Tidal range energy resource and optimization – past perspectives and future challenges

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Abstract

Tidal energy is one of the most predictable forms of renewable energy. Although there has been much commercial and R&D progress in tidal stream energy, tidal range is a more mature technology, with tidal range power plants having a history that extends back over 50 years. With the 2017 publication of the "Hendry Review" that examined the feasibility of tidal lagoon power plants in the UK, it is timely to review tidal range power plants. Here, we explain the main principles of tidal range power plants, and review two main research areas: the present and future tidal range resource, and the optimization of tidal range power plants. We also discuss how variability in the electricity generated from tidal range power plants could be partially offset by the development of multiple power plants (e.g. lagoons) that are comple-

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mentary in phase, and by the provision of energy storage. Finally, we discuss the implications of the Hendry Review, and what this means for the future of tidal range power plants in the UK and internationally.

Keywords: Tidal lagoon, Tidal barrage, Resource assessment, Optimization, Hendry Review, Swansea Bay

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Contents

1. Introduction

Much of the energy on Earth that is available for electricity generation, particularly the formation of hydrocarbons, originates from the Sun. This also includes renewable sources of electricity generation such as solar, wind & wave energy, and hydropower (since weather patterns are driven, to a significant extent, by the energy input from the Sun). However, one key exception is the potential for electricity generation from the tides – a result of the tide generating forces that arise predominantly from the coupled Earth-

Moon system[1]. The potential for converting the energy of tides into other useful forms of energy has long been recognised; for example tide mills were in operation in the middle ages, and may even have been in use as far back as Roman times [1]. The potential for using tidal range to generate electricity was originally proposed for the Severn Estuary in Victorian times [2], and La Rance (Brittany) tidal barrage – the world's first tidal power plant – has been generating electricity since 1966 [3]. However, only very recently has the strategic case for *tidal lagoon* power plants been comprehensively assessed, with the publication of the "Hendry Review" in January 2017 [4].

Tidal range power plants are defined as dams, constructed where the tidal range is sufficient to economically site turbines to generate electricity. The plant operation is based on the principle of creating an artificial tidal phase difference by impounding water, and then allowing it to flow through turbines. The instantaneous potential power (P) generated is proportional to the product of the impounded wetted surface area (A) and the square of the water level difference (H) between the upstream and downstream sides of the impoundment:

$$P \propto AH^2 \tag{1}$$

A tidal range power plant consists of four main components [5, 6]:

- *Embankments* form the main artificial outline of the impoundment, and are designed to have a minimal length while maximizing the enclosed plan surface area. A key factor in designing the embankment is to

[1]The Sun also has an important role in tides, but its contribution is around half that of the Moon.

minimise disturbance to the natural tidal flow.

- *Turbines* are located in water passages across the embankment, and convert the potential energy created by the head difference into rotational energy, and subsequently into electricity via generators.

- *Openings* are fitted with control gates, or sluice gates, to transfer flows at a particular time, and with minimal obstruction.

- *Locks* are incorporated along the structure to allow vessels to safely pass the impoundment.

Tidal range power plants can be either coastally attached (such as a barrage) or located entirely offshore (such as a lagoon). The primary difference between the two refers to their impoundment perimeter. There are also coastally-attached lagoons, where the majority of the perimeter is artificial, potentially enabling smaller developments with more limited environmental impacts than barrages – the latter generally spanning the entire width of an estuary.

Following construction, the manner and how much of the potential energy is extracted from the tides largely depends on the regulation of the turbines and sluice gates [7]. They can be designed to generate power one-way, i.e. ebb-only or flood-only, or bi-directionally. In one-way ebb generation, the rising tide enters the enclosed basin through sluice gates and idling turbines. Once the maximum level in the lagoon is achieved, these gates are closed, until a sufficient head (h_{max}) develops on the falling tide. Power is subsequently generated until a predetermined minimum head difference (h_{min}), when turbines are no longer operating efficiently. For flood generation the whole process is reversed to generate power during the rising tide. In two-way power generation, energy is extracted on both the flood and ebb phases of the tidal cycle, with sluicing occurring around the times of high and low water [8, 9]. A schematic representation of ebb and two-way generation modes of operation is shown in Fig. 1, highlighting the main trigger points during the tidal cycle that dictate power generation. Nonetheless, there are other possible variations of these regimes (e.g. Section 5.1). For example, ebb/flood generation can often be supplemented with pumping water through the turbines to further increase the water head difference values, as considered in studies by Aggidis and Benzon [10] and Yates et al. [11].

In this article, we provide a review of tidal range power plants, with a focus on resource and optimization. The following section provides an overview of the history of tidal range schemes from pre-industrialization to present day, including future proposed schemes. Section 3 compares the various modelling approaches used to simulate tidal lagoon or barrage operation (e.g. 0D versus 2D models), and Section 4 examines the global tidal range resource, with a particular focus on the northwest European continental shelf, and constraints on the development of this resource. Section 5 examines ways in which tidal range schemes can be optimised, e.g. flood or ebb generation, pumping, and the benefits of concurrently developing multiple tidal range schemes. Finally, in Section 6, we discuss future challenges and opportunities facing tidal range power plants, including variability and storage, and the implications of the Hendry Review.

2. A brief history of tidal range schemes

Tidal range technologies have a long history, especially when compared with less mature ocean energy technologies such as tidal stream and wave energy. Energy has been extracted from the tides for centuries. There is evidence of a tide mill in Strangford Lough, Northern Ireland, which has been dated to the early 6th Century [1], where an 8 m wide dam enclosed a 6500 m^2 area of sea water. Such early tidal power plants worked much as modern tidal range projects, but used only naturally-occurring tidal basins to impound volumes of water, which would then be routed through a paddlewheel or waterwheel during the ebb. The extracted energy was, of course, not used to generate electricity, but to provide mechanical motion, for example to mill grain.

2.1. Commercial progress

Locations around the world that are suitable for tidal range exploitation are relatively limited, given a number of physical constraints, including tidal range, grid connectivity, geomorphology, seabed conditions, and available area for an impoundment. There are five tidal range power plants currently in operation around the world, and a number of areas that have either been identified for development, or which exhibit suitable characteristics to merit consideration.

2.1.1. Current schemes

La Rance tidal barrage in Brittany was the world's first fully operational tidal power station [3, 12, 13]. The project, which comprises a 720 m long barrage and impounds an area of approximately 22 km^2 [14], was constructed over a six-year period, and was fully operational in 1966 (Table 1). The barrage houses 24 Kaplan bulb turbines, which provide a combined rated power output of 240 MW and an annual energy output of 480 GWh [15]. Since its inception, there have not been any major structural issues, and very little downtime, although there have been significant environmental impacts [16].

The Kislaya Guba tidal power plant in Russia was constructed in 1968 as a trial project by the government, with an initial installed capacity of 400 kW [14]. It is situated near Murmansk, a fjord on the Kola Peninsula [13]. The installed capacity of this power plant has grown to 1.7 MW, which is relatively low compared with other worldwide schemes, making it the smallest tidal range power plant in operation [17]. However, the success of this scheme has motivated the government to explore other sites, including Mezan Bay in the White Sea and Tugar Bay, with potential installed capacities of 15 GW and 6.8 GW respectively [17]. The former of the two figures is particularly impressive, since this would be the second largest power plant in the world, the largest being the 22.5 GW Three Gorges Dam in China [18].

The Annapolis Royal Generating Station was constructed in 1984, and is located on the Annapolis River, Nova Scotia, Canada. It harnesses the head difference created in the Annapolis Basin, a sub-basin of the Bay of Fundy, which has a spring tidal range of 16 m [19]. This scheme consists of a single Straflo turbine, and produces a peak power output of 20 MW on the ebb tide only [13]. As well as generating electricity, this power plant is also used for flood defence and serves as an important transport link – the latter being a particularly advantageous and unique feature of barrages, for example compared to a tidal lagoon.

The Jiangxia tidal range power plant was opened in 1985, and is located in Jiangxia Port, Wenling, China, an area that is characterised by tidal ranges of up to 8.4 m [13]. The power plant operates bi-directionally, and houses six bulb turbines, the last of which was installed in 2007, providing an installed capacity of 3.9 MW.

The largest (by installed capacity) tidal range scheme currently in existence is Lake Sihwa, which is situated in the mid-eastern region of the Korean Peninsula in the Kyeonggi Bay, South Korea. The power plant stemmed from a disused dam constructed in 1994 to hold irrigation water for agricultural land; however, industrial developments in its vicinity caused pollution issues [20]. To help tackle the pollution problems, the dam was subsequently converted to a flood-operating tidal power plant [13]. The power plant incorporates 10 bulb turbines, with an installed capacity of 254 MW. The success of this scheme has motivated the Korean government to explore other potential sites around the country, including Gerolim and Incheon [13].

2.1.2. Proposed schemes

There are a number of factors that preclude development in certain areas, even if first-order theoretical appraisals of the resource suggest that there is commercial potential. Apart from physical constraints, cost and environmental impacts are other major barriers to development. Environmental issues, particularly for larger scale schemes, have prevented numerous developments from being approved [13]. Without constructing a scheme, its true environmental impact is difficult to quantify, and so governments are hesitant to proceed with development at such scale. Table 2 summarises sites around the world that have the potential for tidal range exploitation.

