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Providing distributed electrical generation through retrofitting disused docks as tidal range energy schemes

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ABSTRACT

As the nature of modern industry has changed, a range of infrastructure such as smaller historic docks have fallen into disuse, and attempts to redevelop these basins typically focus on the development of housing and commercial spaces with a waterside location as a high-value component. These sites provide the opportunity for repurposing as tidal range energy schemes without incurring many of the drawbacks of a traditional scheme. A 0D model was used to ascertain the potential energy output that sites around the UK could generate, using disused dock basins as an initial development case, with a total of 28 basins generating ~34 GWh/year, based on the first quarter of 2022. Due to the size and locations of the docks, the ability of this renewable energy method to generate at times of high demand, a role in which fossil fuels are still dominant in the UK energy mix, was highlighted. Thus, a method to ascertain the feasibility of using infrastructure which utility has declined, or where pre-existing physical characteristics could be well suited to tidal range, to contribute to the energy system is established.

1. Introduction

There is global political drive to achieve a net zero carbon society [1], whilst enhancing access to electricity to those in the Global South, with access to electricity being linked to multiple quality-of-life metrics [2]. To achieve this, the United Kingdom, like many other states, faces the challenge of maintaining or increasing electrical production, whilst reducing the carbon output of its electrical system [3]. As the severity and likelihood of extreme events increases, the demand for energy to heat homes etc. becomes more challenging to anticipate, whilst the potential availability of wind and solar energies cannot inherently be relied upon [4]. As such, energy storage, and balancing mechanisms, along with reliable sources of renewable energy are critical to 'keep the lights on' around the UK [5].

Tidal range energy utilises the rise and fall of water due to tides to generate low-carbon, highly predictable and dispatchable energy. A tidal range scheme (TRS) comprises a few fundamental components: a tidally varying water surface, an internal (impounded) area separated by a boundary wall, and a set of turbines and sluice gates that allow the passage of water across the wall structure. By connecting the internal area to the external area, affected by tides only through the turbines and sluices, the operators can hold the internal level at a given position, until the difference between the inside and outside is at a predetermined value across the turbines to initiate electricity generation (ΔH_{Start}, shown with open-circle marked lines in Fig. 1) [6]. When the turbines are opened they begin to turn and generate energy, and the water flowing across them causes the volume of water and thus water level inside the impoundment to follow the external tide until the two reach a head difference so small that generation is no longer feasible (ΔH_{End}, closed markers in Fig. 1) and thus generation is ceased, with the remaining difference being equalised by opening the sluice gates and allowing water to flow between the two sides. Once the levels are equal, the sluices and turbine housings are closed, and the internal level held until the head difference is once again sufficient to generate, or the sluices or pumps are operated to move the water level to a state that is more beneficial for the upcoming generation periods [7].

This approach differs from tidal stream or wind turbine concepts, as controlling the opening and closing of the turbines can be adjusted to capture periods of higher energy demand, or other operational goals [8, 9]. As the tides are highly predictable, the generation behaviour can be well forecast, and contribute beneficially to the energy system [10]. Multiple tidal range schemes currently operate around the world, with the oldest generating energy (~480 GWh/year) consistently for half a century at La Rance in France, and the scheme with the largest

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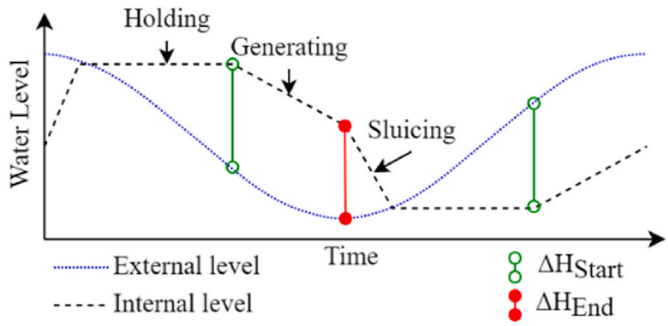

Fig. 1. Example operation of tidal range scheme.

generating capacity is installed at Lake Sihwa in South Korea with a 254 MW capacity [7]. Despite a long history of interest in tidal range energy in the UK, where the second largest tidal range in the world offers significant energy potential, environmental concerns (loss of intertidal area [11], fish mortality [12] and others) and the large capital expenditure required to construct miles of breakwater have largely blocked development [13]. This challenge can also be seen globally, Neill et al. [14] note that the areas in Australia with the largest tidal range potential also suffer from some of the more severe challenges to construction, including distance to significant population centres, and various challenges such as localised hydro-environmental issues. The majority of research in tidal range energy has typically generally aimed to improve the viability of proposed schemes and reduce the environmental impacts of large schemes. These approaches being usually within the classic concept of improving performance, however, alternative design concepts and enhanced technological development, e.g. improved turbine designs, may be able to provide some of the benefits of tidal range whilst mitigating the typical drawbacks.

Developed from the fundamentals of tidal range scheme operation as set out by Prandle [6], 0D models apply a conservation equation to control the volume change within a specified impoundment of fixed or variable area, driven by the difference between the time varying external water level – and the impounded region. This modelling approach (when compared with the use of a physically founded Navier-Stokes based model) provides a method to simulate long durations of operation at a computational cost that vastly outweighs the disparity in energy production (<7.5% per Xue et al. [15]). Thus, the 0D method has been used in particular to carry out optimisation procedures of tidal range schemes, such as optimisation of the design of physical characteristics such as the number and size of turbines [16,17], controlling the generation patterns for maximum yield [18], or with the intent to achieve constant output across a combination of schemes though a collective strategy [19]. The ability to test a variety of configurations and options plays a key role in the early stages of tidal range scheme designs, where the array of options, and computational cost of detailed models can limit the ability to ascertain improved design options.

