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Income optimisation of a fleet of tidal lagoons

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***Abstract*—Tidal lagoons represent a form of renewable electricity generation that remain untested. In the UK, a perceived lack of value for money to the consumer triggered the government's rejection of a recent plan to build and operate a system of six tidal lagoons along the west coast of England and Wales. Tidal energy benefits from a high degree of predictability in its resource, as well as flexibility with regards to the control of the constituent hydraulic structures. An adaptive operation can utilise these factors in order to optimise the operation of a tidal lagoon. We explore here the potential to optimise economically by targeting generation periods to match high demand in the day-ahead energy market, increasing the return on electricity sold. Gradient-based optimisation techniques are applied to a finite difference 0D model of a fleet of seven idealised tidal lagoons. For the generation of site-specific inputs, the model is in turn coupled with *Thetis*, a coastal ocean modelling framework based on the finite element engine *Firedrake*. An adjustment is made to the price signal which reflects the presence of tidal lagoons in energy market trading. Results converge towards a system which utilises the inherent phase difference of the operation of the tidal lagoons to limit price reduction and make significant gains in income when optimising the entire fleet. The high variability of site conditions present in the tidal lagoon fleet is also highlighted, emphasising the importance of flexibility in tidal lagoon operation and design.**

***Index Terms*—Tidal range energy, marine energy, resource assessment, income optimisation, flexible generation**

I. Introduction

COUNTRIES which possess high tidal ranges at their coasts have the potential to harness energy from a predictable and flexible form of renewable electricity generation [1]. Tidal range energy schemes periodically restrict flows on the ebb and/or flood of the tide to generate electricity from the resulting water head difference created between either side of an embankment [2]. The potential ecological, hydrodynamic and morphological impacts of tidal energy schemes are well-documented [3], and studies indicate that tidal lagoons present a less environmentally disruptive option than tidal barrages [4] [5]. This is due to tidal barrages blocking an entire estuary basin, whereas tidal lagoons obstruct only part of it through a coastally-attached or offshore impoundment [6]. In light of this, and off the back of numerous tidal barrage proposals rejected, in particular, by the UK Government, Tidal Lagoon Power (TLP) laid plans for a fleet of six tidal lagoons down the west coast of England and Wales [7]. However, a perceived lack of value for money to the consumer resulted in the Department for Business, Energy & Industrial Strategy (BEIS) dismissing the plans [8]. To this day the UK generates no electricity from tidal range energy schemes, despite possessing sites featuring some of the highest tidal ranges in the world [1] [9]. Globally, there are currently only a handful of operational tidal range based schemes, the largest of which is the Lake Sihwa Tidal Power Station in South Korea, an adapted freshwater reservoir with an installed capacity of 254MW [1]. Despite resembling a tidal lagoon, it was not purposely built as one and is often referred to as a barrage – as such, it can be argued that tidal lagoon technology still remains untested [10] [4].

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In this paper, seven idealised tidal lagoons at various locations along the east coast of the Irish Sea and within the Bristol Channel and Severn Estuary are optimised with a goal of addressing some of the cost problems which have derailed preceding proposals. At each location a tidal signal is generated using a 2D depth-averaged model of the Irish Sea; these provide inputs for 0D numerical optimisation models applied to represent the operation of each proposed power plant. By utilising the flexible window of generation present in tidal range based energy schemes [1] [11], control periods, and therefore flowrates, can be regulated on a cycle by cycle basis [12]. Income maximisation is achieved by optimising these control periods in response to the highly variable hourly price signal stemming from the Day Ahead energy Market (DAM). An algorithm is composed to reflect the competing presence of multiple lagoons through an idealised adjustment imposed on the price signal.

II. Methodology

A. Tidal lagoon operation

The theoretical energy that can be extracted from a tidal range scheme E_{max} from a head difference $H = \eta_o - \eta_i$ can be calculated as:

$$E_{max} = \frac{1}{2}\rho g A H^2, \quad (1)$$

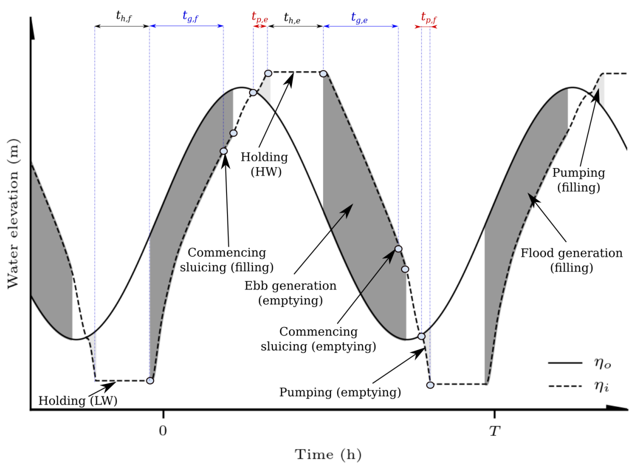

Fig. 1. Generalised operation of a tidal power plant over an $M2$ tidal period [16].