A relatively recent tidal range concept that addresses some of these environmental concerns is the tidal lagoon. These tidal range power plants differ from the more conventional barrage schemes, as they impound a smaller body of water and are therefore less intrusive. One such scheme is the proposed Swansea Bay Lagoon, located in the Bristol Channel, UK, an area that is characterized by tidal ranges that exceed 10 m [21].

Although no tidal lagoons currently exist, the Swansea Bay Lagoon is the closest scheme to commercial viability. The UK Government have recently completed an independent review which considered the feasibility of the power plant in terms of cost effectiveness, supply chain opportunities, possible structures to finance this project, and scales of design [22]. Despite the positive outcome of the "Hendry Review" [4], a marine licence is still required from Natural Resources Wales (NRW)[2], and an agreement on the CfD (Contracts for Difference) price, before the project can proceed to construction. There are a number of other areas in the UK that have been identified for development, as summarized in Table 2. However, it is likely that these will only be approved on the condition that the Swansea Bay "Pathfinder Project" proceeds and is successful.

2.2. Engineering aspects of tidal range power plants

Bulb turbines are used for power takeoff in almost all current tidal range schemes [13]. These are the same, or very similar, to the turbines that are used for low head hydropower applications. When low head hydro was con-

[2]NRW is an environmental body sponsored by the Welsh Government.

sidered as an energy solution for the UK in 1927, the investigating team (the Severn Barrage Committee) found the Kaplan turbine to be the most efficient for low head applications [23]. In the following years, as more research has been conducted in the field of turbines, the bulb turbine, a configuration of a Kaplan turbine, has become the turbine of choice for low head hydro or tidal range schemes. Furthermore, triple regulation (adjustable guide vanes, blade pitch angle and variable speed) of turbines has become feasible in recent years [4, 13, 21], which will accommodate the constant varying head conditions that are inevitable in tidal range applications.

Tidal range schemes will likely utilise this relatively mature turbine technology, with specific adaptations to better suit tidal environments. It is most certain that the largest share of the cost is in the civil engineering work [4]. A potential reduction of the civil costs is proposed, which is the usage of caissons. This would enable the construction of the turbine housing structure on land, as opposed to using cofferdams. It has to be taken into account that in tidal range applications a longer water passage is required, as the bulb turbines may work in two-way generation, as opposed to classical one-way generation [7, 24]. Therefore, a draft tube is required on both sides of the turbine. Recent suggestions for impoundment designs include the use of geotubes and sand [6, 13]. These impoundments would also act as breakwater and sea defence structures, helping protect neighbouring regions from flooding [e.g. 25].

3. Numerical simulations of tidal range power plants

The assessment of tidal range schemes relies on the development of numerical tools that can simulate their operation over time. These span from simplified theoretical and zero-dimensional (0D) models [8, 10, 26, 27] to more sophisticated depth-averaged (2D) and hydro-environmental tools [9, 20, 24, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37] that often require High Performance Computing (HPC) capabilities for practical application.

3.1. 0D modelling

Given (a) known tidal conditions, (b) plant operation sequence, and (c) appropriate formulae that represent the performance of constituent hydraulic structures, it is feasible to simulate the overall performance of a tidal range scheme, and provide an informed resource assessment [24]. The operation can be modelled using a water level time series as input, governed by the transient downstream water elevations at the site location (Fig. 1). This is known as 0D modelling, and has been deemed sufficient under certain conditions, e.g. for smaller lagoons and barrages, as explored in the literature [28, 34, 35, 38].

A multitude of 0D models have been reported for the estimation of tidal power plant electricity outputs [e.g. 27, 34, 39]. However, one commonly used technique is the backward-difference numerical model, developed according to the continuity equation. Given the downstream $\eta_{dn,i}$ and upstream $\eta_{up,i}$ water level at any point in time t (indicated by subscript i), the upstream water level at $t + \delta t$ (subscript $i + 1$) can be calculated as [27]:

$$\eta_{up,i+1} = \eta_{up,i} + \frac{Q(H_i) + Q_{in,i}}{A(\eta_{up,i})}\Delta t \tag{2}$$

where $A(\eta_{up})$ is the wetted surface area of the lagoon, assuming a constant water level surface of η_{up}. Q_{in} corresponds to the sum of inflows/outflows through sources other than the impoundment, e.g. rivers or outflows. The water head difference H is defined as $\eta_{up,i} - \eta_{dn,i}$, and feeds into $Q(H)$; a function for the total discharge contributions from turbines and sluice gates. Theoretically, the flow through a hydraulic structure is calculated as [5]:

$$Q = C_D A_s \sqrt{2gH} \tag{3}$$

where C_D is a discharge coefficient, and A_s is the cross-sectional flow area. In turn, the power P produced from a tidal range turbine for a given H can be:

$$P = \rho g Q_T H \alpha \tag{4}$$

where ρ is the fluid density, Q_T is the turbine flow rate and α is an overall efficiency factor associated with the turbines. In practice, the hydraulic structure flow rates and power output should be represented by hill charts specific to the individual characteristics of sluice gates and turbines, thus incorporating their technical constraints. Examples of such charts for bulb turbine designs can be found in the literature [e.g. 40, 41].

The flow rate Q and power P are also subject to the operation mode of the plant (Fig. 1), which will accordingly restrict/allow flow through turbines and sluice gates at certain times within the tidal cycle. Details of one-way and two-way generation algorithms that dictate the modes of operation over time have been presented in Angeloudis and Falconer [24], with variations schematically represented in several studies [e.g. 28, 30, 34, 35].

Even though a 0D modelling approach is computationally efficient, it often assumes that the impact of the tidal impoundment itself on the localised tidal levels is negligible. Such an assumption can yield over-optimistic results, as reported in Angeloudis and Falconer [27] and Yates et al. [11]. Consequently, the analysis should be expanded to account for the regional hydrodynamic impacts through refined coastal modelling tools tailored to the operation of tidal lagoons.

3.2. 1D modelling

Many candidate sites for tidal range schemes are on estuaries, where it is possible to integrate the flow both vertically and across the width of the estuary [e.g. 42]. Such models may be useful for modelling tidal lagoons and barrages, as they are able to capture some of the changes to tidal hydrodynamics due to the presence and operation of the tidal range power plant [38] without the computational demands of more complex models. There are numerous examples of 1D modelling being used to simulate tidal barrages; examples include semi-analytical models [43, 44, 45] and numerical modelling [39, 46, 47, 48]. Upstream and downstream sections of a tidal range scheme can be simulated independently as two coupled 1D models. For a barrage scheme, the constituent sections are linked at the respective ends, whereas tidal lagoons are treated as junctions to the main channel section [49].

However, conclusions drawn from 1D models need to be treated with caution. Due to the simplifications inherent in a 1D model, the naturally occurring amplitude (i.e. without the barrage present) at the barrage location may be poorly represented (in comparison to 2D models). In general, it has been demonstrated that the performance of 1D models is adequate for simulating relatively small tidal projects (e.g. the Swansea Bay lagoon), but insufficient for simulating larger schemes such as a large barrage [49]. Therefore, significant error bars should be placed on the output from such models. Nevertheless, 1D models are useful qualitatively for assessing the scale of the impact of placing barrages in estuaries, and also useful for analysing operating strategies where computationally efficient models are required to explore or optimise multiple scenarios.

3.3. 2D and 3D models

Hydrodynamic simulations of coastal waters can provide valuable insight into resource assessment, the quantification of the potential impacts from planned coastal engineering projects, and the minimization of any detrimental effects through design optimization. In principle, the capability of depth-averaged (2D) and three-dimensional (3D) numerical models to produce time-series approximations to primitive variable fields, such as velocity and free-surface elevation, make them attractive tools for the study of the extractable energy and potential impacts of coastal engineering structures. However, a wide range of multi-scale processes must be either directly simulated or parameterized in order to ensure the appropriate levels of accuracy required to make them useful tools for impact assessment and optimization studies within planning, operational and research contexts. In particular, tidal, fluvial and wave dynamics, as well as biogeochemical and sedimentological processes, can be considered in both the near- and far-fields. In addition, engineering structures such as turbines, sluices and impoundments need to be incorporated. A formally complete and accurate representation (e.g. via direct numerical simulation) of all these processes is beyond present computational capabilities. As a result, various approximations are employed to study aspects of hydrodynamic flows and environmental impacts. The differing levels of approximation used to model impoundments are outlined in this section, ordered in terms of dimensionality of the solution space.