As long as society has been drawn to the water's edge, be it fresh or briny, the need to alter the waterline to suit the activity needed to prosper has existed. This takes the form of piers, jetties, harbours, docks, breakwaters and more, each developed to solve a location-specific challenge. How these structures are used is like all things: subject to change over time, with some falling into disrepair. As both local and global industries have shifted in their operational methods (such as the advent of containerised shipping) the commercial usage of smaller and historic docks has seen a decline around the UK [20]. In 1999, Hawkins et al. [21] identified 11 ports in the UK with disused dock basins and eight sites of major redevelopment. The focus of this study has been on improving water quality and biodiversity through various methods to increase the mixing of water within the docks, and the introduction of aquaculture. The delicate nature of the terminology of restoration is also raised, implying an intervention to speed transition to a new state (particularly where the original is unobtainable or unknown). The potential issues in water quality experienced at disused docks (particularly relating to algae and lack of water movement) are further discussed by Allen et al. [22] in the case of the Liverpool docks. This was also seen in the case of larger coastal impoundments, such as Cardiff Bay, a 202-ha freshwater coastal reservoir, where dissolved oxygen levels and stratification are ongoing challenges [23], where aeration is used to reduce their impacts. The impact of mixing systems and mussel populations on improving water quality and the restoration process over multiple decades is discussed by Hawkins et al. [24]. These works tend to discuss the state of docks and water quality from the perspective of a typical docklands regeneration, as popularised in the 1980s following the success stories of the Baltimore and London Docklands restoration projects, wherein the housing, social and commercial needs were at the forefront of the development process [25,26]. The dock basins themselves typically provide value in terms of the holistic and social benefits seen by developers of being water adjacent, or through the provision of additional ecological value. The use of said basins to generate renewable energy has not been considered previously, but could bring value to the developments both in terms of electricity generated and the wider aesthetic benefits of water features.

This study considers the previously untested potential of a range of disused docks for usage as the impoundments for micro-scale tidal range schemes, utilising the existing structures and proximity to consumers, and lesser potential for harmful environmental impacts when compared with impounding a classic tidal range scheme region. Much of the physical structure is already in place, reducing construction costs. As the natural environment has been previously significantly altered, and the migration of fish through the scheme is unlikely, repurposed docks will have a lower environmental impact than typical tidal range schemes. Often dock basins are not constructed in single cases, but rather a number of basins are built around a dock or harbour; in this case the potential to use the separate docks together as linked-basin plants may yield a more consistent output at the cost of reduced net output [27]. The value of a fleet of small schemes forming a distributed energy supply system about the country may be more valuable to an evolving gris than a small number of bulk producers, thus a potential outline of how this could be achieved, is developed here for the first time. These docks are found relatively commonly in the UK, however potential impoundments from defunct infrastructure such as harbours, coastal reservoirs, recreational lagoons, and desalination facilities would have potential for use in an equivalent manner. Improved access to renewable energy is a global challenge. There are various infrastructures globally which do not function as before due to evolved industry or new technologies, similar to disused docks as a result of evolved maritime industry as used in this study. The concept of small tidal range however should be expanded to the greatest extent possible, thus the methods and tools developed and used in early-stage assessment such as this were selected to be as open and flexible as possible, to be useable for any suitable basin or impoundment.

To ascertain the value of distributed small tidal range structures, whose capital and environmental costs could be more palatable to developers, a scoping of retrofitting disused docks is considered. To aid in the wider application of the process, a method is laid out with a minimised cost of development. The primary aims of this paper are to:

- Expand the potential for development of novel tidal range energy concepts with possible applications to storage.
- Establish a simple methodology for identifying and assessing potential impoundments to be used as energy generation facilities.
- Utilise the methodology to identify potentially viable dock basins as a case study, namely disused docks around the UK.
- Provide a full example usage of the method for a single location.

- Determine the individual and combined power outputs of the potential docks as identified in the case study using a 0D tidal range scheme model.
- Demonstrate the potential of utilisation of disused docks through consideration of the grid-scale impact of the schemes identified in the case study.

The remainder of the paper is organised as follows: Section 2 presents the methodology for the identification of sites, how they were studied, and the numerical formulation of the model used; Section 3 presents and discusses the results of this process, firstly for a sample site, and then overall for the datasets; Section 4 concludes the paper.

2. Method

The methodology proposed to identify disused infrastructures which can be used as tidal range schemes is laid out in generic terms in Fig. 2, and then broken down in detail later in this section, with an example of the process presented in Section 3.1. Considering a partially closed, tidally connected body of water as the basis for a tidal range scheme can mitigate the costs, both physical and environmental, of tidal range scheme construction, whilst offering an avenue for distributed small-scale energy generation. Whereas historically the entirety of a scheme has been constructed from scratch, comprising some combination of coastline, caissons, and boundary wall extending into the undeveloped ocean, the use of existing engineered structures is the focus herein.

2.1. Identification of sites

With an initial region (step 1) being established as the UK coastline, and the desired physical traits as a disused dock basin (step 2), the collation of a set of initial sites was carried out via an open-source intelligence gathering method. For the purpose of this study, combination of satellite and street view imagery was used and manually assessed to visually identify empty or unused basins at major coastal locations around the UK (step 3), this process however could be automated using remote sensing tools such as those used to detect dams [28], lunar craters [29], and estimation of lake characteristics [30]. The automated