TABLE I
MAXIMUM AND MEAN TIDAL RANGE EXTRACTED FROM A 2D TIDAL MODEL AT MONITOR LOCATIONS BETWEEN 23/09/2016 AND 16/05/2018.

Location	Basin area (km^2)	Maximum tidal range (m)	Mean tidal range (m)
Swansea	39.86	10.9	6.9
Cardiff	39.84	14.6	9.3
Watchet	39.93	13.3	8.5
Colwyn	39.90	10.0	6.6
Liverpool	39.87	10.7	7.1
Blackpool	40.00	10.6	7.0
Solway	39.95	9.8	6.5

where ρ is water density, A is the basin surface plan area and η_o and η_i are the water elevations outside and inside the basin, respectively [13]. In reality, the water must flow through a system of turbines and sluices and, as such, E_{max} is also dependent on numerous other factors, as outlined in greater detail by [12], including hydraulic structure design, efficiency and interaction with local hydrodynamics. Turbines which generate bi-directionally – on both the ebb and the flood tides – produce a daily power output of increased magnitude and spread than those which generate exclusively in a single direction [6] [14]. The addition of pumping to raise or lower basin water levels has also been shown to enhance the overall energy output [12] [15]. Optimising the operation control of hydraulic structures is an easy and inexpensive way of improving the efficiency of a tidal energy scheme [12]. The generalised operation of a tidal power plant over an $M2$ tidal period is shown schematically in Fig. 1, illustrating the typical modes of operation. The holding ($t_{h,f}, t_{h,e}$), generation with no sluicing ($t_{g,f}, t_{g,e}$) and pumping ($t_{p,f}, t_{p,e}$) periods can be controlled to shift the operation for a limited amount of time, as constrained by the governing tidal signal and the capabilities of the hydraulic structures [16].

B. Tidal lagoon locations and case study design approach

The seven locations selected for analysis in this study, shown in Fig. 2 with details in Table I, are all characterised by a pronounced maximum tidal range that varies between 9.8-14.6m. These locations have been previously considered as candidate sites for either tidal barrage or lagoon construction [7] [17]. The decisions which underlie the specific scheme designs of these proposals remain somewhat ambiguous – as such it was deemed appropriate to idealise certain specifications and avoid replicating previous designs. A standardised design for the shape of each tidal lagoon impoundment is assumed: a circular lagoon embankment around a coastal centre-point is generated in each study location, with the radius being such that the basin area of each lagoon is $\approx 40km^2$. The rationale behind the design of this layout is not only to provide consistency between schemes – although differences in coastline shape result in some variations – but also to minimise the length of the lagoon embankment and therefore, in theory, the cost of the scheme. Each lagoon operates bi-directionally with pumping intervals and features identical values for various other lagoon specifications. These includes turbine diameter and power curve, individual sluice gate area, discharge coefficients. Sites with roughly similar coastline shapes are selected, resulting in a fairly consistent embankment length between schemes. Each lagoon is therefore allocated the same space for hydraulic structures. However, it was deemed detrimental to the results for the ratio between the number of turbines and sluices gates to remain the same, given that the plant power output P is proportional to AH^2 [18]. Designs must therefore acknowledge the intertidal area variations (that will affect how the water head difference, H, changes). As the spatial configuration and individual turbine designs of the lagoons remain fixed, optimum utilisation and control of hydrodynamic variations relies on the number of turbines available, the variation of which between lagoons will give a better representation of the individual site potential. Another factor which is kept consistent is the water elevation limits imposed on the inside of the lagoon. Applying these constraints prevents the water level from reaching a value too low for the efficient operation of the hydraulic structures, and too high as to flood the surrounding land. Selected values, -6m and 6m for lower and upper tidal limits, respectively, were deemed sufficient to not excessively constrain the generation potential of the seven lagoons.

C. Numerical modelling

Two numerical modelling approaches have been applied for the design, optimisation and assessment of idealised tidal range structures in this work.