For the majority of research to-date, especially at larger regional scales, the depth-averaged (2D) shallow water equations (SWE) have been adapted to assess the potential resource and impacts of tidal range schemes. These are obtained following the depth-integration of the Navier-Stokes equations which govern fluid flow in 3D, under the assumptions that horizontal length scales are much greater than vertical scales, and pressure is close to being in hydrostatic balance. It is common for these equations to be considered in both non-conservative, as well as the following conservative forms:

$$\frac{\partial U}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial G}{\partial y} = \frac{\partial \tilde{E}}{\partial x} + \frac{\partial \tilde{G}}{\partial y} + S \tag{5}$$

where U is the vector of conserved variables, E and G are the convective flux vectors in the x and y direction respectively, $\tilde{E}$ and $\tilde{G}$ are diffusive vectors in the x and y directions, and S is a source term that includes the effects of bed friction, bed slope and the Coriolis force. The terms in Eq. 5 can be expanded as [30]:

$$U = \begin{bmatrix} h \\ hu \\ hv \end{bmatrix}, \; E = \begin{bmatrix} hu \\ hu^2 + \frac{1}{2}gh^2 \\ huv \end{bmatrix}, \; G = \begin{bmatrix} hv \\ huv \\ hv^2 + \frac{1}{2}gh^2 \end{bmatrix}, \; \tilde{E} = \begin{bmatrix} 0 \\ \tau_{xx} \\ \tau_{xy} \end{bmatrix}, \; \ldots \tag{6}$$

$$\ldots \; \tilde{G} = \begin{bmatrix} 0 \\ \tau_{xy} \\ \tau_{yy} \end{bmatrix}, \; S = \begin{bmatrix} q_s \\ +hfv + gh(S_{bx} - S_{fx}) \\ -hfu + gh(S_{by} - S_{fy}) \end{bmatrix}$$

where u, v are the depth-averaged horizontal velocities in the x and y direction, respectively, h is the total water depth, and q_s is the source discharge per unit area. The variables τ_{xx}, τ_{xy}, τ_{yx} and τ_{yy} represent components of the turbulent shear stresses over the plane, and f refers to the Coriolis acceleration. Here the bed and friction slopes have been denoted for the x and y directions as S_{bx}, S_{by} and S_{fx}, S_{fy} respectively.

For coastal ocean models, when solving either the 2D SWE or the hydrostatic or non-hydrostatic forms of the 3D Navier-Stokes equations, the first decision generally made is whether the domain in question can be adequately described at a discrete level using a structured mesh, or if the flexibility afforded by an unstructured mesh is desired. The latter is particularly useful when accurate representation of complex geometries is required, and/or drastically different spatial mesh resolution is desired within a single computational domain [50]. A key decision is then often whether open source versus proprietary software is used, and in the case of unstructured meshes whether a finite volume or finite element based discretization approach is employed. For the solution of the governing equations, previous studies have applied a variety of coastal models including ADCIRC [35], Telemac-2D [9], EFDC [32, 51], as well as in-house research-focused software [24, 30].

A common aspect in all of these approaches is the manner in which water bodies either side of the impoundment are linked numerically, given that at different times of the lagoon operation they may be completely disconnected, and at others linked through sluices and turbines. A domain decomposition based technique has been the standard approach employed to simulate tidal lagoon operation at a field-scale state [24, 29, 30, 32, 33, 37, 46, 51, 52].

This technique is implemented using two (or more in the case of multiple impoundments) sub-domains: one upstream, and another downstream of the impoundment. Open boundaries connecting the sub-domains are specified in the region of flow control structures, i.e. turbines and sluice gates. Sub-domains are then dynamically linked using available information regarding the behaviour of hydraulic structures, such as tidal turbine hill charts as with simplified 0D approaches (Section 3.1). Dedicated details for the representation of tidal lagoons in a SWE model and the conservation of mass and momentum through hydraulic structures are expanded in Angeloudis et al. [52].

Three-dimensional studies generally commence with an extension of the 2D approach to include a number of vertical layers which, while having been applied to other coastal engineering applications, are yet to be applied to the regional scale modelling of tidal range structures. An expansion to 3D layered methods would produce an appreciation of the three-dimensional conditions generated by the hydraulic structure-induced water jets. In turn, and subject to the substantial growth in the required computational resources, classical 3D hydrodynamic CFD (computational fluid dynamics) approaches could yield even greater insight. At present, these are only generally applicable for smaller scale hydraulic engineering applications, due to current limitations of computational resources, including storage. The use of multi-scale unstructured meshes can of course blur this distinction, but one needs to keep in mind the variations in time scales and the need to parameterise different turbulent processes. In fact, the expansion to fully 3D modelling of tidal barrage/lagoon operations has been scarcely reported to date. At the time of writing, this has been limited to the CFD modelling of laboratory-scale flows expected downstream and upstream of barrages [e.g. 53, 54, 55]. However, 2D models are generally accurate for predicting water levels, and so for most applications, particularly resource assessments, the complexity offered by a 3D model is often not required.

3.4. Observations and validation

The main types of data used to parameterize and force numerical models are bathymetry and boundary conditions. There are many online sources of bathymetry that are suitable for model setup such as GEBCO (global 1/2 arc-minute grid) and EMODnet (European 1/8 arc-minute grid). However, in many circumstances it may be necessary to complement such datasets with local accurate high-resolution survey data, such as LiDAR or multi-beam data, particularly in the inter-tidal. Although many tide gauges exist around the world, providing accurate time series of water surface elevations over many decades, often such datasets do not coincide with model boundaries, or are unsuitable for boundary forcing (e.g. if there are large changes in amplitude and phase along a 2D boundary). Under such circumstances, global or regional tidal atlases are therefore used to generate boundary conditions. One such resource, FES2014 [56], provides both amplitude and phase of surface elevations and tidal currents for 32 tidal constituents at a (global) grid resolution of $1/16 \times 1/16°$.

Although it is not possible to validate a model of a lagoon prior to construction, it is possible to validate a hydrodynamic model in the absence of a lagoon. Confidence in the hydrodynamic model, along with subsequent rigorous parameterization of the tidal lagoon, therefore provides a tool that can be used to explore various tidal range schemes and operating scenarios prior to substantial financial investment.

Generally, a thorough understanding of the resource requires that a time series of the free surface is analysed and split into its astronomical components (e.g. principal semi-diurnal lunar (M2) and solar (S2) constituents), and it is the amplitude and phase of these constituents that forms the basis of model validation. However, in many circumstances, for example for regions or time periods that experience significant non-astronomical effects (e.g. surges), the actual time series can be used to assess the skill and accuracy of the numerical simulation.

4. Tidal range resource

4.1. Theoretical global resource

The analysis described below estimates the global annual theoretical tidal range resource to be around 25,880 TWh, based on reasonable thresholds for energy output and water depth. However, the resource is confined to a few coastal regions (covering 0.22% of the World's oceans). In fact, the majority of the resource is distributed across eleven countries.

Our global resource characterization is based solely on annual sea surface elevations and water depths. The FES2014 tidal dataset was used, which provides tidal elevations (amplitude and phase) at a consistent $1/16° \times 1/16°$ global resolution. FES2014 is the latest iteration of the FES (Finite Element Solution) tidal model, and is a considerable improvement on FES2012, particularly in coastal and shelf regions. Water depths were provided by the GEBCO-2014 gridded bathymetry dataset (`www.gebco.net`), available on a

$1/120° \times 1/120°$ global grid (which was resampled here to a $1/16° \times 1/16°$ grid to match the FES2014 grid points), and referenced to mean sea level.

For each $1/16° \times 1/16°$ grid cell, an annual elevation time series was constructed (using T_TIDE; [57]), based on the following 5 tidal constituents: M2, S2, N2, K1, and O1. For each time series, the tidal range (H) of consecutive rising and falling tides were calculated, allowing the annual potential energy (PE, per m^2), to be calculated as follows:

$$PE = \sum_{i=1}^{n} \frac{1}{2} \rho g H_i^2 \tag{7}$$

where the subscript i denotes each successive rising and falling tide in a year ($n \approx 1411$), ρ is the density of seawater, and g is acceleration due to gravity. The resulting contour map of global potential energy density (in kWh/m^2) is shown in Fig. 2.

Some assumptions have been made about areas that are suitable for lagoon developments, and we have calculated how much energy there is in just these areas. The true limit of any development will be when the energy yield does not increase the financial return sufficiently compared with the development and running costs (Section 5.2). Here, we assume a minimum acceptable annual energy yield of 50 kWh/m^2 (based on the energy yield from a constant tidal range of 5 m), and also a maximum water depth of 30 m (since construction costs of the embankment would likely be prohibitive in deeper waters). Applying these criteria, the global annual potential energy is approximately 25,880 TWh; distributed across the coastal regions of eleven countries, as detailed in Table 3.

However, for the majority of the year, the largest theoretical resource, the Hudson Bay area, contains substantial sea ice (`http://nsidc.org/`) and steep bathymetric gradients (i.e., the resource in water depths less than 30 m is constrained to the near coastal strip); and would therefore be impractical to exploit. This region is also rather isolated from a demand perspective. Sea ice is also prevalent in Alaska [58] and northern Russia [59], where we calculated significant potential energy. However, lagoons can be designed to take account of static and dynamic ice loads on the structures. Taking into account the impracticality of Hudson Bay for tidal range energy exploitation, the global annual potential energy is approximately 5,792 TWh. Generally, regions with desirable characteristics, i.e. regions where the tidal wave is amplified due to resonance, are limited, and indeed 90% of this resource is distributed across the coastal regions of just five countries, as shown in Table 3: Australia, Canada, UK, France, and the US (Alaska).