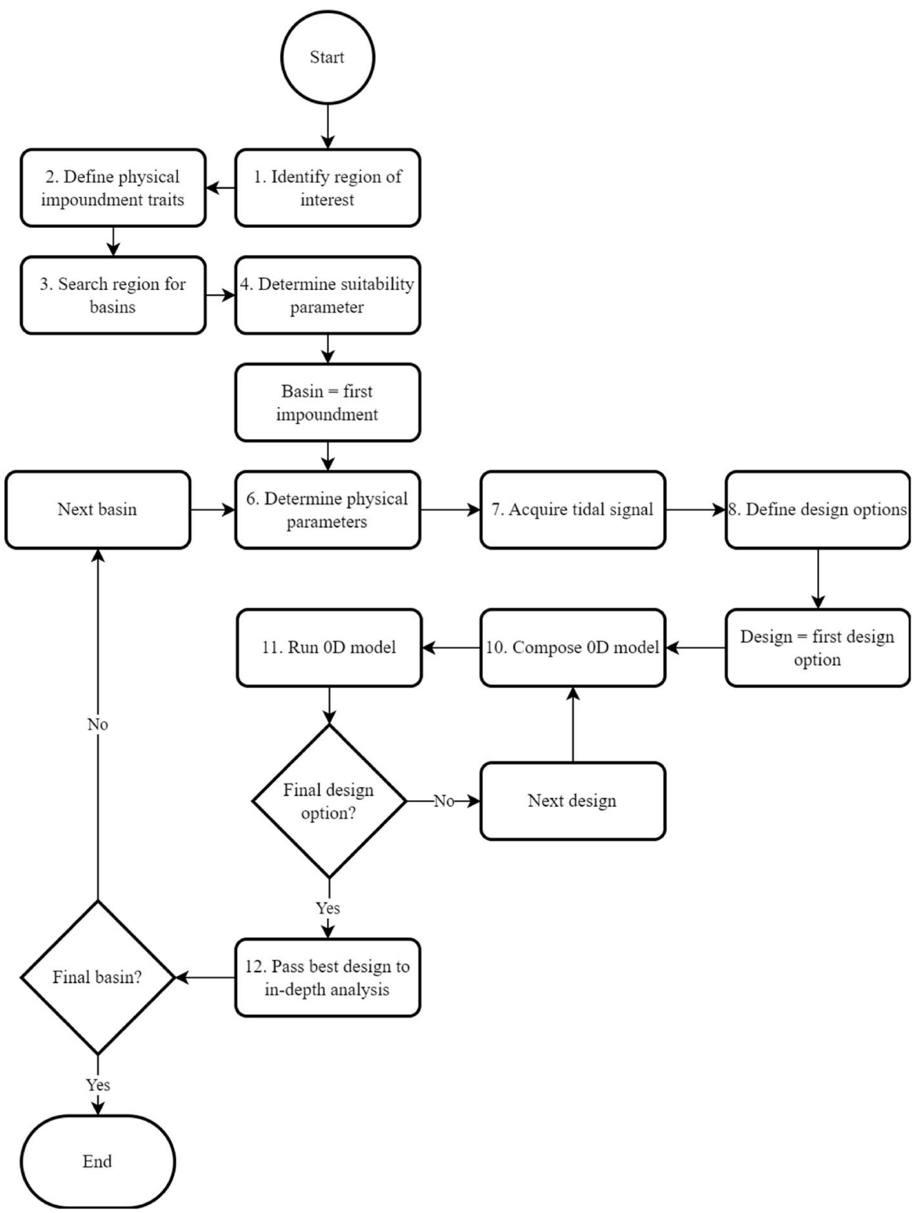

Fig. 2. Flow chart of small tidal range scheme initial assessment process.

method was not deemed to be suitable here due to limited area needed to be covered and the balance of time investment required for automated method versus time used for identifying sites manually. By any mechanism (manual or automated), this process is likely to yield a relatively high number of false positives, such as where identified basins have changed usage since photographing, or have a usage that is not easily visible. When expanded to automated methods, this step is still highly subject to training data availability, image quality, and area coverage and manual assessment for validation is still required. Manual search however can yield a first-case dataset, this could then be used as training data for automated systems, alongside providing a set of potential developments at a variety of realistic sizes at a variety of feasible locations. With further operational modelling only relying on the tidal water levels and a satellite image, this method aims to act as a precursor to a more detailed but costly engineering design and analysis, and to form a basis for remote sensing driven expansion of the process.

2.2. Assessment overview

The areas of the basins were calculated using the 'measure distance' function on Google Maps (step 6), with the tidal water levels (step 7) being extracted from a range of available sources (such as the global tidal models of the Permanent Service for Mean Sea Level data system [31], WorldTides [32], or TPXO [33]), in this study this was taken from the POLTIPS-3 software developed at the National Oceanography Centre, UK [34]. To provide an indicative measure of the energy generation potential of the sites, a set of simple design cases were determined for a tidal range scheme built into the sites. These were represented in a 0D model with operation run for an entire year using a flexible head generation scheme, two-way operation (generating on both the ebb and flood tides), and parallel sluicing (opening the sluice gates during generation to increase volume change). The schemes were operated using the 'every half next' mode of control (as suggested by Xue et al. [15]) whereby optimal operation for the upcoming 12.4 h is identified at every half tide, i.e. 6.2 h. The schemes were operated to optimise revenue of energy produced, acting both to produce a financially viable operation, and as a surrogate for the ability to delay production to suit the needs of the system. The energy price used was the System Sell Price (SSP), with the recorded data obtained from the Elexon data portal [35], the recorded value of energy sold to the national grid in that 30 min window (step 4 in Fig. 2).

The turbines used were scaled down from the Andritz Hydro 9 m Bulb Turbine presented by Aggidis and Feather [36], and as used in a number of tidal range studies due to its position in the public domain, and thus facilitating a benchmark component to allow comparison between studies and aiding reproducibility. Pumping was not included in the operation to ensure the water level remained within the natural tidal range, and as such the basins would not be dried out or flooded on the respective tidal points. Besides, pumping beyond the natural tidal range would require further structural analysis of the schemes to ensure their integrity.

As the price of energy varies at a half-hourly interval, a tidal range scheme is able to improve performance by expediting or delaying generation to capitalise on periods of increased energy value at the cost of total energy generation [8]. In this study the schemes used the system's sell price (SSP) to maximise revenue, acting as a surrogate for demand or imbalance. Future study would likely yield improved performance with pumping, allowing the scheme to operate more as an energy storage system, and thus potentially capitalise further on the varying price of energy, as has been seen in the case of traditional tidal range proposals [37], though this would require limitation based on the safe water level range at the sites.