1) Zero-dimensional operation modelling: Zero-dimensional modelling is widely considered to be an effective and computationally efficient approach for providing an informed resource assessment for tidal energy schemes [1], prior to more comprehensive hydrodynamic modelling studies. A finite difference method is utilised to simulate scheme operation and

Fig. 2. Map of the UK showing the locations of the seven lagoons modelled in this study.

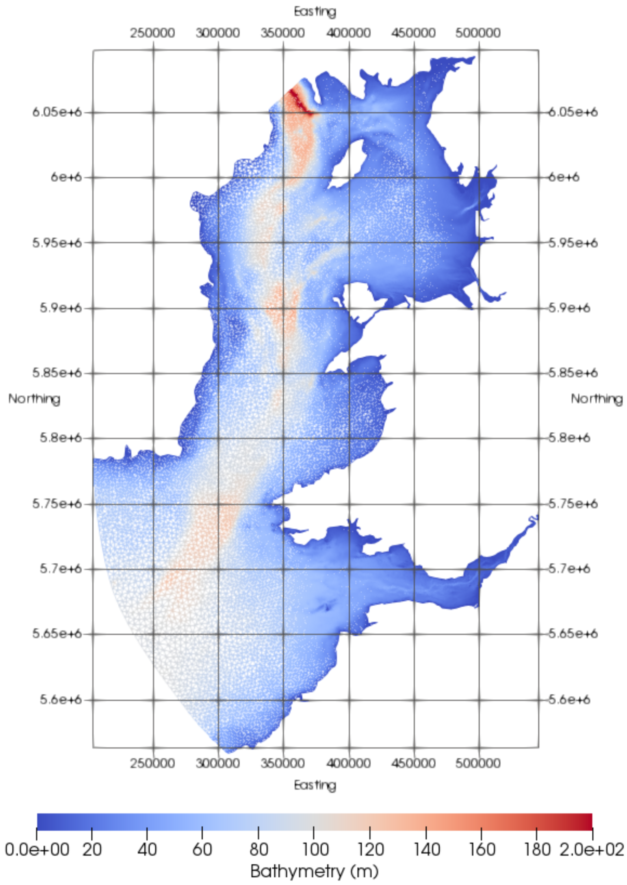

Fig. 3. The computational domain for the 2D model of the Irish Sea. The bathymetry is interpolated using data from Edina Digimap Service [24]. Coordinates are plotted using a UTM zone 30N projection.

provide iterative power output P estimates for the optimisation framework. Details of the 0D model used in this study, including the paramaterisation of hydraulic structures, are outlined in Angeloudis et al. [12]. Once coupled with the optimisation framework, the 0D model returns suitable design and operation scheduling plans for the hypothetical tidal range structures along the UK's western coastline.

2) Two-dimensional hydrodynamic modelling: Modelling tidal power plants in two or three dimensions, whilst more computationally demanding, is advantageous to 0D modelling as it takes into account both the impacts of the structure on tidal levels, and the hydrodynamic interaction between the plant components and the surrounding coastal environment. It is thus generally used for a more accurate (and often more modest) resource assessment [14], as well as a tool for the minimisation of environmental impacts [1]. While modelling multiple tidal lagoon cumulative effects and local hydrodynamics in this manner is outside the scope of this paper, a 2D depth-averaged model of the Irish sea without lagoons was created in order to generate a site-specific tidal signal. This tidal signal is then used as η_o input for the 0D model. Details of the modelling used, which utilised models built using *Thetis*, *Firedrake* and *qmesh*, can be found in [19]–[22] with more information on the methods applied to tidal range energy-related simulations reported previously [12] [23]. Fig. 3 presents the unstructured mesh and bathymetry of the computational domain, whose eastern extent spans the coastlines of England, Wales and the south of Scotland. Coordinate-specific data extraction of water levels was aided by the presence of virtual tide gauge monitoring points across the domain. These were placed in a central part of the considered embankments for each tidal lagoon – a likely location for hydraulic structures in practice.