4.2. Theoretical resource of the European shelf seas

For more detailed analysis, we focus on the resource of the northwest European shelf seas (NWESS), since this is a region that includes existing (La Rance) and proposed (Swansea Bay) tidal range schemes (Section 2), in addition to hosting around a quarter of the global theoretical resource (Table 3). In order to estimate the NWESS tidal range resource, the 3D ROMS model (Regional Ocean Modeling System) was used to simulate tidal elevations, and subsequently the potential energy in both the flood and ebb phases of the tidal cycle. The model domain extends from 14° W to 11° E, and 42° N to 62° N, but the region analysed is shown in Fig. 3. The domain was discretised in the horizontal using a curvilinear grid, applying a variable longitudinal resolution of 1/60° (0.87-1.38 km), and a fixed latitudinal resolution of 1/100° (∼1.11 km). The bathymetric grid is based on GEBCO global data (www.gebco.net) at 1/120° resolution. The vertical model grid consists of 10 layers distributed according to the ROMS terrain-following coordinate system. The open boundaries of the model were forced by tidal elevation (Chapman boundary condition) and tidal velocities (Flather boundary condition), generated by 10 tidal constituents (M2, S2, N2, K2, K1, O1, P1, Q1, Mf, and Mm) obtained from TPX07 global tide dataset at 1/4° resolution [60]. The validation procedure for elevations, based on harmonic analysis performed at 20 tide gauges distributed throughout the domain, produced scatter indices (SI)[3] of $<8\%$ and $<6\%$ for M2 and S2 amplitudes, respectively. Further information about the model set up and validation can be found in Robins et al. [61]. Tidal analysis from a 30-day simulation was used to calculate the following 5 dominant tidal constituents, which were used to construct annual elevation time series at each model grid cell: M2, S2, N2, K1, and O1. Following the method outlined in Section 4.1 and using Eq. 7, the annual energy yield (in kWh/m^2) over the northwest European shelf was calculated (Fig. 3).

Here, we assume a range of minimally acceptable annual energy yields and also a maximum water depth of 30 m. Based on Tidal Lagoon Power's planned scheme in Swansea Bay, the lagoon has a surface area of 11.7 km^2 and a PE of approximately 84 kWh/m^2 (i.e. a total PE of around 1 TWh)[4]. Other lagoon schemes typically have an annual yield of 60 kWh/m^2, and the energy yield based on an M2 amplitude of 2.5 m is approximately 50

[3]Scatter Index is the RMSE normalised by the mean of the observations.

[4]Assuming the surface area at high tide does not reduce through the tidal cycle.

kWh/m^2.

If we assume initially that exploitable areas are those with water depths <30 m and an annual yield above 50 kWh/m^2, then approximately 31,415 km^2 of sea space (landward of the black contour lines in Fig. 3) is exploitable throughout the NWESS, which equates to a total potential energy of 1,261 TWh per annum; 683 TWh per annum (54%) of which is found in UK waters, with the remaining 578 TWh per annum (46%) found in French waters. These estimates are similar to those calculated from the global analysis (Section 4.1), although the more detailed analysis here produces a 14% lower resource than the global estimate, due to the improved model resolution. To put these values into context, annual demand for electricity is around 309 TWh in the UK, and the UK theoretical tidal range resource is about double this.

By increasing the threshold to 60 kWh/m^2, the exploitable sea space reduces by 18% (to 26,682 km^2; areas landward of the red contour lines in Fig. 3), but the resource decreases only slightly to 1,154 TWh per annum; 53% of which is found in UK waters, with the remaining 47% found in French waters. Increasing the threshold yield further to 84 kWh/m^2 (the PE of Swansea Bay lagoon) reduces the total resource to 832 TWh per annum (now with 44%, i.e. 366 TWh, found in UK waters). Based on our criteria, the theoretical resource is concentrated along the UK coasts of Liverpool Bay, the Severn Estuary & Bristol Channel, the Wash, and southeast England. In France, the resource is located along the northern coasts of Brittany and Normandy (Fig. 3).

To put the above resource estimates into further context, the total M2 energy flux onto the European shelf has been estimated using models and satellite altimetry to be approximately 250 GW [62, 63], which equates to an annual energy yield of 2,190 TWh. However, the total potential energy might be higher than this, because the potential energy is moving around the system all the time and, hence, it is difficult to obtain a definitive theoretical value. If we take energy out of the system via lagoons, it is presently unclear how this will affect the energy dissipation on the shelf and the energy flux across the shelf edge (i.e. influencing other energy systems globally). Further, since discrete lagoons within the European shelf may interact with one another, it is possible that the theoretical resource would alter from that calculated above (Section 5.4).

Our resource estimates are based on theoretical energy yields, which are a function of tidal range and water depths. In practice, the technical resource will be considerably lower than the above theoretical estimates. For example, Prandle [8] estimated that approximately 37% of the theoretical resource was available for dual (flood and ebb) schemes.

Of course, not all areas with sufficient yield can be exploited, due to practical difficulties with development at this scale, together with political and practical constraints regarding planning. It is also unlikely that, in the near future, lagoon designs would consider water depths greater than approximately 20 m (Mike Case, Tidal Lagoon Power; Pers. Comm.), although barrage designs might. Therefore, our resource calculations in regions suitable for lagoons should be considered an over-estimate. Moreover, it is unlikely that lagoon designs at this scale could maintain the high tidal amplification near to shore. For instance, if a very large lagoon was developed, then the tidal range within the lagoon would be reduced to approximately that at the lagoon wall. Using models, lagoon optimization studies may reveal that several smaller strategically sited lagoons within a region could lead to a greater energy yield than one larger lagoon.

4.3. Non-astronomical influences on the resource

The previous analysis, and indeed most studies of tidal range resource, assume only astronomical tides, and typically apply harmonic tide theory to predict water levels. However, the tidal resource can be influenced by non-astronomical effects, namely storm surge. Hence, potential reliability problems within tidal range energy schemes could be due to storm surges [64], as negative surge events reduce the tidal range, with the converse occurring during positive surge events. Tide-surge interaction, which results in positive storm surges being more likely to occur on a flooding tide [65], may also reduce the annual tidal range energy resource estimate. In a recent paper by Lewis et al. [64], water-level data at nine UK tide gauges suitable for tidal-range energy development (i.e. where the mean tidal amplitude exceeds 2.5 m [23]) were used to predict tidal range power with a 0D model. Storm surge affected the annual resource estimate by between -5% to +3%, due to inter-annual variability in the 12 year tide gauge records. However, instantaneous power output was significantly affected (Normalised Root Mean Squared Error: $3-8\%$, Scatter Index: $15-41\%$) [64]. Therefore, a prediction system [e.g. 66, 67] may be required for any future electricity generation scenario that includes a high penetration of tidal-range energy; however, annual resource estimation from astronomical tides alone appears sufficient for resource estimation, because uncertainties in resource assessment due to design and modelling assumptions appears greater.

4.4. Long timescale changes in the tidal range resource

Mean sea-level rise, which occurs incrementally over decadal timescales, results from variations in ocean mass and ocean water density (thermosteric and halosteric changes) caused by global warming and subsequent ice melt, due to changes in anthropogenic or natural land-water storage and from changes in ocean circulation [68]. Global mean sea level is likely to rise by $0.44 - 0.74$ m (above the $1986 - 2005$ average) by 2100 [69]. However, there remain large model uncertainties in sea-level rise projections, in particular when predicting the volume contribution from melting ice sheets [69], and projections could increase to 1.9 m [70].

Future mean sea-level rise is likely to affect tidal dynamics by impacting on the position of amphidromic points and by changing resonant effects on shelf seas [71, 72, 73, 74], with variation in regional (relative) sea-level changes due to ongoing local and far-field isostatic effects [69, 75]. In the UK, observed MSL rise is broadly consistent with global MSL rise [76]. A study by Ward et al. [72] indicated that projected sea-level rise over the 21st century is likely to alter both tidal amplitudes and tidal phases. Such changes in sea levels will influence the tidal range resource, although uncertainties in modelling the potential impacts are significant. A preliminary study by Robins et al. [77] investigated how these changes are likely to affect the theoretical resource at the top eight tidal range sites around the UK. There was generally an increase in tidal range at these sites ($1 - 3\%$, results not shown), causing the resource capacity to increase. However, when the aggregated power density from multiple potential lagoon locations was considered, tidal phase shifts tended to reduce the base-load capacity of the aggregated system. In one example future scenario, simulated sea-level rise clearly predicted an increased aggregated resource capacity, although the corresponding phase shifts led to reduced resource minima, which is a potential consideration for firm power generation. This preliminary work can be improved upon by considering how the feedbacks of a tidal energy extraction site on the local tidal dynamics (i.e. on the resource itself) might vary with changing sea levels [e.g. 72, 73].

4.5. Socio-techno-economic constraints on the theoretical resource

It is clear that not all potential tidal range sites will be developed to their fullest extent. Large infrastructure projects of this type will always be modified in societies where there is a democratic involvement in the planning process by the local population. For example, a factor in the lack of progress of the Severn barrage has been the concern of decision makers about the public acceptability of the scheme. An important element of public acceptability is the impact of a scheme on the local environment. This is part of planning law in many countries, and within the EU is legislated by the overarching Marine Strategy Framework Directive (MSFD) [78]. The most recent formal review of the Severn Barrage examined environmental concerns, and concluded there would be major impacts on migratory fish and other protected species [79]. Therefore, if the UK government were to approve such a scheme, it would be vulnerable to a legal challenge under the MSFD. Any lagoon in the Severn would have to consider the same receptor species and habitats as the barrage, and may have to provide compensatory habitat, increasing the capital cost of the project. As an example of environmental concerns limiting the resource capture of a project, even though the Swansea Bay lagoon has gained (partial) planning consent, the shape is deliberately placed to minimise interference with the Tawe and Neath rivers [80].