Different scenarios considered for each site were composed using Equation (1), this being step 8 in Fig. 2. For a basin mouth width of W *(m)*, the design uses n_{tb} *(−)* turbines of diameter D_{tb} *(m)*, here 2.5 m, with a power rating of 3 MW. Each scheme also used either no sluices ($A_{sl} = 0$) or a 100 m^2 gate where possible to manage the number of scenarios and maintain a level of comparability. For each dock, the sluice width was assumed to be the area A_{sl} divided by the mean tidal amplitude $\overline{\xi}$ *(m)*. The maximum number of turbines assumed that each turbine would require a 5 m wide installation, twice the width of a turbine which includes the housing [38]. For a classical tidal range scheme additional features such as ship-locks and fish passes are required, however, it was assumed that the passage into/from the dock is not required and therefore these were omitted at this stage.

$$2 \bullet n_{tb} \bullet D_{tb} + A_{sl}/\overline{\xi} \leq W \tag{1}$$

2.3. 0D model

The 0D model used here applies the conservation of volume V *(m^3)* within the dock (2), as described by the flow into the dock Q *(m^3/s)* over a given time period dt *(s)*. For a volume with a constant surface area A *(m^2)*, which is the case in most docks, unlike TRSs being built in the natural coastlines, the internal water level η_{up} *(mOD)* varies based on the volume change (3). This model, written in C++ is based on the work of Xue et al. [15], and is methodically consistent with the 0D models used to study tidal range in the past [16,17]. It has been validated for use on tidal range schemes to previous studies, with differences in energy output of 2% at Mersey Barrage, and 1.5% for West Somerset Lagoon [39].

$$\frac{dV}{dt} = Q \tag{2}$$

$$\Delta\eta_{up} = \frac{\Delta V}{A} \tag{3}$$

This can be discretised to the first order explicit (Euler) form (4), where the flow is split into the environmental inflows (Q_{in}), the flow through the sluices (Q_{sl}), and the turbines (Q_{tb}). Allowing the water levels at a time $n + 1$ to be determined based on the conditions at the previous time n.

$$\eta_{up}^{n+1} = \eta_{up}^{n} + \frac{\left(Q_{in}^{n} - Q_{sl}^{n} - Q_{tb}^{n}\right)}{A}\Delta t \tag{4}$$

The sluice flow is determined using the orifice equation (5) as commonly used in TRS studies following recommendation by Baker [40]. This is driven by the head difference ΔH *(m)* between the upstream (or internal) and downstream (external) levels, η_{up} and η_{down} respectively (6). With a discharge coefficient C_D *(−)*, cross section area A_{sl} *(m^2)*, and gravity g *(m/s^2)*. Where δ *(−)* is a directional parameter based on the head difference ΔH shown in (7).

$$Q_{sl} = \delta \bullet C_D \bullet A_{sl} \bullet \sqrt{2g \bullet |\Delta H|} \tag{5}$$

$$\Delta H = \eta_{up} - \eta_{down} \tag{6}$$

$$\delta = \begin{cases} -1, \Delta H < 0 \\ 1, \Delta H \geq 0 \end{cases} \tag{7}$$

The flow through the turbines is determined based on the Hill Chart for a 9 m bulb turbine, hence to account for smaller turbine sizes flows scaled per Equation (8) (with the same method for power output). This was used as a large turbine requires not only a large housing, but a deep enough installation to ensure submergence throughout operation.

$$Q_{scaled} = Q_{base} \times \frac{D_{scaled}^{\ 2}}{D_{base}^{\ 2}} \tag{8}$$

Modal control of the scheme is driven within the model by the head difference across the scheme, using a classical cycle. Assuming an initial state of holding, the scheme is held until the head difference is greater than the starting head (ΔH_{Start}, open-circle marked vertical lines on

Fig. 1). Generation continues until the head difference is less than or equal to the ending head difference trigger (ΔH_{End}, closed-circle marked lines on Fig. 1). From here the scheme sluices until the internal and external water levels reach parity, finally the system is once again held, beginning the cycle again. All schemes used a two-way operation, governed by an Every Half Next optimisation process [8,15], where a range of starting heads from 2.0 to 7.5 m, and ending heads of 0.5–3.5 m, using a grid-search method with a 0.1 m step. By this method, the range of start and end head difference triggers is tested every half tidal cycle for a duration of one tidal cycle, balancing immediate yield with future basin state.

3. Results

3.1. Sites identification

Twenty-eight potential locations were identified in the case study region using the methodology discussed in Section 2, while the main focus had been on major coastal cities (shown in Fig. 3). The process (presented in full for Barry Docks as a typical example) shows how a tidally connected basin can be modified to form a small tidal range scheme. The docks identified in the study were sized up to 200,000 m^2, and the majority being smaller than 5000 m^2 with shapes varying from relatively square spaces designed to allow multiple operations, to long narrow dry docks (Fig. 4). In general, the best operation of the locations was found to be achieved with turbines alone as the narrow width of the openings often provides negligible space for additional sluices. The locations were designed under the assumption that the basin would not need to be accessible via ship-locks and would only be used as a power generation site.