D. Calculating tidal lagoon income

A method for quantifying interactions between tidal lagoons and the energy market is required in order to be able to model the income of an individual tidal energy scheme. In the UK, renewable energy schemes traditionally sell electricity under a Contract for Difference (CFD) framework. Accordingly, a pre-agreed strike price based on minimum levelised energy cost is drawn up, and the government subsidises the difference should the energy scheme fail to meet this price [25]. Whilst this method of trading certainly benefits generators of renewables such as wind and solar, it has been argued that for tidal range energy, trading based on a framework such as the Day-Ahead energy Market (DAM) could be advantageous [16]. In the DAM, one hour slots are sold via auction the day before generation at a price dependant on the time of day – times of higher electricity demand, such as 7–8am or 6–7pm when demand surges on a daily basis, are sold at a higher price [26]. The predictability and flexibility of tidal power plant technology means that operational modes can be expedited or delayed to a more optimum time, increasing income and, by extension, reducing costs to the consumer [16]. Modelling this form of trading is also consistent with the idealised nature of the modelled lagoons in this study – by using the hard data available from the N2EX DAM, assumptions specific to lagoon or location, such as the strike price, are avoided. The available data allows the income of the lagoons to be calculated under two scenarios, as follows.

1) Original price signal: The first scenario assumes that the presence of tidal lagoons in the DAM would have no impact on the price. As such, historic price data obtained from Nord Pool [27] is processed as an hourly price signal $p(t)$, in $£/MWh$. The income of a lagoon over one hour $I_{h,l}$, in £, can be calculated using

$$I_{h,l} = p_h \times E_{h,l}, \tag{2}$$

where $E_{h,l}$ is the energy generated by the lagoon in MWh and p_h is the price of electricity, both in the given hour. The total income over one year (approximated as $n_c = 705$ tidal cycles of 12.42 hours) for a single lagoon $I_{yr,l}$ can then be calculated as follows:

$$I_{yr,l} = \sum_{i=1}^{n_c} I_{h,l_i}. \tag{3}$$

Generators trading in the DAM are not aware of the sale price until after the auction takes place, so any knowledge of the price is a forecast estimate [26]. In order for this price signal data to be used as a legitimate model input, this study therefore assumes that the price has been predicted with 100% accuracy.

2) Adjusted price signal: The presence of one or more tidal lagoons, each with an installed capacity of over 1GW, would serve to have a noticeable effect on the price signal [28]. The algorithm used in this paper to model this effect employs $p(t)$ [27] and an hourly time series of the volume of energy sold on the DAM $E_m(t)$, also obtained from Nord Pool [29]. It is assumed that the historic data resembles a perfect forecast of both $p(t)$ and $E_m(t)$, and that the total energy generated by the whole fleet in a given hour $E_{h,lf}$ has an effect on p_h proportional to the total energy sold during that hour on the DAM $E_{h,m}$. Effectively, this is applied as

$$p_{h,adj} = p_h \times \frac{E_{h,lf} + E_{h,m}}{E_{h,m}}, \tag{4}$$

where $p_{h,adj}$ is the adjusted price of electricity for that hour, giving rise to an adjusted price signal $p_{adj}(t)$. $E_{h,lf}$ is determined by the energy output results in the fixed control optimisation, the details of which are outlined in the next section.

E. Optimisation of tidal lagoons

The flexibility and predictability present in the operation of tidal energy schemes allows for the precise determination of optimum control periods. In the following scenarios, to $t_{h,f}$, $t_{h,e}$, $t_{p,f}$ and $t_{p,e}$ make up $\boldsymbol{\tau}$, the vector of control parameters in a limited memory Broyden-Fletcher-Goldfarb-Shanno with limits (L-BFGS-B) optimisation framework as detailed in Angeloudis et al. [12] and Harcourt et al. [16]. These studies both explore the potential of individual and smaller schemes than the fleet considered herein, so methods to improve upon the computational efficiency of the optimisation was sought. Whilst it was concluded in [16] that the use of Basin Hopping (BH) was an approach which yielded higher energy output and income through multiple runs of a changing local optimiser, the L-BFGS-B method, which is limited to a single run of a local optimiser and is therefore significantly faster, was selected for use in this work. In addition, the more flexible BH algorithm benefits were not reflected in the 2D hydrodynamic model. The aforementioned studies also sought to optimise the generation without sluicing control periods, $t_{g,f}$ and $t_{g,e}$, so to cut down on optimisation time these were kept consistent at 3.5 hours for both the ebb and flood variables.

1) Maximum energy optimisation: Seeking to optimise the design of tidal energy scheme with a goal of maximising the generated energy is a widely undertaken activity [1]. Previous work has looked into finding optimum physical parameters [30] [31], generating head [32] or control periods [12]. Energy maximisation in this paper utilises variation in control variables and the quantity of installed turbines.

