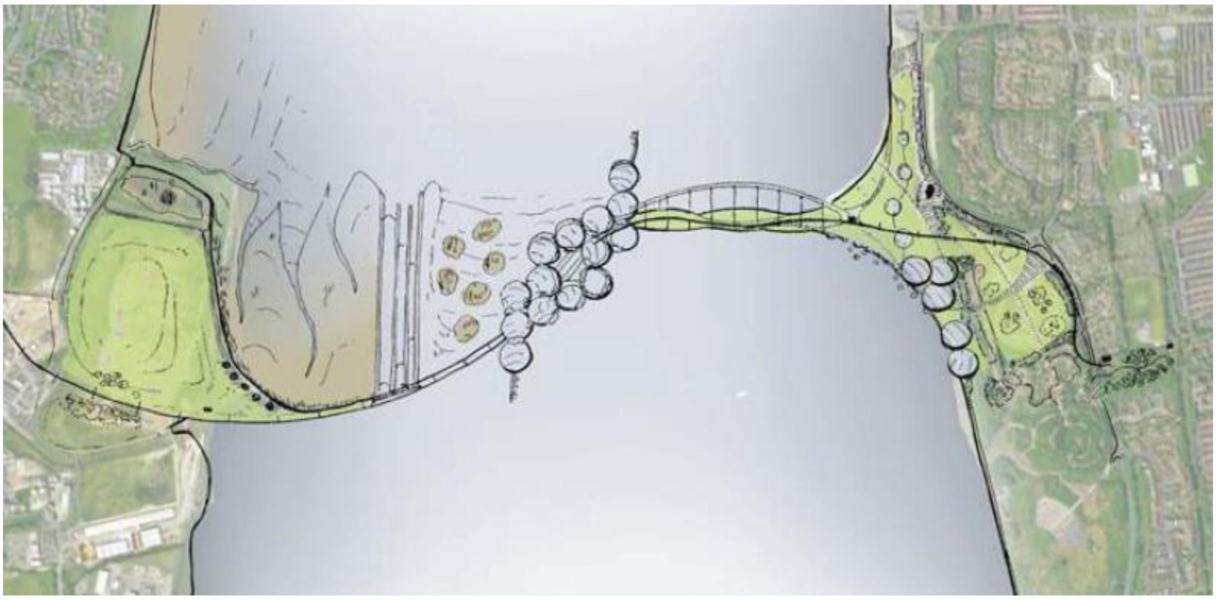

Figure 4: Artistic outline of barrage in situ

3.2 Connecting Communities

"Joining two waterfront parks" - The location of the Peel Holdings barrage proposal and the lack of waterfront urban green space in Liverpool led us naturally to the concept of creating a green bridge. The idea of creating a green bridge (Figure 5) also holds connotations of environmental understanding. This awareness of the environmental implications of imposing a dam across the river Mersey is a key aspect of our proposal.

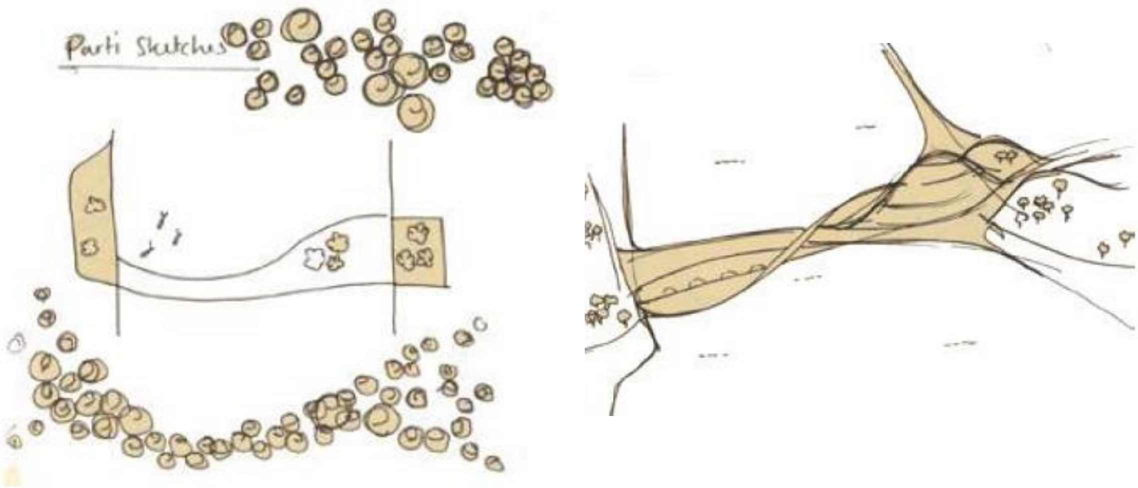

Figure 5: Artistic sketch - The Green Bridge concept

Continuous elements such as paths for pedestrians and cyclists and the Monorail link tie the whole scheme together as well as to the context and transportation networks. The proposal connects St Michaels train station, Liverpool with Port Sunlight Station, Wirral via an overhead monorail system. The monorail itself will stop at three points along its route. The monorail will also be fundamental in providing service access to the largescale development in the middle of the Mersey in addition to water-based access. In this way, the servicing and maintenance aspect of the development is kept separate from the pedestrian walkways and cycle routes. Furthermore, the potential for the use of a suspended monorail system pays homage to Liverpool's former overhead railway, (also known as the "Dockers Umbrella" because Dockers walked beneath it as they went about their business, and it could protect from the rain) which was closed in the late 1950's. Examples of suspended monorails from Wuppertal, Germany have been used as inspiration.

3.3 Repurposing the Structure

"A symbiotic relationship with a living creature" - Currently there is a differentiation between the widely accepted and acclaimed idea of using renewable energy to sustain the planets resources and the generally imposing physical infrastructure that allows us to do that. In other words, the physical infrastructure required to generate renewable energy is generally seen as "ugly" and detrimental to the value of generated renewable energy in the mind of the public (Bonar, et al., 2015). However, the Swansea Bay tidal lagoon project has shown how through public consultation and engagement this prejudice can be negated (Manley, 2016). One of the key aims of the Mersey barrage concept is to assimilate the physical imposition of a barrage with the purity of the concept of renewable energy. To do this is we can use architecture and landscape design to imagine a symbiotic relationship with the barrage, viewing it as a living creature from which we advance our knowledge and to which we apply poetry and activity. Visualising the barrage and all engineering components of the project as the whale (Figure 6) upon whose back we build our civilisation helps us to imagine a two-way relationship between architecture and engineering, which is especially integral to the project.

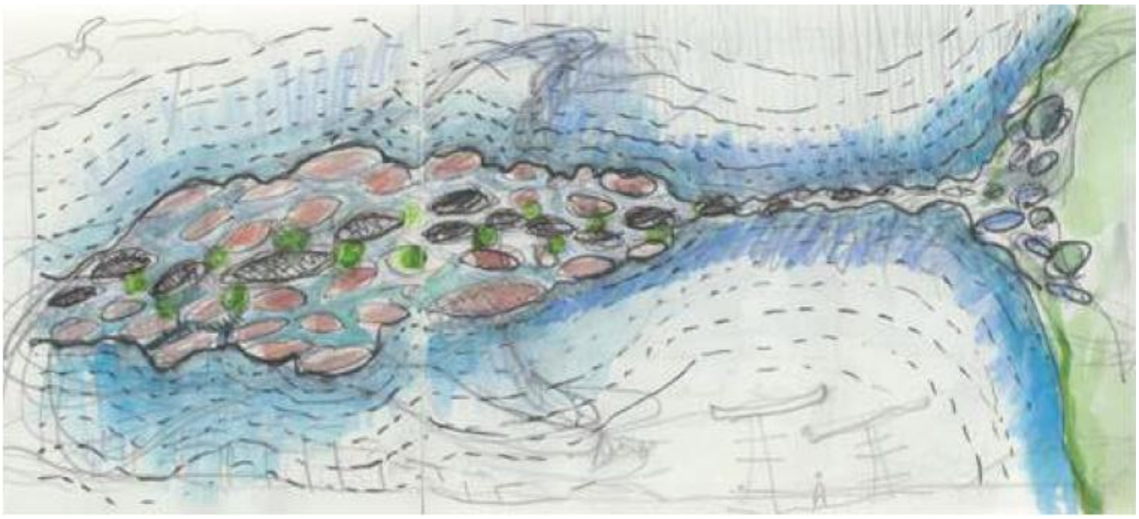

Figure 6: Artistic sketch - Reimagined Infrastructure

As part of the symbiotic relationship with nature, the project aims to employ biomimicry as a design approach. Drawing structural inspiration from habitats and anatomy can help improve the efficiency of the project in terms of the amount of material needed to construct certain parts of the barrage (Pawlyn, 2011). One example of biomimicry is the nest of the Reed Warbler (Figure 7), which is weaved as a sling basket between several reed stems. This can be incorporated into the structure by creating a parasitic form of architecture that attaches to the ridged infrastructure that serves it, the system is analogous to the Tree Hopper concept idea (Figure 8), where a number of tree tents would be arranged around a pre-existing tree trunk.