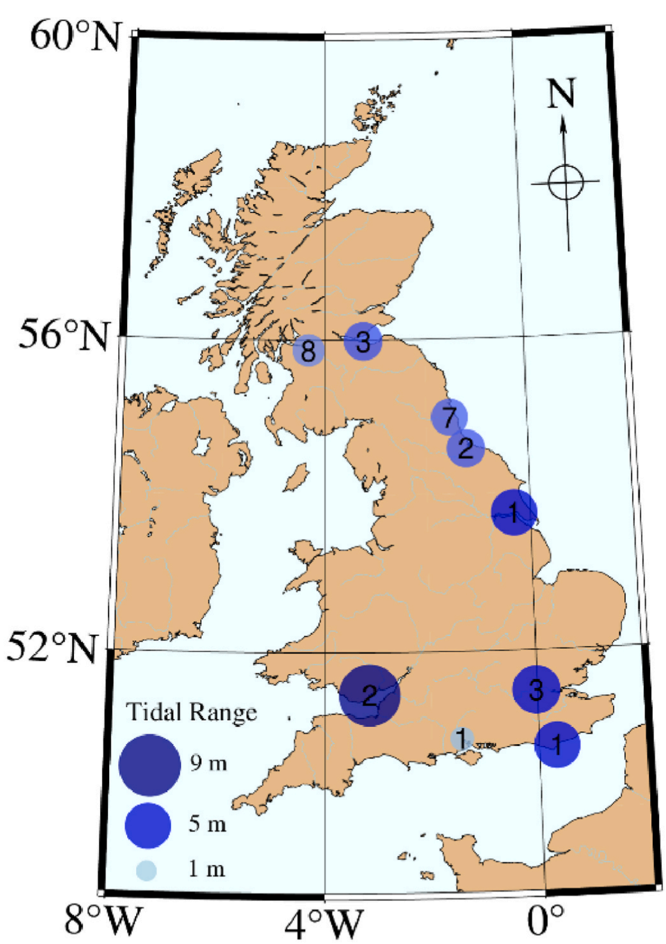

Fig. 3. Number of suitable basins identified around the UK.

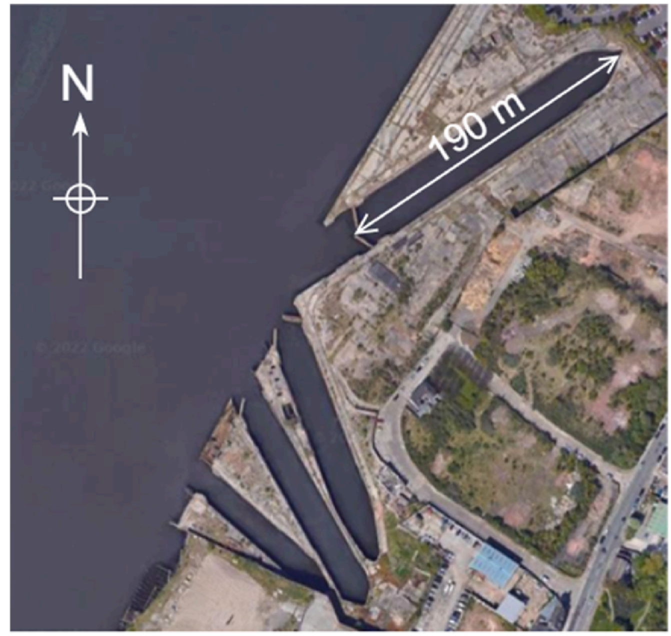

Fig. 4. Multiple adjacent basins in South Shields (Google Maps).

Some cities were found to contain multiple suitable or adjacent basins such as South Shields (Fig. 4), indicative of a pattern of areas changing in their activities. This proximity to end users is advantageous in comparison to remote pumped storage facilities, thus reducing the burden on the grid. All possible locations were identified through a survey of Google Maps around the coastline. It is likely that some of the locations identified here are not suitable based on current or future usage plans. This is expected to be identified in the next stage where more detailed investigation of the selected sites would be carried out. Furthermore, the variety in size and location of the sites identified here allows assessment of the methodology. Additionally, a number of non-tidal basins were identified as part of this process; in this case extra engineering works to develop a tidal connection could allow operation in the manner as assessed here.

The large tidal range seen in the Bristol Channel has long been a key factor in the consideration in the development of a traditional tidal range schemes. Cities in this area (such as Bristol [41], Cardiff [42], and Swansea [43]) have undergone major docklands regeneration projects in recent times, and so were found to have few empty basins. The Liverpool region has been assessed for tidal range schemes [44], and has been the subject of multiple dock regeneration projects (including the construction of a new football stadium [45]), however, the walling of the docks to make them more suitable for traditional purposes makes potential basins non-tidal, and would require a more significant investment to convert.

As shown in Fig. 3, the tidal range docks identified are spread around the country, developing a variation in the tidal phase between them (as tidal phase is a function of location), and allowing for different sites to meet the needs of the system at different times, where a singular large scheme is far more bound to the specific tide. The easy access to the turbines afforded by construction of a scheme such as this in a former dry-dock eases modification of the scheme post-construction; installing more turbines or those of an alternative design later in the life of the scheme. This modification could be carried out at a site once the physical proof-of-concept has been established, reducing the potential capital expenditure, and allowing long-term flexibility or usage as a testing facility for turbines.

3.2. Sample process – Barry Docks

The process used to assess the docks is presented here for the Barry Docks connecting basin. This process was used for all the sites identified in Section 3.3; details are only provided for Barry Docks as a typical example. This basin was measured 185 by 150 m with a generally rectangular area of 27,750 m^2. The access channel has a width of approximately 25 m, connecting the basin to an average tidal range of 8.9 m. A marked-up satellite view of this basin is shown in Fig. 5. This basin was used as the entryway to the inner docks (North-West on Fig. 5), before being superseded by the Lady Windsor Dock that runs parallel and adjacent to the South-West wall of the basin [46].

The 0D model was employed using a set of simple design combinations to calculate the energy generated by each design configuration. Simulations were run with the number of turbines ranging from 1 to 5, and due to the narrow channel identified (25 m) no sluice area was used. Each model operated on a flexible two-way generation scheme as described in Section 2.3, with a timestep of 250 s. The water level data supplied was taken from the POLTIPS-3 service [34], with a 15 min interval – and linear interpolation used for intermediate timesteps. Scaled Andritz-Hydro bulb turbines were used due to their established position in the tidal range industry [36]. The results of these 0D models run for Q1 of 2022, with output multiplied by four to give an indicative annual operation are presented in Table 1. This assumption is carried across all the schemes considered herein; a full operational assessment would be expected as part of a detailed design study, along with surveying of the internal geometries, and structural stability of the basins.

The best performing operation for this scheme was found to be using a single turbine, generating the most energy of the available configurations, 725 MWh in the three-month period, or ~2.9 GWh per year. A sample day (February 14th) from this operation is presented in Fig. 6. Additional turbines caused the internal water level to drop faster during the generation phase, keeping a larger head difference for longer ensuring that the turbine spends more time operating at a higher power output, an effect that has been seen in large tidal range schemes previously [18]. It is likely that a turbine of an alternate design could offer improved production of electricity, for example a lower flow rate at the head ranges used could extend the generation window by slowing the rate of change in the basin, or a turbine designed to work at lower head differences may generate more electricity whilst the internal and external levels are closer – widening the potential generation windows.