Fixed control parameter operation: An initial optimisation was carried out for each tidal lagoon to determine turbine number, sluice number and a fixed value for the different control parameters. In this case, $\boldsymbol{\tau}$ also includes turbine number N_t as well as the four variable control parameters. To maintain structural consistency between lagoons, the sluice number N_s was determined by filling the remaining span of the embankment dedicated to the placement of hydraulic structures, L_{hs} estimated as $1500m$, assuming a value of 15m for each turbine and sluice unit length, L_t and L_s. The sluice number is thus given by

$$N_s = \frac{L_{hs} - N_t L_t}{L_s}, \tag{5}$$

and the objective functional defined to maximise energy output is given by

$$\max_{\boldsymbol{\tau}} \int_{t=0}^{t=t_s} P(\boldsymbol{\tau}, H, t)\, dt. \tag{6}$$

A year-long period of tidal lagoon operation was simulated in each iteration of the optimisation to determine optimum values. Fixed control periods were stored in $\boldsymbol{\tau}_c$ to be used in the subsequent adaptive operation optimisations.

Adaptive operation: The next stage was to introduce adaptive operation, by altering control parameters on a cycle by cycle basis [12]. Herein, and in the following maximum income optimisation case, variations of $\boldsymbol{\tau}$ include just the four control parameters – values of N_t and N_s are fixed as per the results of the fixed control optimisation. A two-cycle approach is adopted, as per the objective functional

$$\begin{aligned} &\text{for } i = 1 : n_c \\ &\max_{\boldsymbol{\tau}_i} \quad \int_{t=i\times T}^{t=(i+1)\times T} P(\boldsymbol{\tau}_i, H, t)\, dt + \\ &\qquad \int_{t=(i+1)\times T}^{t=(i+2)\times T} P(\boldsymbol{\tau}_c, H, t)\, dt \\ &\text{subject to} \quad \boldsymbol{\tau}_l \leq \boldsymbol{\tau}_i \leq \boldsymbol{\tau}_u \end{aligned} \tag{7}$$

formulated in [16], where $n_c = 705$. In the first cycle of each iteration of the optimisation i, control parameters are subject to variation of $\boldsymbol{\tau}_i$ within the limits $\boldsymbol{\tau}_l$ and $\boldsymbol{\tau}_u$, and in the second cycle they are specified using the results obtained previously for the fixed cycle optimisation $\boldsymbol{\tau}_c$. The second cycle successively becomes the first cycle in the next round of optimisation. This approach helps to avoid sub-optimum inner water levels η_i, which could have a detrimental effect on the optimisation of the subsequent cycle [16].

2) Maximum income optimisation: Optimisation to maximise income requires the aforementioned DAM price signal $p(t)$ [27] or its adjustment $p_{adj}(t)$. The income maximisation objective function, as per Harcourt et al. [16] and Merlin et al. [33], is given by

$$\begin{aligned} &\text{for } i = 1 : n_c \\ &\max_{\boldsymbol{\tau}_i} \quad \int_{t=i\times T}^{t=(i+1)\times T} p(t) \times P(\boldsymbol{\tau}_i, H, t)\, dt + \\ &\qquad \int_{t=(i+1)\times T}^{t=(i+2)\times T} p(t) \times P(\boldsymbol{\tau}_c, H, t)\, dt \\ &\text{subject to} \quad \boldsymbol{\tau}_l \leq \boldsymbol{\tau}_i \leq \boldsymbol{\tau}_u \end{aligned} \tag{8}$$

III. Results

F. Generation of inputs and model setup

In order to set up the 0D models for optimisation and analysis of the tidal lagoon fleet, site-specific inputs were first generated. A 2D model of the Irish sea, simulated for a period of 30 days from 8am on 06/05/2003, provided adequate information for the extraction of tidal harmonic constituents throughout the domain, which in turn can be used for the extrapolation of site-specific tidal elevations over longer periods. Validation of these inputs for the purposes of this work was carried out qualitatively by comparing historic tide gauge data provided by the British Oceanographic Date Centre (BODC) [34] with tidal elevation data extracted at the same gauge coordinates, as shown in Fig. 4. The predicted elevation profile of the simulations follow the BODC tide gauge data closely, although further work will seek to improve the calibration of the model. Nevertheless, these results were deemed to be sufficient for the purposes of this study, that aims to assess the systematic potential of multiple tidal range schemes. 2D modelling also gave rise to the surface plan area/elevation input required for the 0D model, which is shown in Fig. 5, along with indications of the allowable tidal range limits imposed inside the lagoons. The final stage of input generation was to determine the ratio of turbines to sluices and