Figure 7: Nest of the Reed Warbler

Figure 8: Tree Hopper

Furthermore, part of the societal benefit will be the development of the World Centre for Hydropower research, which will form the main architectural proposition for the Mersey barrage scheme (Figure 9). This will be a world-class facility for both academic research with collaboration from a number of global institutions and for public education. Initially it was conceived that this centre in the middle of the river would have a strong identity as a self-sufficient organisation with a unique water-based atmosphere and composition. To achieve this, the initial design saw the development rising out of the water in a dome shape that enclosed the barrage creating an end to the dam before reaching the locks. This has been altered to create a wave shape by lifting one side of the dome to reveal reed-like stilts supporting buildings underneath the dome shell.

In parallel with the idea of public engagement, the idea of creating an inhabited water tower for the residential blocks on either side of the river was conceived to increase the efficiency of the tidal barrage. The height of the tower blocks needed to generate sufficient revenue for the project could also be used to store excess energy created by the barrage. In theory, surplus energy could be used to pump water to a high place and then released through a turbine when needed. Recognising the potential in this idea its application took a more central role in the development of the scheme. Locating a cluster of water towers in the centre of the barrage introduces a visible engineering component to the scheme upon which to showcase the junction between architecture and engineering.

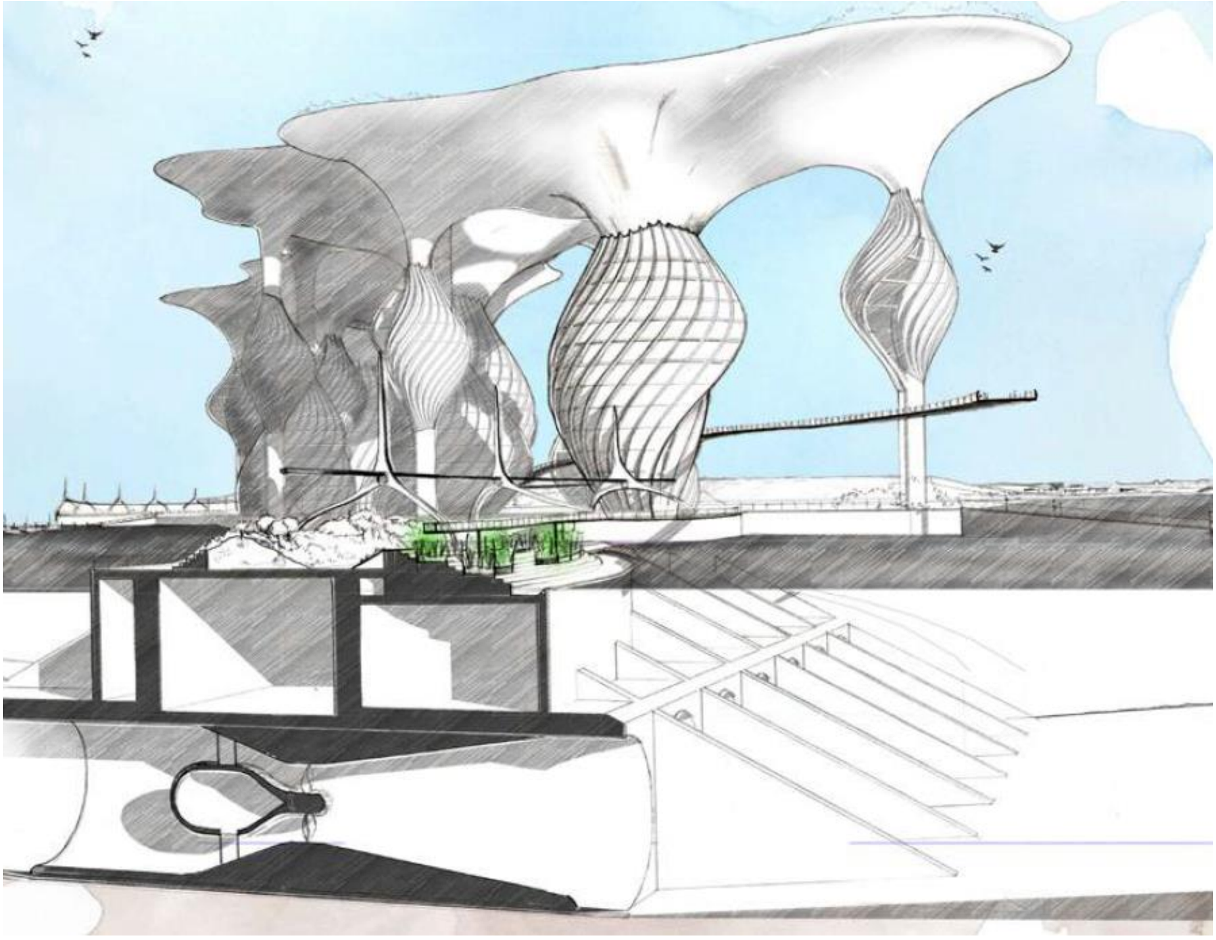

Figure 9: Section through turbine house with residential water towers and World Hydropower Research Centre above

3.4 Integrating Wildlife

"Encouraging growth" - Consideration for the wildlife affected by the project has been a key driver of the design from the initial zoning up to the final proposal. According to Article 6(4) of the 'Habitats Directive' 92/43/EEC: development cannot go ahead in an area that hosts significant natural habitat and species, unless proven to be of overriding public interest and specific to that location (European Commission, 1992) . If these two requirements are met, the next stage is to supply compensatory habitat to offset the loss of inter-tidal mud caused by the implementation of a tidal barrage. Based upon the report on "The Evolution of the Artificial Wildbird Tidal Mudflat in Fukuoka, Japan" (Docto & Walls, 2012) we intend to recreate the conditions most frequently visited by birds in the Mersey within our design proposal. Given the size of the area affected it is impossible to fully accommodate a like for like compensatory habitat on site, instead we propose to increase the biodiversity of the area but introducing a range of habitats that will encourage the population of other species of bird in the area. This includes mud flats, wetlands, grasslands, reed beds and rock pools.

The scheme has developed to provide an array of habitats by way of compensation as well as a large area of new intertidal mud (Figure 10) (Figure 11). The creation of mud flats on the Port Sunlight side of the river informed the curve of the dam that stretches away from the mound. Pushing the dam back towards the southern corner of the park creates an alcove between the mound and the locks where mud can be allowed to build up and water levels controlled just as it does in the wetland area of the park and the mud flats adjoining New Ferry.