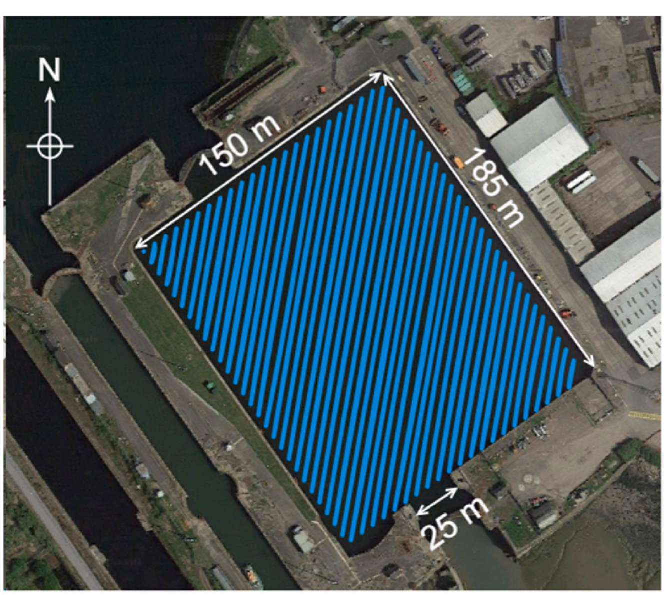

Fig. 5. Barry docks assumed basin (annotated).

Table 1
Barry Docks, 0D modelled energy generated [MWh] per annum.

n_{tb} [−]	Energy [MWh/year]
1	2900
2	2828
3	2780
4	2660
5	2568

These windows could be expanded by the inclusion of pumping in the operation, which could have the tidal docks operating predominantly as pumped storage schemes.

The operation of all the schemes (as shown for Barry in Fig. 6) was typically to produce a short period of power close to the peak of head difference and energy price (Fig. 9). At sites with lower tidal range, a lower head rated turbine could result in performance improvements, as the turbines used here are often used in tidal range scheme assessments, which tend to be at sites with large tidal amplitudes, and are more efficient at head differences over 2 m. The short duration period is also a function of the size of the schemes, whereby the internal volume is very small when compared to a classical tidal range scheme.

The rapid change in the internal level and relatively large flows into/from the dock basin peak flows in the region of 50 m^3/s in a channel 25 m wide (shown in Fig. 6), would have a turbine exit velocity in excess of 10 m/s at the turbine runner, and so have the potential to cause harm if proper safety measures were not developed around the generation process. This would likely make the docks unsuitable for usage by other users if converted to tidal range docks. Draft tubes however are typically fitted to turbines of this nature and assuming a draft tube with double the diameter of the runner (as would be able to fit within the design assumption Equation (1)) reduces the exit velocity to 2.86 m/s, less than the peak ebb and flood velocities at the site (3.1 and 2.9 m/s respectively), per Admiralty Chart 1182. Alternatively, smaller turbines or very low head turbines designed specifically for such an environment could be more efficient. However, the methodology developed here will be applicable if alternative turbine technology is implemented. These short generation phases can nonetheless be beneficial, as extracting the majority of the energy contained in the basin over a short period of time allows the generation to occur at a preferential time based on the value of energy, whereby a balance will be struck between the tidal phasing (maximum energy) and peak energy value.

3.3. Accumulated generation in the UK

The key data on the full suite of identified potential docks is shown in Table 2. The schemes were all operated flexibly, aiming to maximise revenue based on the System Sell Price (SSP) of the national grid at the time (shown for one example day in Fig. 9). The best configuration for each scheme listed in Table 2 was the combination of turbines and sluices that produced the most energy over the sample period, calculated using a flexible two-way operation, controlled via a grid-search optimisation method within a 0D model, for each configuration at each scheme.

As some cities were found to contain several suitable basins, these have been grouped together in Table 3 as the development of multiple smaller basins may be more palatable to developers looking to take a more conservative stepwise approach, developing each basin in turn based on the performance of those already constructed, and to grid operators desiring the increased level of flexibility available from a collection of centrally operated basins. These combined energy yields are mapped in Fig. 7. In particular, Glasgow and the River Tyne area (Newcastle and South Shields) had a large number of small basins, and have not seen significant consideration in the field of tidal range energy prior to this, likely due to their relatively small tidal ranges (2.5 and 3.2

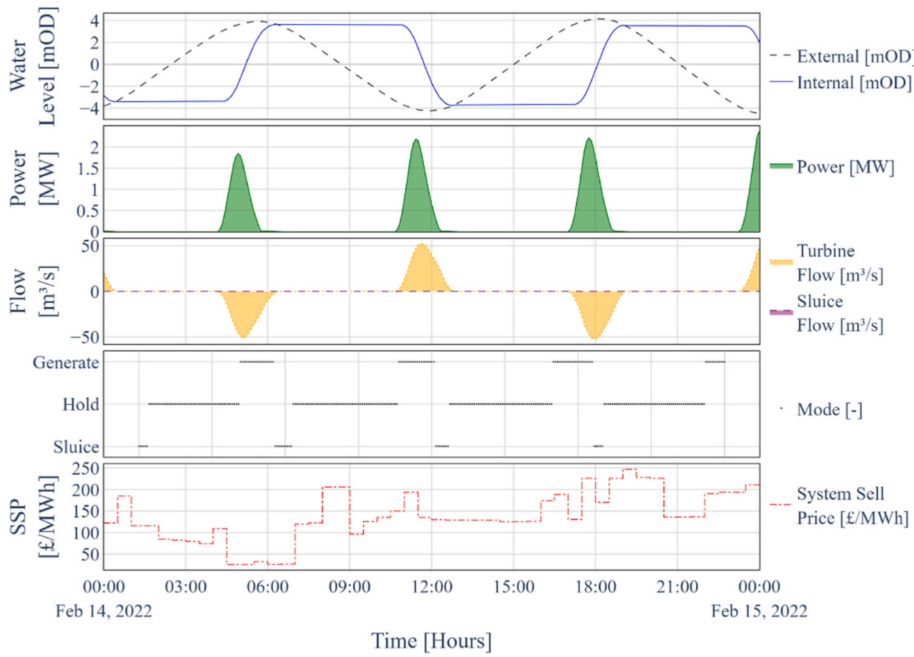

Fig. 6. Sample day of operation – Barry single turbine.