The coastal zone provides humans with extensive ecosystems services, and include visual amenity, including coastal seascapes [81]. Swansea Bay lagoon is an example of siting a structure to mitigate visual impacts; the structure is located in the northern part of Swansea Bay, next to the dock infrastructure, and away from the desirable residential areas and tourist seafront located to the west of the bay [80].

Many European countries are developing Marine Spatial Plans [82], so that they have a strategic long term oversight of economic activity in the oceans. The shipping industry has an historic presumption of safe navigation to port, and most coastal waters have navigational zones and marked shipping channels. The large scale development of lagoons could interact with these channels, and any perceived impediment to navigation would be contested robustly. A Marine Spatial Plan attempts to resolve these differences at an early stage; however, the consequences are that lagoon shapes and sizes will evolve from the most economically desirable geometry due to harbour access. When other uses of the sea are taken into account, including marine aggregates, offshore wind, and aquaculture, the space available for lagoons could be significantly constrained. One solution could be the Multiple Use of Space (MUS), with the inside of the lagoon providing an area that is protected from wave action and consequently suitable for a number of other uses. The MarIBE project [83] considered a number of MUS projects, and proposed suitable business models for future exploitation. In particular, the combination of aquaculture and a lagoon was investigated [84].

A previous project [85] considered a number of factors related to deployment of tidal stream turbines in the Severn Estuary, including a preliminary navigational risk assessment. Although the study is not directly applicable to lagoon deployment, there were two key findings. Firstly, early engagement with local pilots established that the "best" location for turbines from a resource perspective was co-incident with an area of sea that is key to vessel logistics. Secondly, the majority of the channel is $20-30$ m relative to LAT[5], and larger container vessels are routinely 16 m draft, making large areas of the channel practically unusable for the largest vessels. Applying this result to all areas with high tidal range, the application of good spatial planning could lead to the deeper channels available for vessels, and shallower areas designated for lagoon technology.

Building a lagoon is a significant item of infrastructure, and good port facilities are essential, in a similar way to the investments in round 3 wind farm construction on the east coast of the UK [86]. Tidal Lagoon Power Plc commissioned a supply chain study that outlines the infrastructure requirements [87]. Locations with theoretical resource but devoid of suitable ports in close proximity may not be practical for this reason. The construction techniques used also have a relevance to the port facilities required. La Rance barrage made use of a Bund construction [88], and hence was effectively a conventional land based civil engineering construction. However, such methods take a considerable amount of time, and may not be suitable for larger lagoons.

[5]Lowest Astronomical Tide.

Therefore, concrete caissons have been under consideration for a considerable period of time. Clare [89] considered the caisson requirements for the 1980s STPG Severn Barrage, which proposed the use of the majority of deep water ports in the UK, together with towing large caissons over considerable distances. Finally, and importantly, a lagoon must of course be able to export power to the grid, and so proximity to a suitable grid connection is a key constraint.

5. Optimization

There are two main categories of tidal lagoon optimization. The first is optimization of the operation of the turbines and sluices to maximize the energy yield from the lagoon, and the second is optimizing the overall economic design of the lagoon to minimize the cost of energy. The academic literature has focused on energy optimization, while industry tends to focus more on the economics.

5.1. Energy optimization

The optimization of lagoon operation has generally been achieved through the application of 0D models (Section 3.1), although other approaches have been attempted. Prandle [8] used an analytical approach to solve the 0D model through a number of simplifications. These included the use of a single tidal constituent, a constant lagoon bathymetry, and a constant turbine discharge rate.

Numerical solution of the 0D model has been undertaken numerous times [8, 10, 26, 27, 34, 39], and is the basis for most energy yield estimates. The codes seek to find the optimal generation start and stop times, and in most cases this is achieved through the use of fixed start head values for the ebb and flood tides. By considering a wide range of start head values, the optimal energy yield can be obtained, as shown in Fig. 4. This example plot was obtained through solving the 0D conservation of mass equation using a 4th order Runge-Kutta variable time-step method. Realistic turbine operation paths, lagoon bathymetry and tides were used for illustrative purposes only; however, the code has been applied to a range of commercial tidal energy projects including the Mersey Tidal Power project and Swansea Bay Lagoon. Fig. 4 clearly shows the optimal start heads for the ebb and flood phases at around 3.7 m and 2.7 m, respectively.

Yates et al. [28] have shown that energy yields can be increased through the use of pumping, and this tends to be in the region of about 10% of the potential energy. Due to the increase in computational power, the approach typically used in industry has moved away from fixed start heads to full optimization of the operation path. In this approach, the basin water level is discretised, and every possible path from the initial water level is calculated through the required period, typically one year. The optimal path can then be identified.

This approach is computationally expensive, and while the fixed start head simulations can be run in several seconds, the full optimization simulations can take significantly longer, with the exact time dependent on the water level discretization and selected time-step. There has been very little published on this approach [90], but the selection of these values is highly significant in terms of energy yield estimates. More work is needed in this area.

Prandle [91] and Rainey [44] used an electrical circuit analogy to model the potential energy yield of a tidal power plant. Although this approach takes into account some of the potential hydrodynamic effects, it does not allow for the discrete operation of the lagoon, as in the standard numerical approaches.

2D modelling tends to produce lower energy returns than 0D modelling due to the impact of hydrodynamics on the system (e.g. see Section 5.3). As the computational cost involved in running these models is high, few optimization studies have been performed, and they tend to be used only to provide an estimated correction to the 0D energy yield numbers.

5.2. Economic optimization

Economic optimization is an essential step for any realistic tidal lagoon development. The operational optimization is part of this process, but a much wider range of data regarding economics and other constraints (e.g. environmental or practical) have to be accounted for. The basic approach is to determine the Levelised Cost of Energy (LCoE) for a given lagoon design, and to then vary the design to determine the minimum value [92]. The LCoE is derived through:

$$LCoE = \frac{C_I + \sum_{n=1}^{N} \frac{OM_n}{(1+r)^n}}{\sum_{n=1}^{N} \frac{E_n}{(1+r)^n}} \tag{8}$$

where C_I is the capital investment, OM_n represents the operation and maintenance costs in year n, E_n is the energy yield in year n, and r is the discount rate. The design of the lagoon includes the cost of the embankment, which determines the enclosed basin area, the number and size of turbines and sluices. Each design affects the cost and energy yield. The optimal design is found through varying all of these parameters, and yields the optimal turbine design, number of turbines and sluices, and the optimal lagoon operation path. The size and power rating of a turbine can have significant impacts on the cost of energy for a scheme, and so should be thoroughly investigated. In Fig. 5, the minimum LCoE has been calculated using Eq. 8 for a fixed wall position for different turbine designs. For each turbine design, the optimal number of turbines and sluice gates is determined, together with the optimal operating heads. The capital costs for each design are calculated through simple design assumptions, and the O&M costs are fixed percentages of the capital. Fig. 5 shows that the optimal design, for this illustrative lagoon, is a 6 m diameter 5 MW turbine. The exact number of sluices and turbines and the operating heads for this turbine can then be extracted from the calculated data.

5.3. Implications of regional hydrodynamics for individual lagoon resource

Lagoons act as obstructions to the otherwise undisturbed tidal dynamics and will, therefore, alter natural flow conditions. Accurately quantifying their local and far-field impact is crucial for ensuring their feasibility. Hydro-environmental impact assessments of tidal range structures have been the subject of several studies [6, 9, 24, 29, 36, 52], and it is now well established that tidal impoundments can lead to changes in regional hydrodynamics, with implications for existing water quality and sedimentary processes. By extension, it must also be acknowledged that the presence of the lagoon may impact regional tidal amplitudes and water levels.

The output of a tidal power plant is fundamentally proportional to the downstream amplitude and the water head differences across the upstream and downstream sides of the lagoon. Therefore, since the marine structures themselves can sometimes interfere with these parameters, coastal modelling tools (2D/3D) can be employed to account for the altered hydrodynamics on the lagoon energy outputs. In contrast, generic 0D models assume no interference of the lagoon structure on regional hydrodynamics and are therefore unsuitable for capturing potential losses, thereby making the expansion to coupled hydrodynamic-operation models essential for accurate resource assessment of advanced proposals. Previous studies demonstrate the disparity between 0D and 2D predictions [24, 28, 52], with some indicative results shown in Table 4. The general trend has been that as the project scale increases, so does the hydrodynamic impact, as seen when comparing the Severn Barrage and the two coastally attached tidal lagoons. However, this is not an absolute; the Clwyd impoundment in the study is substantially larger than the Swansea Bay lagoon, but features a lesser relative hydrodynamic impact on its energy output. More factors also come into play, such as the operational sequence (e.g. ebb-only, flood-only or two-way) as shown by the Severn Barrage STPG simulations of the particular study.