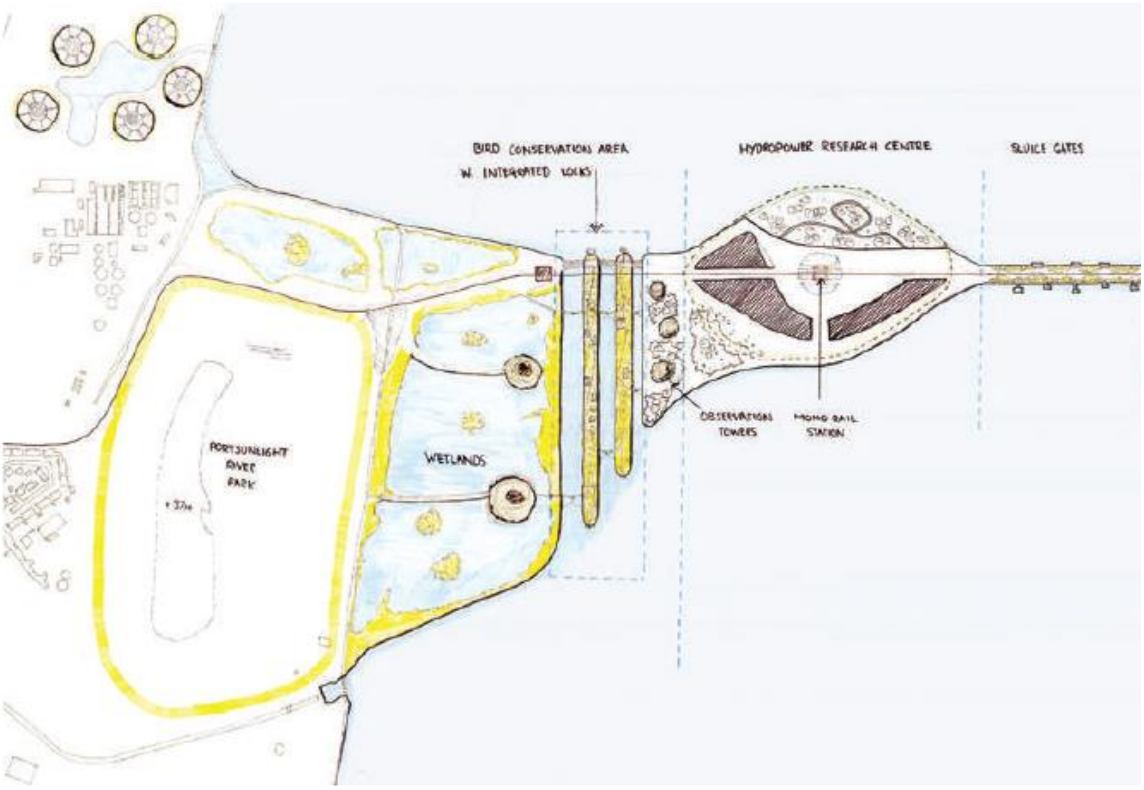

Figure 10: Initial sketches of compensatory wetlands

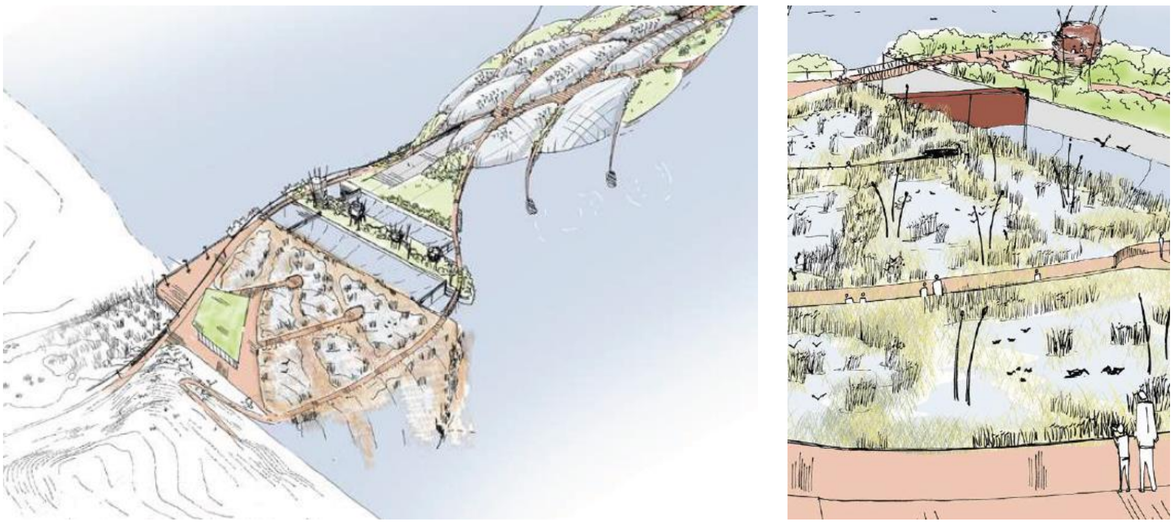

Figure 11: Initial artist rendition of compensatory wetlands

3.5 Engineering Options and Construction Strategy

Situated either side of the central island the riverbed is dug away to form trenches in which the sluice gates and turbine casing sit. Landscaping on top of these accommodates areas reserved for pedestrians', cyclists and wildlife. Beyond these, the shipping locks and artificial mudflats sit to the south approaching Port Sunlight and the reclaimed festival gardens and fish ladder to the north, adjoining Liverpool.

The final design consists of 15 concrete columns around which is suspended a steel and glass construction consisting of multiple levels, housing the World Centre for Hydropower research and other living and recreational facilities (Figure 12). The ground floor is devoted to public spaces with views of the Kaplan turbine plant above on the next two floors. The following eight floors are the research labs. A typical view from the research levels can be seen in Figure 13. Vertical circulation and services are carried up the central column with a spiral staircase and two lifts wrapped around the water pipe that leads down to the turbine below.

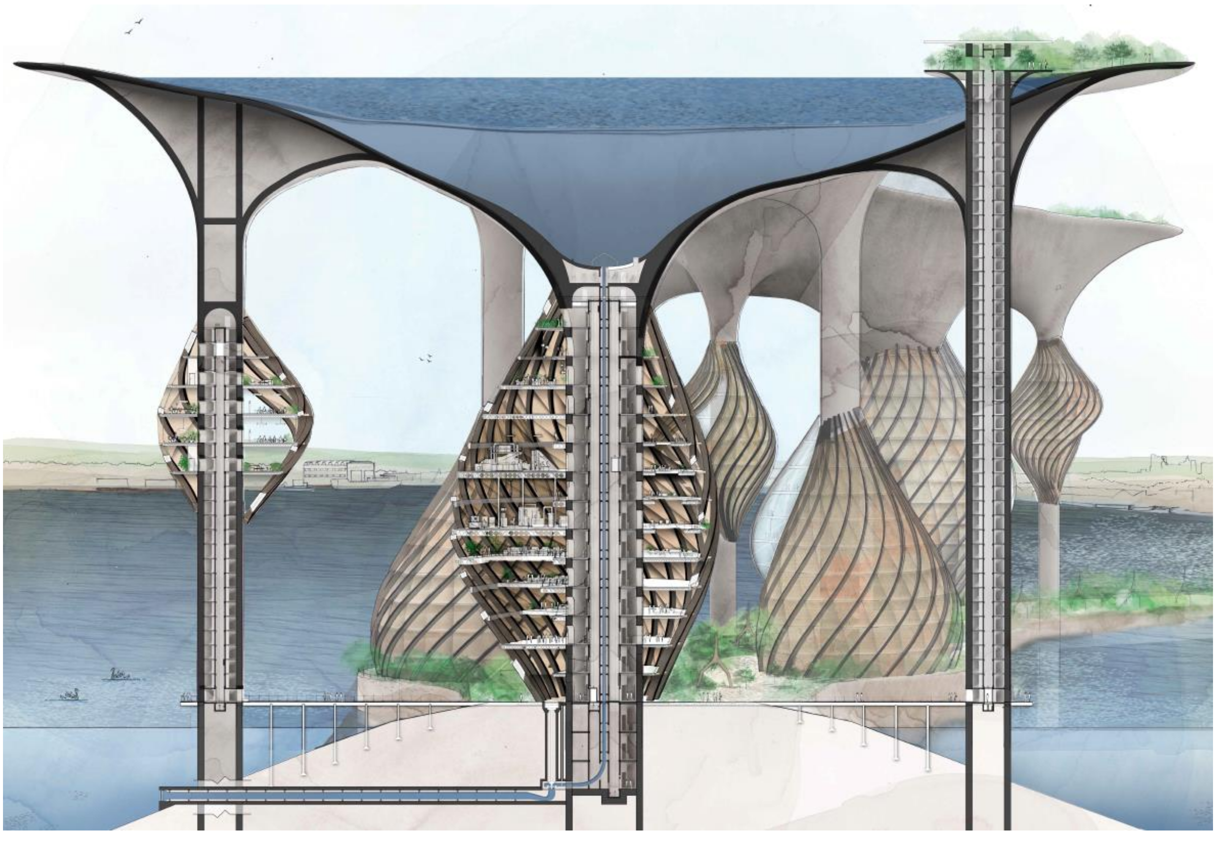

Figure 12: Section through single water tower

The floor plan is split into five zones:

1. Primary research space - This is where large scale testing happens
2. Secondary research Space - This is where smaller scale testing happens
3. Write up space - An office environment for the write up of research and experiments

4. Break out space - A comfortable lounge space with kitchenette
5. Storage and services - Workshop storage, toilets and utilities.