Table 2
Full docks results Q1-2022.

City	Mean Tidal Range	Area	Wall	Max Turbines	Max Turbines (sluice)	Best Output	Peak Generation	Best Config: No of Turbines	Best Config: Sluice Area
	[m]	[m²]	[m]	[–]	[–]	[MWh]	[MW]	[-]	
Cardiff	8.9	203,660	30	6	1	5098	18.0	6	0
London	5.4	133,405	35	7	0	1074	10.2	7	0
Barry	8.9	27,750	25	5	0	725	3.0	1	0
Eastbourne	5.1	47,750	150	30	22	581	12.4	28	0
Middlesbrough	3.4	100,000	25	5	0	306	4.4	5	0
Hull	5.0	10,725	20	4	0	117	2.4	4	0
Southampton	1.4	16,600	40	20	8	113	5.6	14	0
Rosyth	3.3	15,500	100	18	1	74	4.8	12	0
Newcastle	3.2	10,000	55	8	0	68	3.2	8	0
Grays	4.9	3025	30	11	0	56	2.8	7	0
Glasgow	2.5	24,700	90	5	0	42	2.0	5	0
Edinburgh	3.5	6100	25	6	0	39	2.3	6	0
Newcastle	3.2	6125	30	6	0	34	1.6	4	0
Glasgow	2.5	10,000	65	13	0	31	4.0	10	0
Glasgow	2.5	9000	30	10	0	28	3.5	9	0
Stockton-on-Tees	3.4	4400	50	6	0	27	1.6	4	0
South Shields	3.2	4500	25	5	0	25	1.2	3	0
Grays	4.9	1825	25	5	0	24	2.0	5	0
Newcastle	3.2	3100	20	4	0	17	0.8	2	0
South Shields	3.2	2575	15	3	0	14	0.8	2	0
South Shields	3.2	2525	20	4	0	14	0.8	2	0
Glasgow	2.5	4350	55	11	0	14	1.6	4	0
Glasgow	2.5	3900	20	4	0	12	1.6	4	0
Glasgow	2.5	3600	35	4	0	11	1.6	4	0
Glasgow	2.5	3570	20	7	0	11	1.6	4	0
South Shields	3.2	1300	15	3	0	7	0.4	1	0
Glasgow	2.5	1025	20	4	0	3	0.4	1	0

m respectively). The balance between performance and cost has trended towards large tidal ranges due to the need to compensate the level of expenditure required to impound a large coastal area, however minimising the development cost allows the expansion of the concept to lower-performing sites both in the UK and further afield where the tides are smaller but the need for low-carbon energy is present. This is representative of the expansion in assessment of tidal range from a bulk energy producer to a mixed storage/generation facility, where the tidal motion is used as an external pump.

The combined output of the locations studied equated to 8.5 GWh of electricity in a quarter year (energy yield for Q1 2022 shown in Fig. 8), or ~34 GWh/yr. The best-performing operation for each of these schemes were classed as 'Small Power Stations (<50 MW)' by the National Grid guidance, and would likely be deemed mid-sized storages based on market limits. The schemes were operated to generate energy at the most profitable times, as can be seen in Fig. 9 (using the same

Table 3
Docks grouped by city, energy generated over three month period.

City	Tidal Range [m]	Total Area [m^2]	Count [−]	Total Energy [MWh]
Cardiff	8.9	203,660	1	5098
London	5.4	133,405	1	1074
Barry	8.9	27,750	1	725
Eastbourne	5.1	47,750	1	581
Middlesbrough	3.4	100,000	1	306
Glasgow	2.5	60,145	8	182
River Tyne	3.2	30,125	7	166
Hull	5.0	10,725	1	117
Rosyth	3.3	15,500	1	113
Southampton	1.4	16,600	1	68
Grays	4.9	4850	2	63
Edinburgh	3.5	6100	2	42
Stockton-on-Tees	3.4	4400	1	28

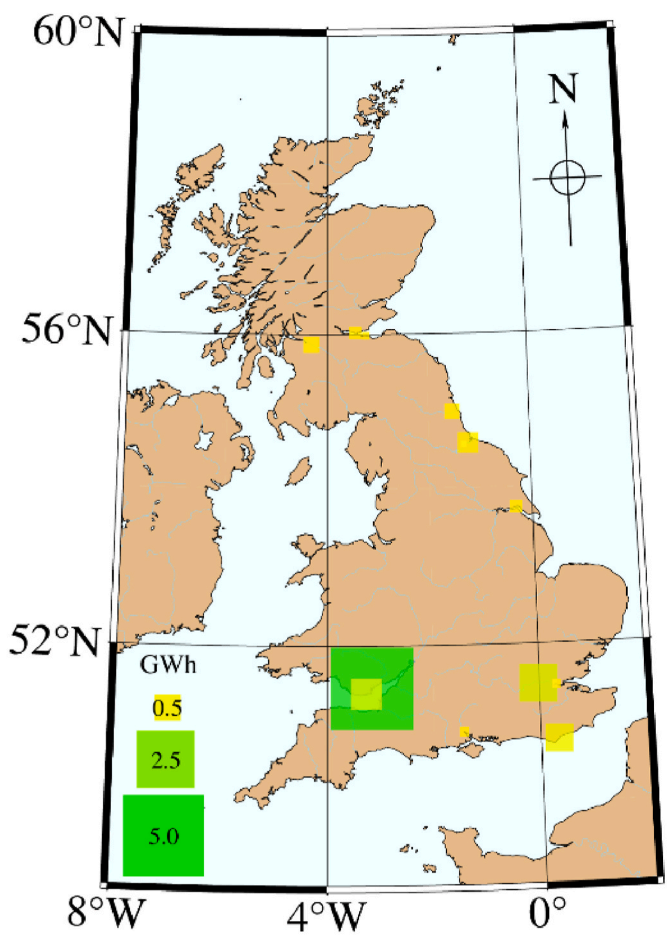

Fig. 7. Maximum three month energy generation, markers scaled and coloured on best output (plotted using Generic Mapping Tools [47]).