5.4. Multiple lagoon resource optimization

The tidal range structures listed in Table 4 were assessed as discrete projects, but the manner that power is generated over time (Fig. 6) illustrates the advantage of concurrently developing multiple tidal energy schemes. For example, tidal lagoons can be strategically developed in locations that have complementary tidal phases, similar to the phasing that has been suggested for tidal stream projects [93]. For instance, projects in North Wales could partially offset the variability of power output from projects developed in the Bristol Channel, and *vice versa*. However, providing continuous tidal range power to the system remains a challenge during neap tides. For more information, the interested reader is directed to the work of Yates et al. [28], where the complementary nature of multiple tidal energy technologies has been examined for the UK.

Introducing multiple tidal range schemes within a regional tidal system, as expected, corresponds to cumulative hydrodynamic impacts, which could affect the energy output performance of the individual lagoons. This becomes particularly pronounced once tidal power plants are developed in the same channel or estuary, as with some proposals that are under consideration within the Severn Estuary and Bristol Channel. It has been reported that if the Swansea Bay Lagoon (Table 4) is operated in conjunction with the larger Cardiff Lagoon in the Severn Estuary under the same two-way operation, its annual energy output is expected to reduce by approximately 2% [24]. The performance of multiple lagoons could be improved through the development of optimization tools that treat the operation of the plants as a system that has the flexibility to adapt to the transient national demand for electricity. A potential advantage of having multiple small-scale projects rather than a single large-scale project is that tidal power will be fed to the grid at several locations rather than being concentrated at one particular point; this will contribute to a more efficient electricity distribution [28], and could perhaps alleviate cumulative hydrodynamic impacts [24].

6. Challenges and opportunities

6.1. Variability and storage

Present UK electricity generation strategies rely on thermal power stations to supply the majority of baseload capacity [94]. Despatchable generation (e.g. gas and hydroelectric) resolves intermittency and fluctuations in demand [95]. The future vision is that renewable power stations will play an increasing role in the generation mix, as reliance on polluting and finite fossil fuel reserves (in addition to environmental issues associated with nuclear power) is unsustainable. Although the design of 100% renewable energy systems is a long term goal [e.g. 96, 97], established renewable energy technologies such as wind and solar have issues, such as their stochastic/intermittent nature, or are provided from micro generation plants distributed over large geographic regions. The number one key challenge in integrating a number of intermittent/variable sources into an electricity supply grid is *storage* [98].

A future strategy could involve initially implementing renewable installations that are complementary in phase to one another (Section 5.4), in order to optimize baseload capacity and generation from these multiple sources. Future steps could be to then deal with the more complex issue of load following supply and demand using supergrids or smartgrids. In-depth reviews covering the potential cost and technical implications of such a task have been provided by Macilwain [99], Hammons [100], and Blarke and Jenkins [101].

Marine renewable energy, and lagoon (tidal range) power generation in particular, could offer the closest thing to despatchable, load-following generation, of any of the renewable energy sources. Scope exists to alter generation by holding water within the impoundment for a limited period, and by pumping into or out of the system. This is constrained by the need to allow the basin to empty or fill for the next cycle, and by the costs associated with pumping, e.g. pumping during periods of low demand (when the cost of electricity is low) and recouping the costs by generating during periods of high demand [10, 102], as well as the potential environmental impacts associated with such an operation. The potential of tidal range power plants for storage is a particularly powerful concept when we consider several plants operating in harmony. Although no research has yet been conducted on this topic, there is scope for optimizing the scheduling (both generating and pumping) of several tidal range schemes to resolve some of the issues associated with temporal variability.

Similarly to tidal elevations, tidal streams are also predictable, and so complementary phasing of sufficiently large tidal stream arrays, in conjunction with tidal lagoons, offers the potential to increase baseload generation capacity from multiple facets of a single renewable resource. A limitation is that both tidal range and tidal streams concurrently exhibit intermittency at spring/neap timescales, and so do not necessarily offer peak generation during times (day, week, season) of peak demand. Phase optimizing tidal energy in conjunction with wind and wave energy that naturally peaks during winter months [103], might help address this seasonal variability in demand; however, suitable predictive, coupled modelling techniques should be employed to robustly assess the true generating potential and interactions between technologies and schemes [e.g. 27, 104].

6.2. Additional socio-economic benefits through multiple use of space

Tidal lagoons could be incorrectly perceived as taking up large areas of sea space for very little local benefit. The production of renewable electricity is generally agreed to be worthwhile, but it is conceptually very difficult to equate one individual household's requirements with the generating capacity of a particular power station. However, a managed area of sea, protected from waves by a breakwater, has significant opportunities from Multiple Use of Space (MUS) [83]. A study of MUS for the proposed Swansea Bay tidal lagoon location [84] reviewed existing plans and proposed the following business propositions, in addition to electricity production:

1. Nine million UK and one millon overseas tourists take an overnight trip to Wales each year. Therefore, a visitor centre located on the lagoon wall is expected to attract similar numbers per year as the existing barrages in Brittany (70,000) and Nova Scotia (40,000) [21]. A boating centre will be built, arts, cultural and sporting events will take place, and the structure will provide amenity value for recreational fishing, walking and cycling.
2. Aquaculture could be developed to use some of the 11.5 km^2 of enclosed area. To improve water quality, it is proposed that Integrated Multi-Trophic Aquaculture (IMTA) is implemented [105], with by-products from one species feeding another. Fin fish are not recommended, as these will place a high oxygen demand on the ecosystem, but a combination of shellfish and seaweed species would be suitable. These are already harvested in the region. Such a concept could be extended to any lagoon location, provided suitable species are selected. The market

size is expected to grow from 52.5 million tonnes in 2008 by 62% before 2030 [106], partly due to the depletion of wild fish stocks.

Overall, MUS provides sustainable, long term jobs, and fosters local ownership of energy conversion projects, therefore helping to alleviate some of the perceived negative aspects of tidal range power plants.

6.3. Implications of the Hendry Review

In February 2016 the UK Government commissioned an independent review of tidal lagoons, entitled the Hendry Review of Tidal Lagoons, with the review led by the Rt Hon Charles Hendry. Specifically, the review invited comments on the following questions: (i) Can tidal lagoons play a cost-effective role as part of the UK energy mix? What is the value of the energy from a UK-wide programme of lagoons? (ii) What is the potential scale of opportunity in the UK? (iii) What is the potential scale of opportunity internationally? (iv) What are the potential structures for financing lagoons? (v) What size of lagoon should be the first-of-a-kind (and should there be one)? (vi) Could a competitive framework be put in place for the delivery of tidal lagoon projects?

The Hendry Review was published in January 2017 [4], entitled "The Role of Tidal Lagoons", with the review supporting the development of a relatively small-scale project in Swansea Bay as soon as reasonably practicable and calling it a 'no-regrets' option. However, the project still requires a marine licence from Natural Resources Wales, and the company promoting the lagoon, namely Tidal Lagoon Power, are yet to agree a Contracts for Difference (CfD) price with the UK Government. A key recommendation in the

Hendry Review report was that Swansea Bay lagoon, termed a "pathfinder project", should be operational for a reasonable period of time before construction commences on any larger-scale projects, so that the full range of impacts can be monitored over time. This, in part, is a response to the environmental, ecological and fish migration concerns raised over potential lagoon impacts on marine habitats and species. Changes in the hydrodynamic, water quality indicator and morphological processes can be assessed, as well as the accuracy of the hydro-power predictions associated with the turbines/pumps and sluice gates and their operational efficiencies.

The report makes over 30 recommendations in supporting a tidal lagoon programme and delivering maximum benefit to the UK, with some of the key recommendations including: (i) an allocation by a competitive tender process for large-scale tidal lagoons; (ii) informing the consenting process with a National Policy Statement from the UK Government for tidal lagoons, similar to Nuclear new build, where specific sites are designated as being suitable for development; and (iii) the establishment of a new body (namely a Tidal Power Authority) at arms-length from Government, with the goal being to maximise the UK opportunities from a tidal lagoon programme. There is no doubt that this positive and comprehensive Hendry Review towards the role of tidal lagoons in the UK and internationally has raised the interest of a wide range of stakeholders in developing tidal range technologies in the UK. New interest and companies are now being established in a range of related areas, including new turbine technologies, re-focused research programmes and, in particular, increased interest from international – as well as national – investors, in funding tidal range projects in the UK. Examples of projects currently at various stages of development, in addition to the Swansea Bay project, are Tide Mills UK & Africa[6] which is investigating the feasibility of restoring historic tide mills (and which has attracted Innovate UK funding), and a much larger Severn Barrage project [107].

7. Conclusions

Following publication of the 2017 "Hendry Review", which made over 30 recommendations in support of a tidal lagoon programme, tidal range power plants, particularly tidal lagoons, are gaining governmental support and generating commercial interest. The technology that is required to build a lagoon has been around for over 50 years (and has improved considerably over this time period), but there are several challenges to overcome, the most pressing being an assessment of the environmental impact of such schemes. However, there are many opportunities, such as predictable electricity generation, and the potential for tidal range power plants to provide storage.

This review has shown that 90% of the global tidal range resource is distributed among just five countries, and that Australia is host to 30% of the global tidal range resource. The review finds that concurrent strategic development of multiple lagoons would minimise variability by optimizing the scheduling of several such power plants operating in harmony, in addition to exploiting the phase difference between spatially distributed sites. Finally, there is potential for cost reduction of tidal lagoon power plants by considering Multiple Use of Space, for example by integrating aquaculture or

[6] http://gtr.ukri.org/projects?ref=132492

combining with leisure activities.