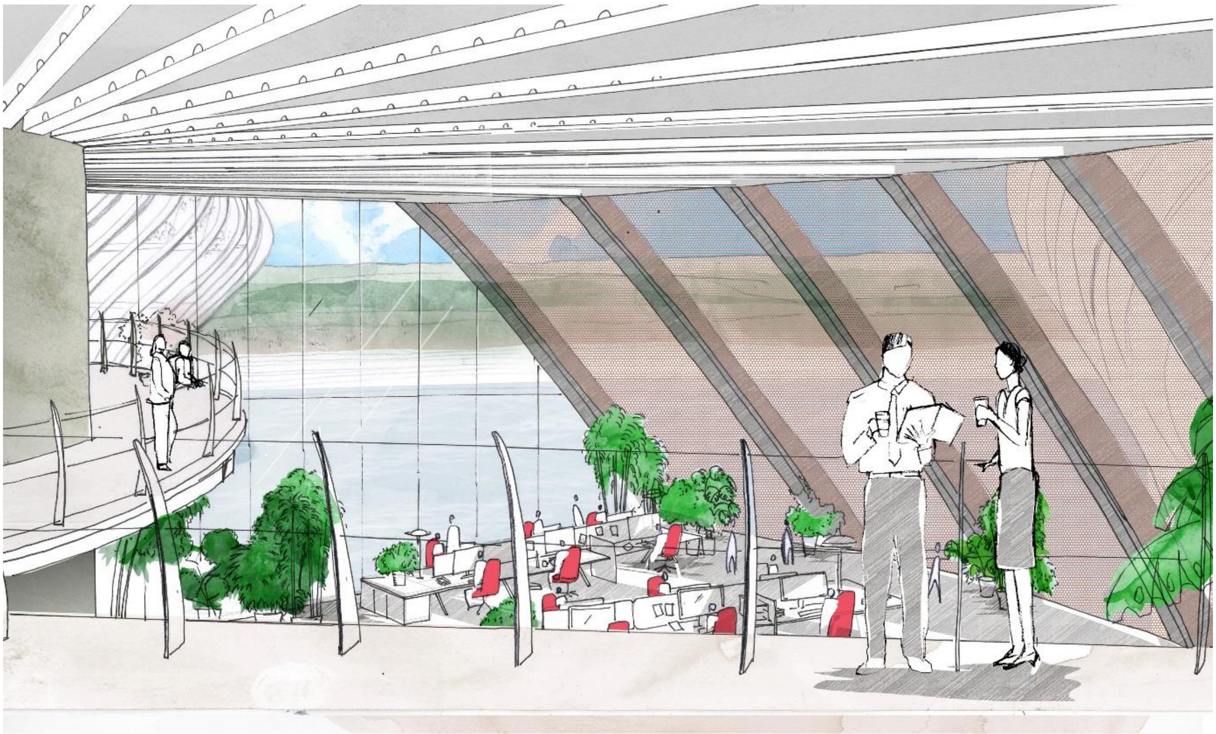

Figure 13: Internal view from research levels

4 Conclusions

The purpose of this paper was to consider the auxiliary opportunities that tidal range projects can offer beyond energy generation based on a framework developed from the North West Hydro Resource Model. As a case study the Mersey tidal barrage was chosen. With this in mind the aims of creating a hydropower landmark, connecting communities, integrating wildlife into our design and having a global impact have been considered, which we have called WHALE (Figure 14).

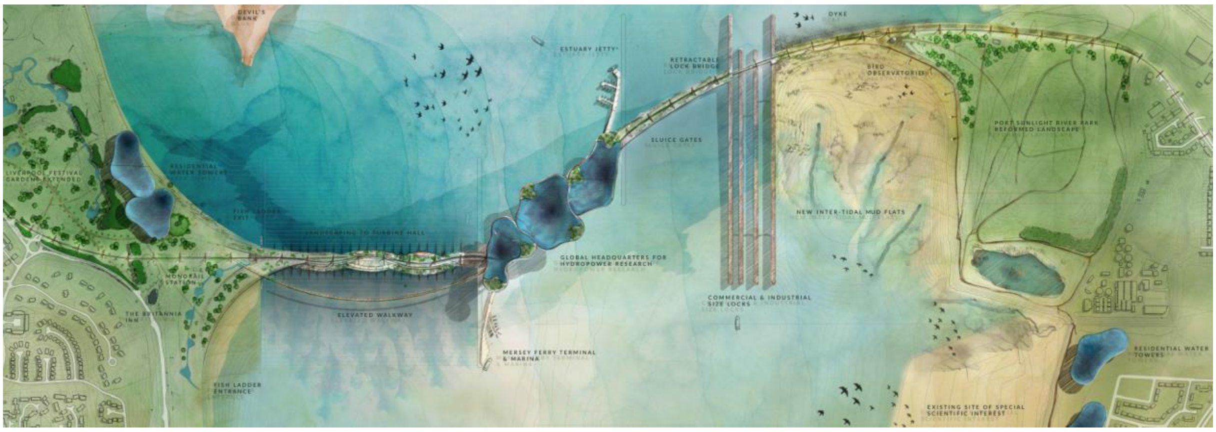

Figure 14: The WHALE Mersey Barrage

The WHALE Mersey barrage would undoubtedly be a beacon for hydropower, being only the third large scale tidal barrage in operation globally. With the hydropower research community not currently having a centralised research centre, this would be well known in the academic community. The scale of the built form will also impact the already iconic Liverpool skyline, confirming itself as a landmark for the city.

The WHALE barrage successfully connects both sides of the River Mersey through a myriad of routes including fast and slow paths for both pedestrians and cyclists in addition to a dedicated commuter route in the form of a monorail. Reclaimed land breaking the shoreline and new transport connections bring the two communities physically and perceptually closer. New routes are also created through the ferry terminal which would add a new stop on the route of the Mersey Ferry. With the WHALE being a global destination for hydropower research there would also be international connections made through Liverpool John Lennon International Airport, which would be connected to the development through its connections to the existing rail networks.

Our strategy to mitigate the environmental impact of the tidal barrage was to promote biodiversity within the area. The total area of the intertidal mud flats that will be lost cannot practically be replaced, therefore we took the approach that if we couldn't reinstate the volume of habit we would add to the variety of environments. Along the barrage there are a number of varied habitats ranging from artificial inter-tidal mudflats to a selection of international gardens on the expanded International Garden Festival Site. The new inter-tidal mudflats combined with Port Sunlight River Park would create a bird airport for migrating birds and would encourage new species of bird to visit the estuary. The WHALE would also have a dedicated research building which would focus on further mitigating the effect of hydropower technology on the environment.

Along with the aforementioned global impacts that the WHALE project will have, we have also proposed a new typology of parasitic architecture that would allow existing water towers to be transformed into power generators, as well as becoming inhabited structures. This will bring hydropower to areas where currently it is not possible, regions that are far away from the sea, rivers or lakes for instance.

4.1 Final Remarks

The experiences at La Rance and Lake Sihwa have demonstrated both the function and longevity of tidal barrages, however a UK based project has never progressed beyond the planning stages. The Mersey tidal barrage project stalled in 2011, but tidal power in general has seen a sustained interest since then. It has been argued that in order to form a long term energy strategy tidal barrages and lagoons can offer significant advantages over other sources of renewable energy due to the inherent auxiliary opportunities, which make them more attractive in terms of both environmental and social considerations. Indeed it has long been noted that the success of a tidal barrage scheme depends upon striking the right balance between the mode of operation and biological harmony (Retiere, 1994).

Energy from renewable sources has been steadily increasing since 2000, with some estimates predicting that at least another 20 GW capacity would be required to meet 2020 requirements for 30% of electricity from renewable sources (House of Commons Energy and Climate Change Committee, 2016). However in 2016 only 8.9 % of total energy consumption came from renewable sources and latest predictions suggest the UK will fall short of this target (Department for Business, Energy and Industrial Strategy, 2016) (EU Commission, 2017). In this arena the UK has significant untapped tidal resource potential to bridge this gap, though high start-up costs have been a major inhibitor for further development. Indeed the high capital cost of tidal barrages, which must be offset by reasonable estimable gains of energy production, is reliant on developers matching the CfD support prices currently set by the UK government for offshore wind, which are as low as £57.50/MWh (4C Offshore, 2017) (Department of Energy and Climate Change, 2015) (Pöyry, 2014). There are clear motivators for wind and solar energy - principally it is the only renewable energy source that is scalable and economically viable to fulfil the required renewables growth in the period 2018-2020. In spite of this, tidal range power offers a higher capacity factor that other RES (Clarke, et al., 2006), which is an important economic consideration of any renewable energy project (Leijon, et al., 2003) (Chen & Liu, 2017) and the subsidies for wind merely reflect how the industry has matured and supply chain costs have decreased over time as installed capacity increases. However, it is well documented that increasing integration of volatile, unpredictable sources of renewable energy such as wind power and solar power jeopardises the stability of the power grid (Krenn, et al., 2012). In addition, these sources do not provide the system inertia, readily available from large synchronous generators, necessary for the ancillary services of the grid to perform under fault condition; tidal power will be crucial in ensuring that the grid can operate under fault condition.

By consideration of the social, environmental and economic opportunities that arise and by presenting a discussion of a number of the barriers affecting the development of tidal barrages in line with the North West Hydro Model, a fully holistic assessment of the feasibility of a tidal barrage across the Mersey is presented. Finally, it is hoped that this study could offer some further insight for the utilisation of tidal barrages to achieve a sustainable future.