colouring as Fig. 7), particularly around 18:00 where the price of energy (SSP, shown on the lower axis) is highest for a short period of time. This flexibility in dispatch allows the tidal range docks to be a beneficial contributor to the energy network providing a degree of peak capture that other renewables are not well suited to, and with alternative control philosophies could be used as a hydro-power storage system. This would be particularly aided by pumping of the internal level beyond the natural levels at sites with lower tidal ranges, however, to assess this, the precise levels of the dock walls above the high-water marks and the internal minima would need to be known, as overfilling or drying out of the docks would likely be damaging to the machinery, structure, or surroundings.

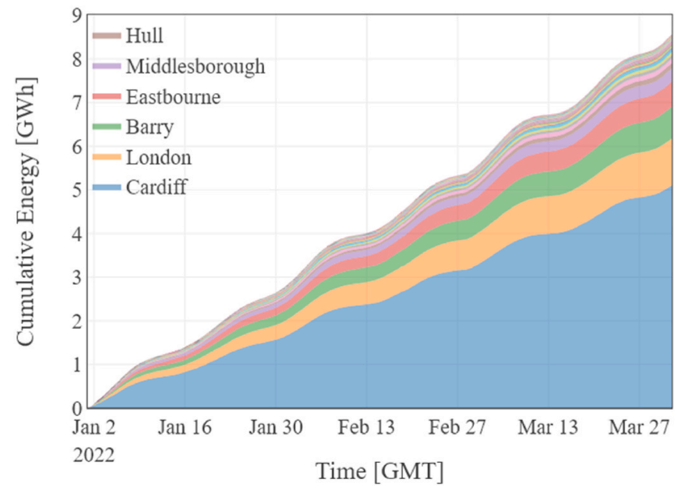

Fig. 8. 2022, three months stacked energy production from assumed tidal dock basins.

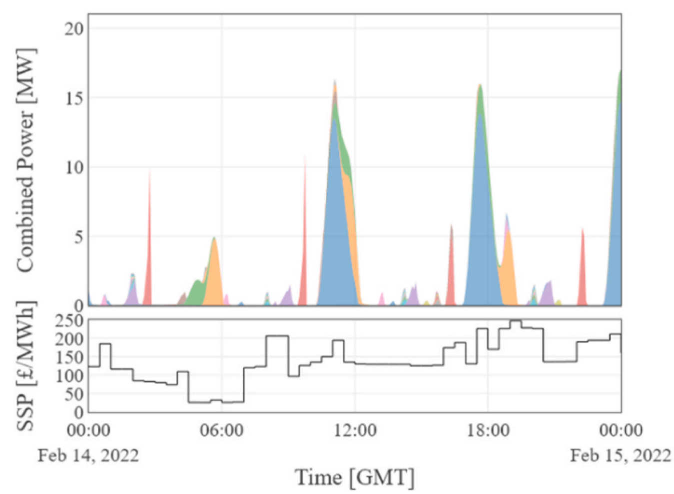

Fig. 9. Sample day of stacked generation from all sites, with energy price (SSP) shown.

4. Conclusions

In order to expand the energy generation options required as part of the global transition to low-carbon operation, tidal range energy has been applied to a new design concept. The historically mitigating cost, and potential environmental impact, required high levels of energy production for tidal range proposals to be economic, leading to schemes being considered only in regions with globally high tidal ranges with large impoundments. To expand the options provided by the tidal range method, the previously untested repurposing of disused infrastructure was considered due to the benefits that can be wrought at a lower cost and environmental impact. As an initial case, 28 potential tidal range docks were identified at 13 UK cities, mapped in Fig. 3 with performance shown in Fig. 7. This was done via open-source intelligence to determine the number and size of potential basins, and the available space to install turbines and sluices for those basins. Through presentation of a widely applicable methodology, developed around a 0D modelling study, a variety of design options were tested at each of the identified basins and the best performing design was identified at each site.

The net yield of the schemes was estimated to be approximately 34 GWh per year, with the best performing being those in Cardiff, London and Barry, benefitting both from large area and tidal range as is typical for tidal range. The combined contribution of the full set of schemes was presented for a sample day shown in Fig. 9. The schemes were operated to generate at times of highest energy price as a surrogate for assumed demand, demonstrating the ability to produce energy at times of highest need. The repurposing of disused structures mitigates the capital expenditure required, and has the potential to bring further benefits to an area such as employment opportunities, and the holistic benefits often seen with waterside development. The geographic spread of the schemes also demonstrates an example of a distributed set of tidal range schemes and how they may contribute to the energy mix. The method used here was developed to be openly applicable to any small basin, fully or partially enclosed impoundment, with the need for a large tidal range shown to be less critical than when considering a large scheme due to the short, targeted generation windows and significant reduction of cost of construction due to utilisation of existing infrastructures. The inclusion of pumping could feasibly allow these schemes to be operated as pumped storage systems, widening the generation periods and increasing their value. This study is expected to highlight the methodology and potential of retrofitting existing infrastructure as distributed electricity generation and energy storage facilities, and to facilitate further utilisation of such schemes in the route to net zero.

CRediT authorship contribution statement

Nicolas Hanousek: Conceptualization, Methodology, Software, Validation, Data curation, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Reza Ahmadian:** Conceptualization, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Emma Lesurf:** Conceptualization, Investigation, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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