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FIGURES

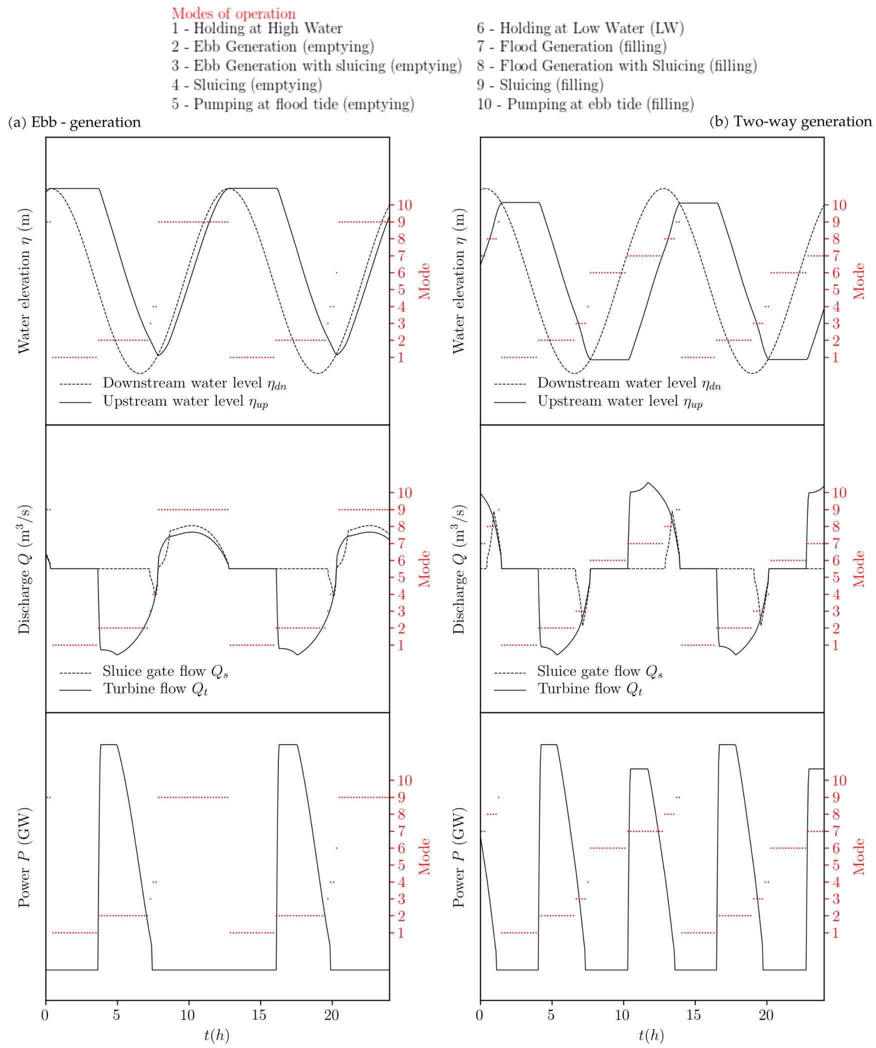

Figure 1: List of possible modes of operation, and two examples of tidal range power plant operation strategies, simulated using a 0D model and shown as time series of water elevation, flow rate, and power output. (a) ebb-generation is illustrated on the left, and (b) two-way generation on the right. η_{up} is the upstream water elevation (m), η_{dn} is the downstream water elevation (m), Q_s is total sluice gate flow (m^3/s), Q_t is total turbine flow (m^3/s), and P is Power output (GW).

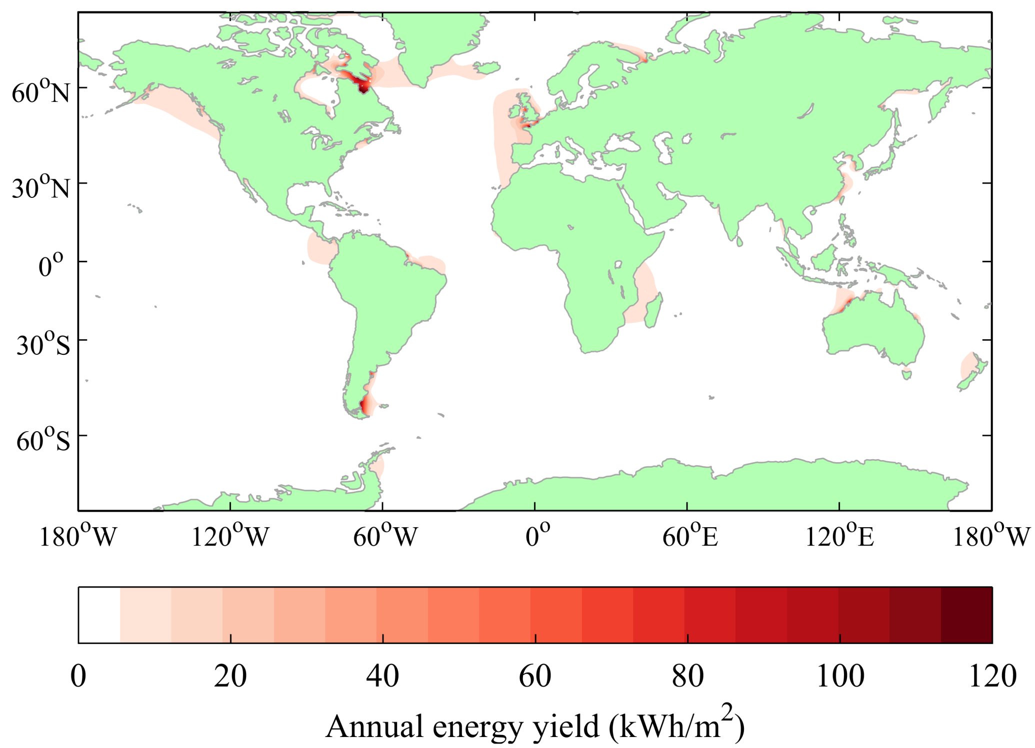

Figure 2: The global theoretical tidal range energy resource calculated as annual energy yield (kWh/m^2) per model grid cell ($1/16° \times 1/16°$).

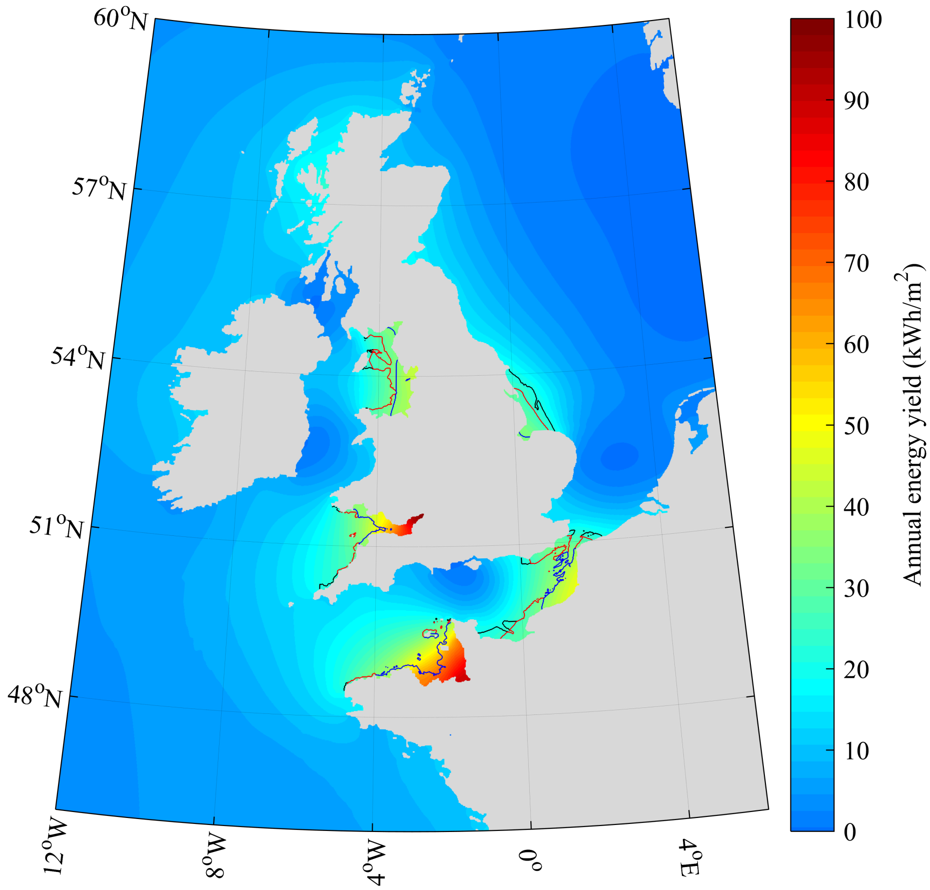

Figure 3: The theoretical tidal range energy resource over the northwest European shelf seas, calculated as annual energy yield (kWh/m^2). Areas landward of the [blue, red, black] contour lines denote regions with water depths less than 30 m and where energy density exceeds 84, 60, and 50 kWh/m^2, respectively.