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Figure 1

Figure 1: Photograph of La Rance tidal barrage from above (de Laleu, 2009)

Figure 2

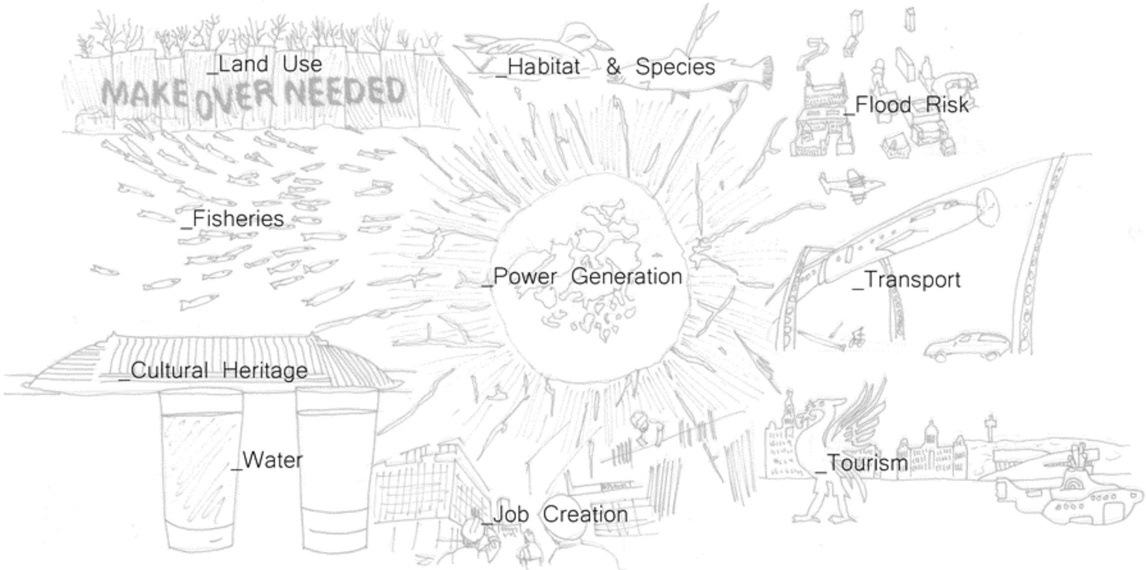

Figure 2: Design Manifesto - from the North West Hydro Resource Model

Figure 3

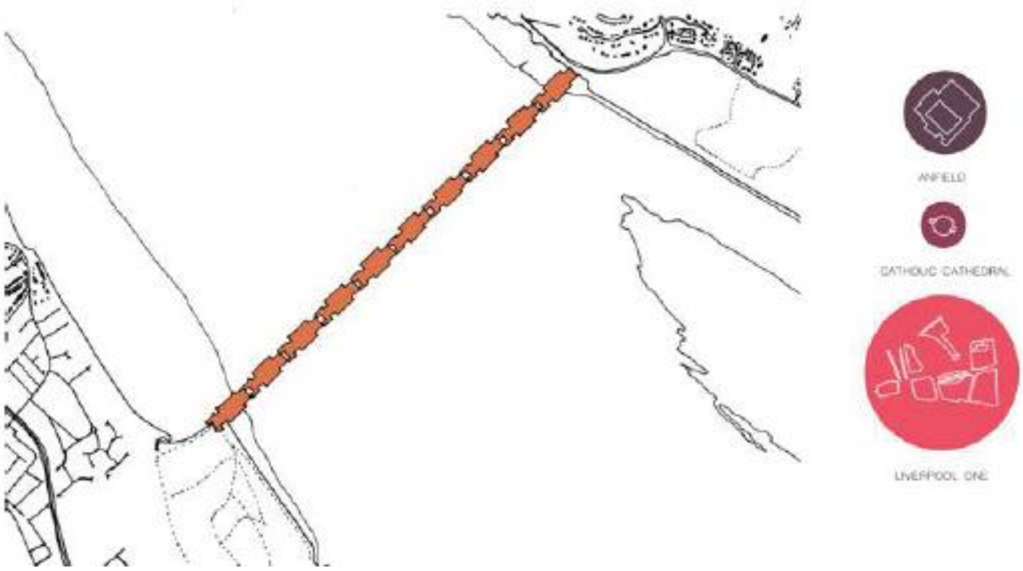

Figure 3: Scale diagram with 10 Anglican Cathedrals highlighted in orange

Figure 4

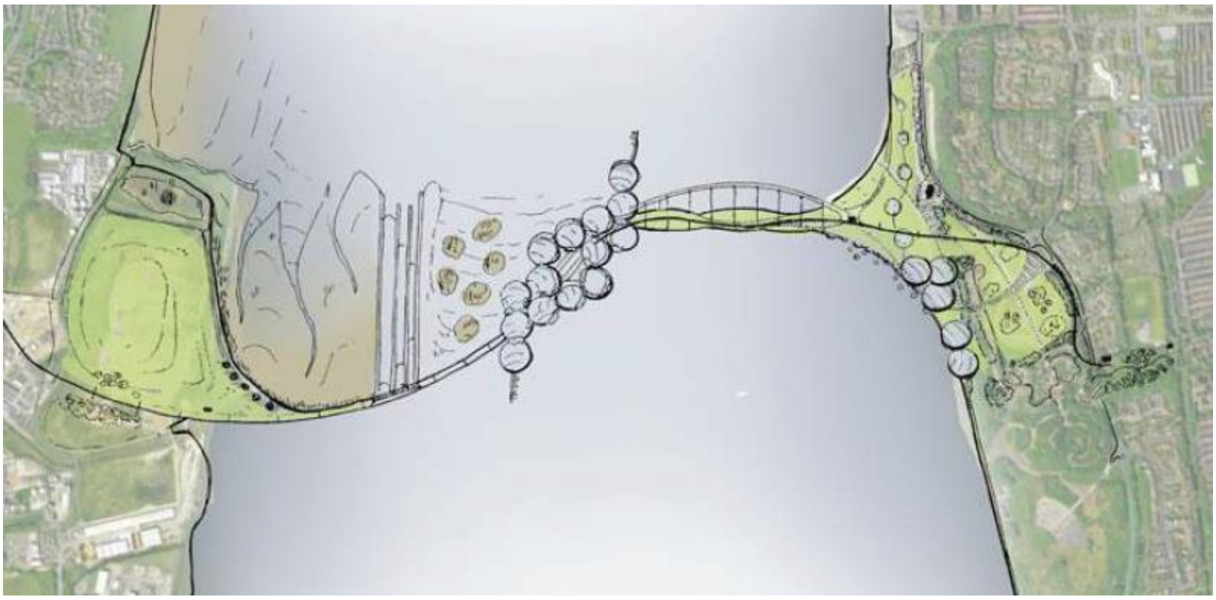

Figure 4: Artistic outline of barrage in situ

Figure 5

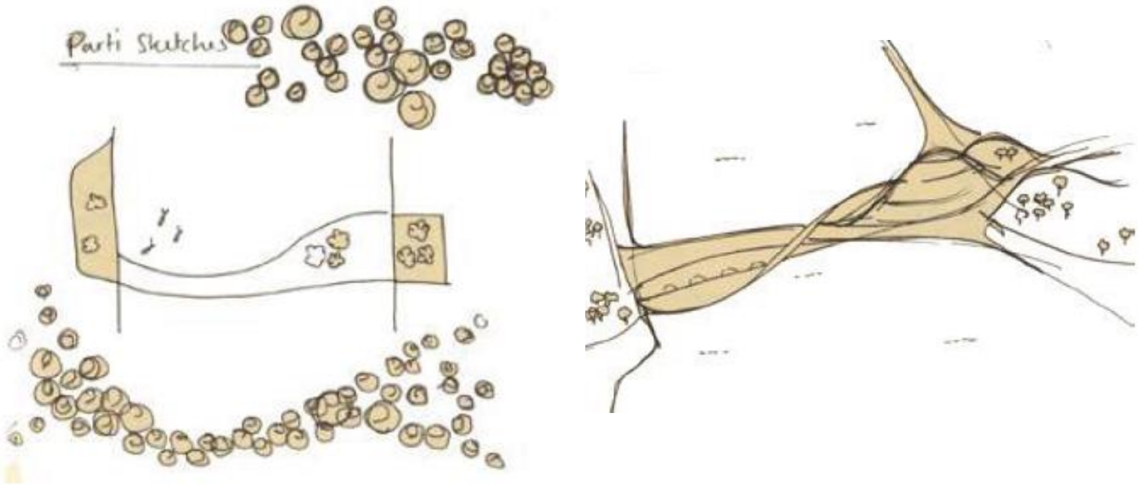

Figure 5: Artistic sketch - The Green Bridge concept

Figure 6

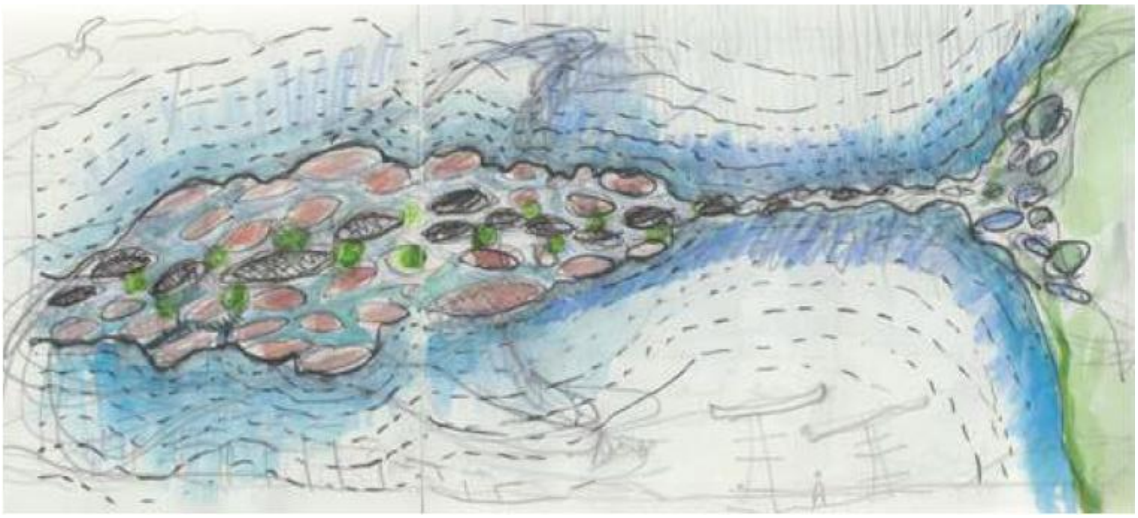

Figure 6: Artistic sketch - Reimagined Infrastructure

Figure 7

Figure 7: Nest of the Reed Warbler

Figure 8

Figure 8: Tree Hopper

Figure 9

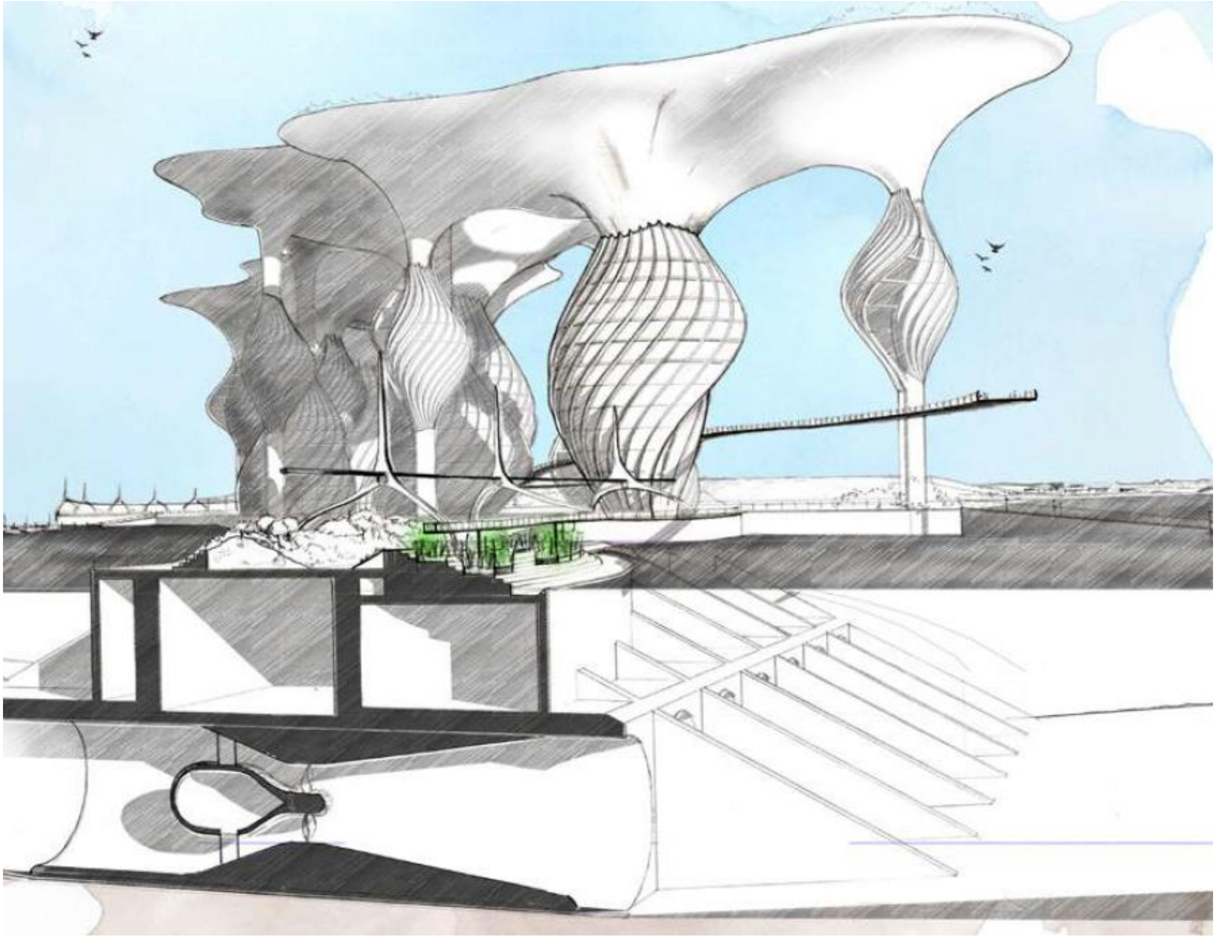

Figure 9: Section through turbine house with residential water towers and World Hydropower Research Centre above