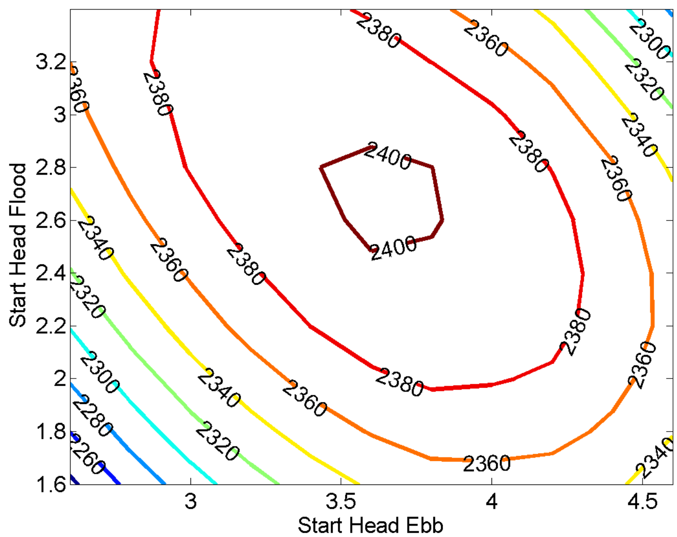

Figure 4: Energy yield (in GWh) obtained through a fixed start head 0D model as the start head values are varied.

Figure 5: LCoE contour plot showing optimal cost (in £/MWh) as turbine design varies.

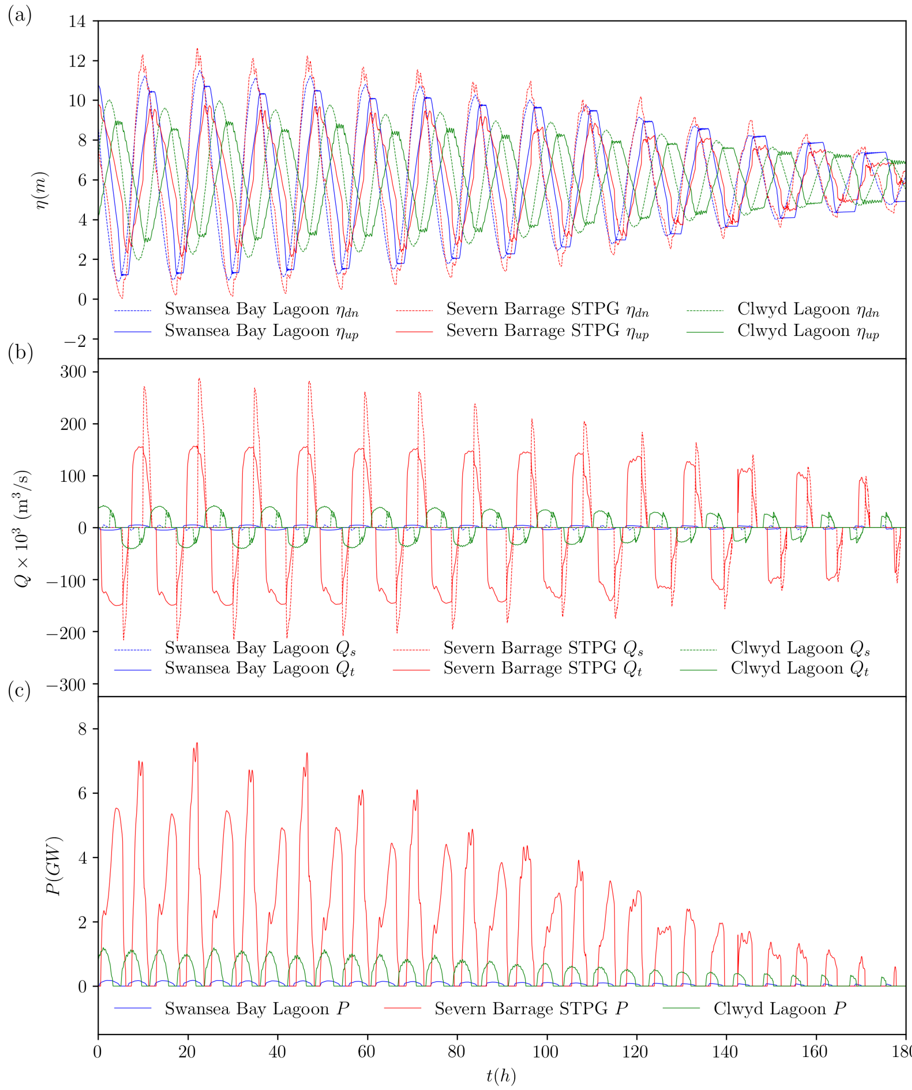

Figure 6: (a) Elevations, (b) hydraulic structure flows, and (c) power production in the transition from a spring to a neap tide for three projects of varying scale (i.e. the Swansea Bay Lagoon (11.6 km^2), the Clwyd Lagoon (126 km^2), and the Severn Barrage STPG (573 km^2)), assuming two-way operational sequences. Notice the phase difference between the Bristol Channel schemes (Swansea Bay Lagoon & Severn Barrage) and the Irish Sea project (Clwyd Lagoon). Adapted from Angeloudis et al. [52].

TABLES

Table 1: Characteristics of existing tidal barrage schemes.

Power Plant	Year	Capacity (MW)	Basin area (km^2)	Operation mode
La Rance, France	1966	240	22	Two-way with pumping
Kislaya Guba, Russia	1968	1.7	2	Two-way
Annapolis Royal Generating Station, Canada	1984	20	6	Ebb only
Jiangxia, China	1985	3.9	2	Two-way
Lake Sihwa, Korea	1994	254	30	Flood only

Table 2: Tidal range locations around the world that have been identified as being technically feasible [adapted from 13, 21, 108]

Country	Site	Type	Mean tidal range (m)	Basin area (km^2)	Proposed capacity (GW)	Estimated annual output (TWh)
Argentina	San Jose	Barrage	5.9	-	6.8	20
Australia	Secure Bay 1	Barrage	10.9	-	-	2.4
	Secure Bay 2	Barrage	10.9	-	-	2.4
Canada	Cobequid	Barrage	12.4	240	5.34	14
	Cumberland	Barrage	10.9	90	1.4	3.4
	Shepody	Barrage	10	115	1.8	4.8
India	Gulf of Kutch	Barrage	5.3	170	0.9	1.7
	Gulf of Cambay	Barrage	6.8	1,970	7	15
South Korea	Garorim	Barrage	4.7	100	0.48	0.53
	Cheonsu	Barrage	4.5	-	-	1.2
Mexico	Rio Colorado	Barrage	$6-7$	-	-	5.4
	Tiburon	Barrage	-	-	-	-
UK	Severn	Barrage	7.0	520	8.64	17
	Mersey	Barrage	6.5	61	0.7	1.5
	Wyre	Barrage	6.0	5.8	0.047	0.09
	Conwy	Barrage	5.2	5.5	0.033	0.06
	Swansea	Lagoon	-	-	0.32	-
	Newport	Lagoon	-	-	0.75	-
	Bridgewater	Lagoon	-	-	2	-
	Cardiff	Lagoon	-	-	$1.8-2.8$	-
	Colwyn Bay	Lagoon	-	-	1.5	-
	Blackpool	Lagoon	-	-	1.0	-
US	Passamquoddy	Barrage	5.5	-	-	-
	Knik Arm	Barrage	7.5	-	2.9	7.4
	Turnagain Arm	Barrage	7.5	-	6.5	16.6
Former Soviet Union	Mezen	Barrage	9.1	2,300	15	50.0
	Tugur	Barrage	-	-	10	27.0
	Penzhinskaya	Barrage	6.0	-	50	27.0
	Cauba	Barrage	-	-	-	-

Table 3: Annual potential energy per country.

Country	Annual PE (TWh)	Percentage of global resource
Global (disregarding Hudson Bay)	5,792	100
Canada (Hudson) (extensive sea ice)	*20,110*	-
Australia	1,760	30
Canada (Fundy)	1,357	23
UK	734	13
France	732	13
US (Alaska) (partial sea ice)	619	11
Brazil	298	5
South Korea	107	2
Argentina	62	1
Russia (NW) (partial sea ice)	42	<1
Russia (NE) (partial sea ice)	33	<1
India	19	<1
China	12	<1

Table 4: Typical Annual Energy Predictions of a number of tidal range scheme case studies of different scales (adapted from [24] for lagoons and [52] for barrages). Hydrodynamic impact in the right hand column is defined as the difference between the 2D and 0D total accumulated energy predictions over the same simulation period, expressed as a percentage. STPG = Severn Tidal Power Group; HRC = Hydro-environmental Research Centre, Cardiff University.

Case study	Operation	Area (km^2)	Location	0D Prediction (TWh/yr)	2D Prediction (TWh/yr)	Hydrodynamic impact on power production (%)
Swansea Bay Lagoon	Two-way	11.6	Bristol Channel	0.53	0.49	6.8
Clwyd Impoundement	Two-way	125	North Wales	2.74	2.63	3.8
Severn Barrage HRC	Two-way	573	Severn Estuary	25.01	22.05	38.9
Severn Barrage STPG	Ebb-only	573	Severn Estuary	23.03	15.77	31.5