Figure 10

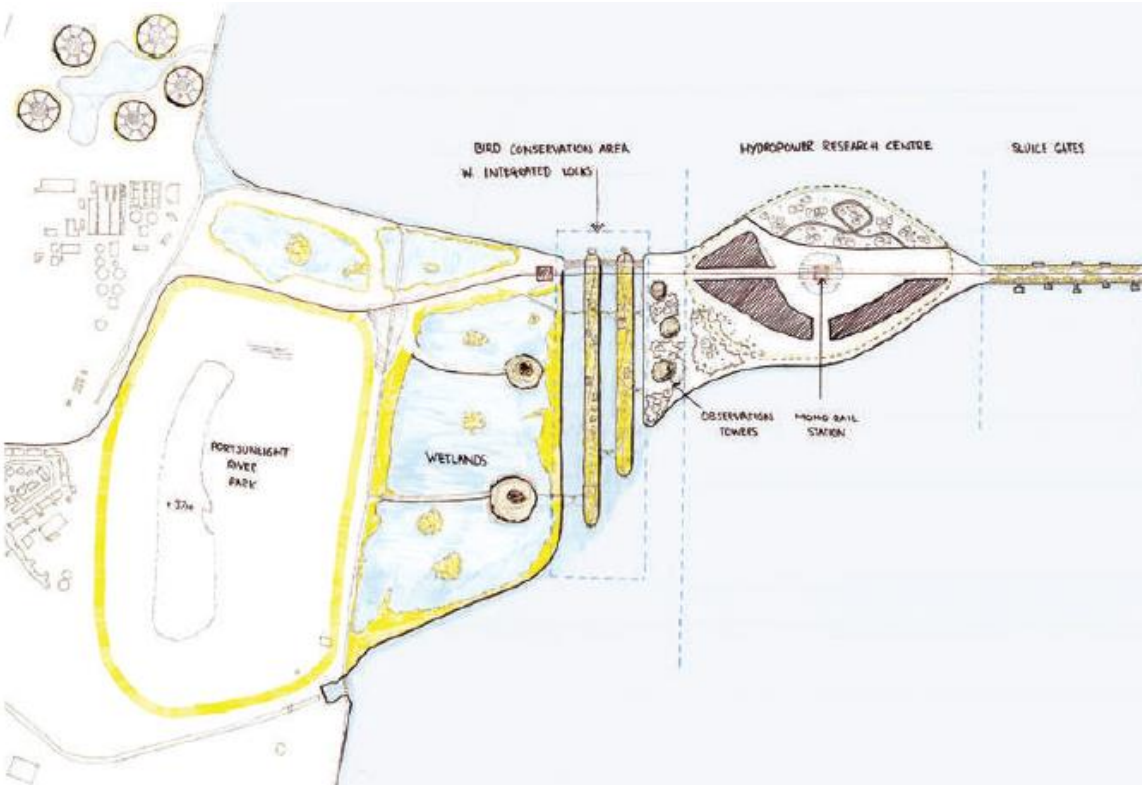

Figure 10: Initial sketches of compensatory wetlands

Figure 11

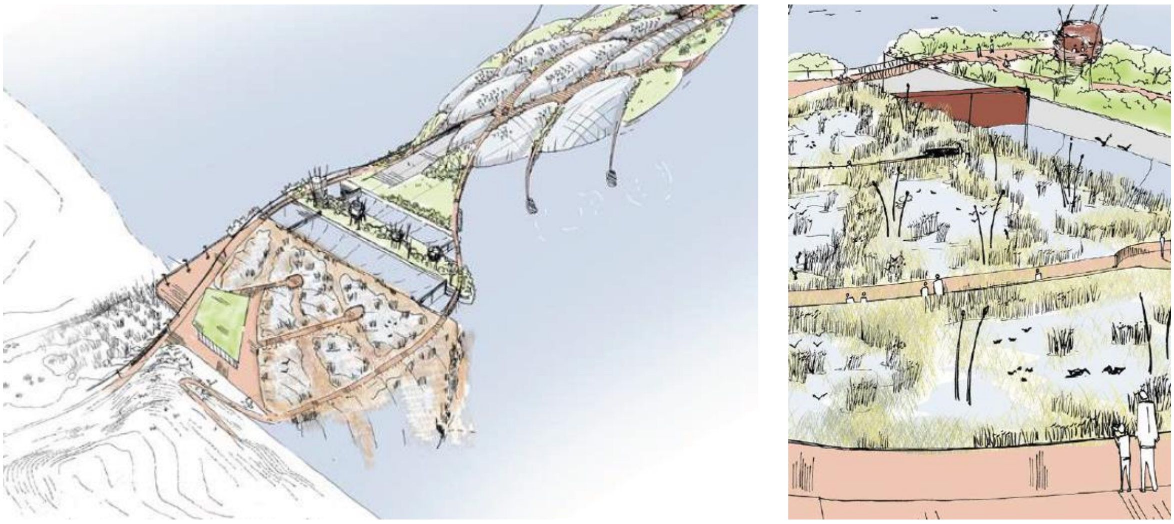

Figure 111: Initial artist rendition of compensatory wetlands

Figure 12

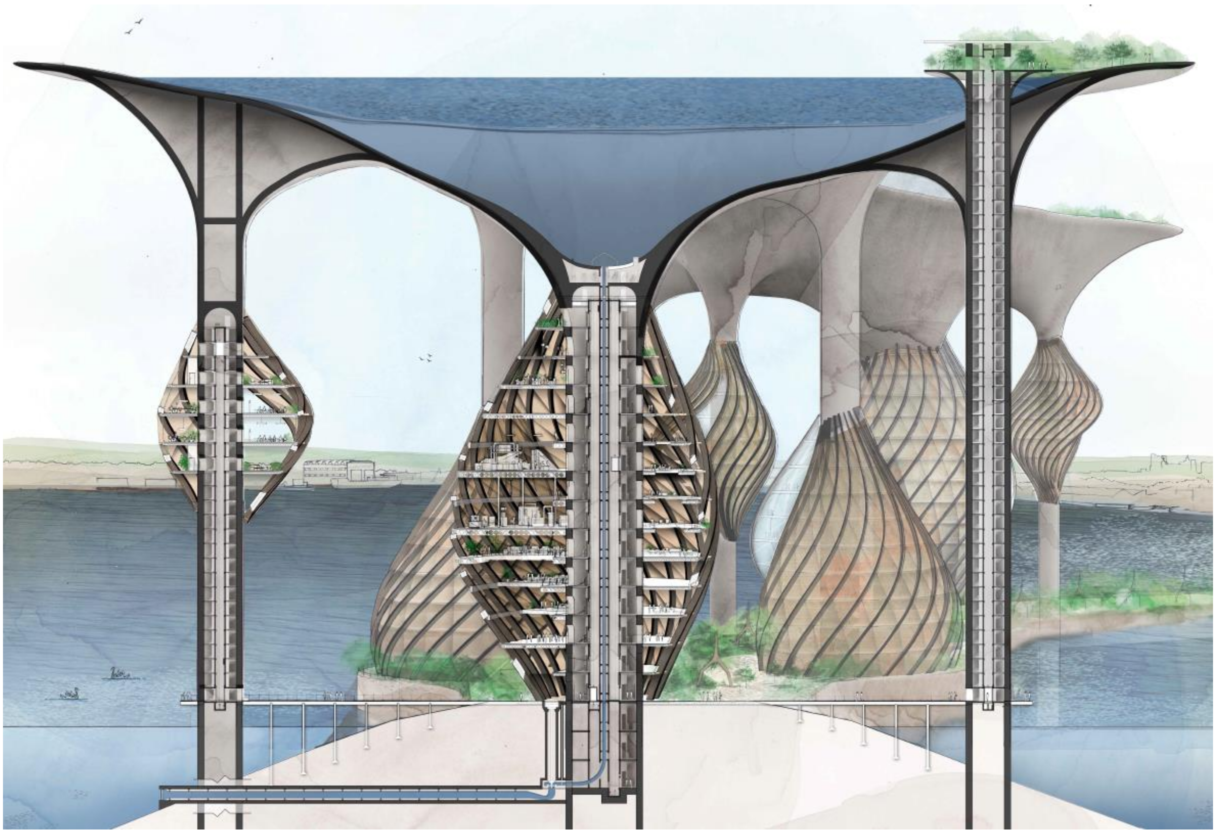

Figure 12: Section through single water tower

Figure 13

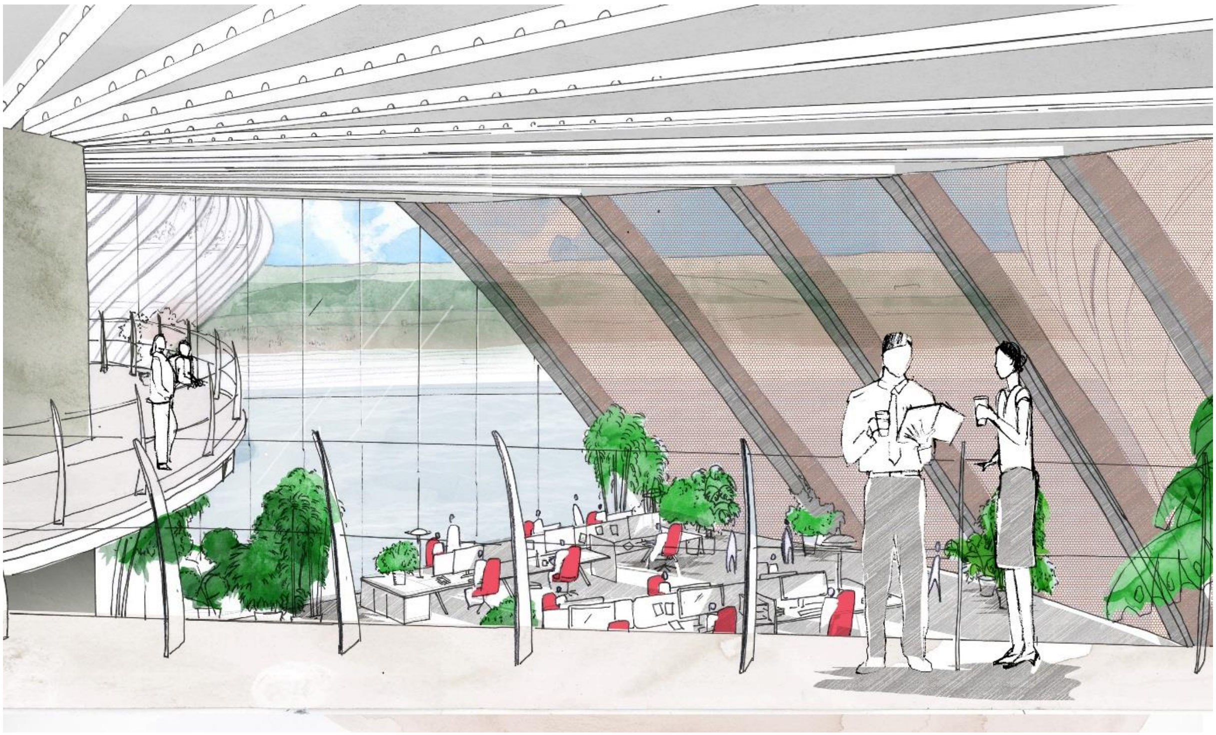

Figure 13: Internal view from research levels

Figure 14

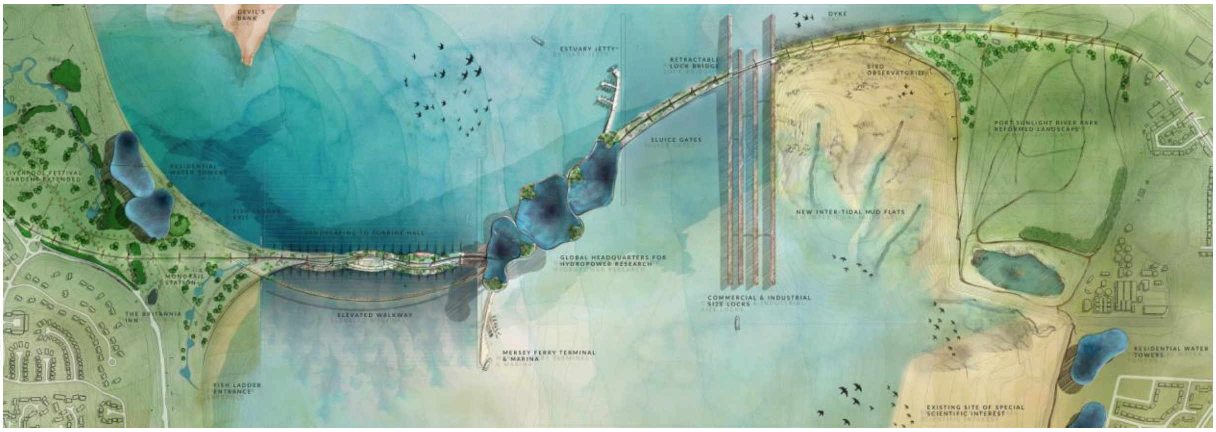

Figure 141: The WHALE Mersey Barrage

Table 1

Location	**Mean Tidal Range (m)**	**Potential Output (TW h/yr)**	**Latest Reporting**
Severn	9.8	16.8	It was estimated that the Severn Barrage could alone generate 5% of UK electricity needs, however since 2011 when the project was shelved by the UK government there have been no new proposals (Melikoglou, 2018).
Solway	5.5	9.44	No tidal range energy schemes are publicly planned for the Solway however there is a number of reports of significant potential (Neill, et al., 2017).
Swansea Bay Lagoon	8.5	0.53	Tidal Lagoon Power Ltd have proposed a 320 MW tidal lagoon, which was awarded a Development Consent Order in 2015 (Tidal Lagoon Power Ltd, 2018). With the aim to begin construction in 2018.
Wyre	6.6	0.3	New Energy Wyre proposed at 160 MW tidal barrage across Wyre Estuary. As of November 2017 Atlantis Resources signed terms with the Duchy of Lancaster for an option for the long-term lease of the riverbed (Atlantis Resources, 2017).
Morecambe Bay	6.3	4.63	A barrage construction across Morecambe Bay is one of a larger scheme as part of Northern Tidal Power Gateways Ltd proposals, currently in review stage (Mott MacDonald, 2017).
Mersey	6.45	0.92	Peel Energy part of Peel Holding who own Port of Liverpool proposed in 2011 a 700 MW

			scheme, though progress stalled due to cost agreements implications (BBC, 2017).

Table 1: UK tidal range schemes and proposals

Table 2

Study	Year	Capacity (MW)	Output (TWh/yr)	Physical and operational parameters	Source
Department of Energy	1984	621	1.32	27 x 7.6 m ∅, 23 MW turbines, with 18 sluice gates. Ebb generation	(Peel Energy, 2011)
Mersey Barrage Company	1991	700	1.45	28 x 8 m ∅, 25 MW turbines, with 47 channel sluices. Ebb generation	(Sustainable Development Commission, 2007)
University of Liverpool, Joule project	2009	621	1.07	27 x 7.6 m ∅, 23 MW turbines, with 18 sluice gates. Ebb generation (	(Burrows, et al., 2009)
University of Liverpool, Joule project	2009	621	0.98	27 x 7.6 m ∅, 23 MW turbines, with 18 sluice gates. Ebb and flood generation	(Burrows, et al., 2009)
University of Liverpool, Joule project	2009	1863	1.72	81 x 7.6 m ∅, 23 MW turbines, without sluice gates. Ebb and flood generation	(Burrows, et al., 2009)
Mersey Tidal Power	2010	700	0.90	28 x 8 m ∅, 25 MW turbines, with 18 sluice gates. Ebb generation with fixed starting head of 3.9 m	(Aggidis & Benzon, 2013)
Mersey Tidal Power	2011	700	0.92	28 x 8 m ∅, 25 MW turbines, with 18 sluice gates. Flexible ebb generation with starting head optimised for maximum energy for 8 months and head limited to 3 m for 4 months of every year	(Peel Energy, 2011)

Table 2: Comparison of configuration and predicted energy outputs of previous Mersey barrage studies (Becker, et al., 2017)

Table 3

Key Issues	Key Strategies
Scale	Reclaiming land from the Mersey tackles both the scale and issue of building on water, Figure demonstrates the scale of the project by showing the length of the barrage in terms of 10 Liverpool Anglican Cathedrals
Building on Water	Nodes will be created along the barrage to break up the journey
Elegance	Using sweeping curvilinear forms to contradict the traditional straight line of a dam
Environment	Create a diverse range of habitats
Interaction	Floating elements and gardens to maintain contact with the water

Table 3: Design Masterplan key issues and strategies

Opportunities for tidal range projects beyond energy generation: using Mersey barrage as a case study

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Evaluation of "Opportunities for tidal range projects beyond energy generation: using Mersey barrage as a case study"

Responses to reviewers

General remark: the English language has now been improved and reference style of the journal adopted.

Reviewer 1:

1. Is this a new and original contribution?
   Yes. But adds knowledge in the literature

The authors would like to thank the reviewer for this positive comment.

2. Does the title of this paper clearly and sufficiently reflect its contents?
   Yes

The authors would like to thank the reviewer for this positive comment.

3. Are the presentation, organization and length satisfactory?
   Yes

The authors would like to thank the reviewer for this positive comment.

4. Can you suggest brief additions or amendments (words, phrases) or an introductory statement that will increase the value of this paper for an international audience?
   No

The authors would like to thank the reviewer for this positive comment.

5. Can you suggest any reductions in the paper, or deletions of parts?
   Yes, Introduction and Conclusion needs improvements. " 2.1. The Mersey Barrage" could be added.

The authors would like to thank the reviewer for this positive comment, section 2 has now been reorganised to help the readers understanding and offer a more linear structure. Furthermore, the conclusions have been amended and bullet points removed.

6. Is the quality of the English language satisfactory?
   Yes

The authors would like to thank the reviewer for this positive comment.

7. Are the illustrations and tables necessary and acceptable?
   Yes. But figures are too big

The authors would like to thank the reviewer for this positive comment, Figures 3, 5 and 13 from the original manuscript have now been removed as they were deemed no longer necessary.

Reviewer 2:

1. This work is an interesting investigation on opportunities for tidal range projects beyond energy generation.

The authors would like to thank the reviewer for this positive comment

2. The novelty of the research is quite relevant being interesting the point of view of the authors to investigate the auxiliary opportunities that tidal barrages can offer beyond energy generation based on a framework developed from the North West Hydro Resource Model.

The authors would like to thank the reviewer for this positive comment.

3. In this work, the authors presented the results about the study on tidal barrages design with a review on the Mersey tidal Barrage as a case study. The authors presented a panorama of the theme and results and conclusions are explained, identifying also limitations of the work proposing for example to work in future on striking the right balance between the mode of operation and biological harmony.

The authors would like to thank the reviewer for this positive comment.

4. Anyway the work has only partially linear structure: i.e. section 2 is enough clear on the prior art, but then section 3 is not well integrated within the whole core of the publication, then you have section 4 on design development and respective subsections with a small description and again similarly on final section 5 conclusions.

The authors would like to thank the reviewer for this positive comment, section 3 and 4 have now been integrated together to help the readers understanding and offer a more linear structure.

5. My personal suggestion is to create a more readable and explicit table overview in order to facilitate the comparison and the comprehension of the options to the readers. Maybe referring to references as outlined in the final remarks.

The authors would like to thank the reviewer for this positive comment, section 3 and 4 have taken the original headings from the final remarks and incorporated them as part of the manuscript in order to provide an improved comprehension to the reader. Furthermore table 3 has now been added to provide an overview of the key issues. We hope the reviewer agrees with our changes.