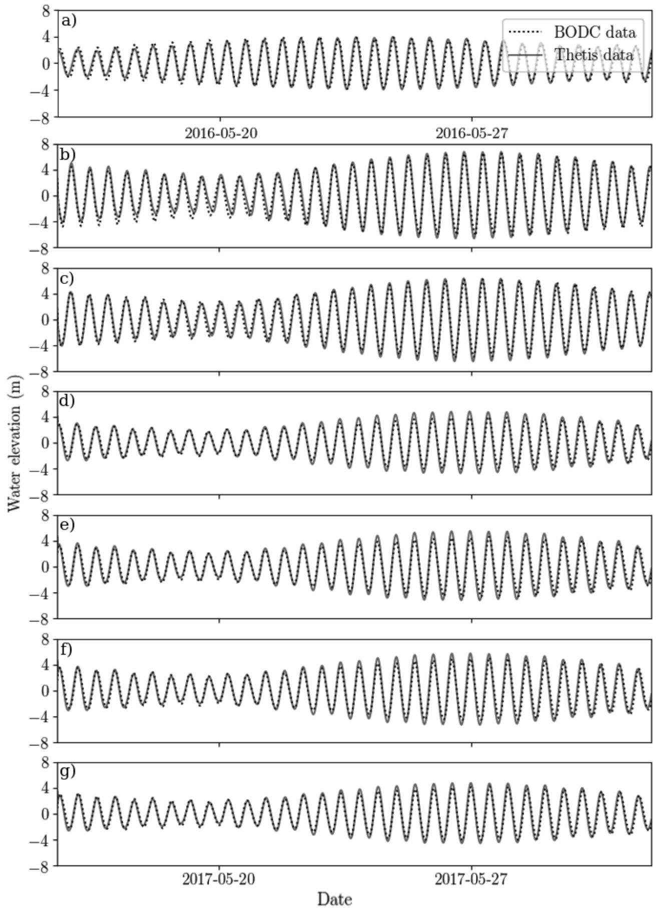

Fig. 4. Comparison of the reconstructed tidal signal from the Thetis results and the BODC data. Figures a) to g) show results for the BODC tide gauge detectors near Swansea, Cardiff, Watchet, Colwyn, Liverpool, Blackpool and Solway, respectively. BODC data for the year 2017 was unavailable for Swansea so 2016 data is shown instead.

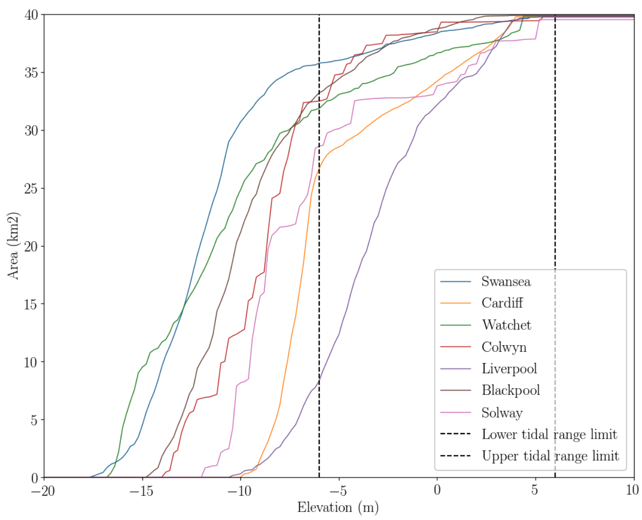

Fig. 5. Graph showing the relationship between basin surface plan area and water elevation within the seven considered lagoons.

fixed control parameters, obtained from the fixed cycle energy optimisation shown in Eq. 6. These serve as an initial guess and provide the values for $\boldsymbol{\tau}_c$ in the "two-cycle" [16] energy and income optimisations. The simulations spanned one year, from 7am 01/01/2017, and the results are presented in Table II.

TABLE II
RESULTS FROM THE INITIAL OPTIMISATION WHICH DETERMINED FIXED CONTROL PARAMETER PERIODS (FC-OP) AND THE NUMBER OF TURBINES. NUMBER OF SLUICES IS DETERMINED BY THE ALLOCATED SPACE FOR HYDRAULIC STRUCTURES IN THE EMBANKMENT.

	Hydraulic structure setup		Optimised fixed control parameters (hours)			
Location	Turbines N_t	Sluices N_s	Holding, ebb $t_{h,e}$	Holding, flood $t_{h,f}$	Pumping, ebb $t_{p,e}$	Pumping, flood $t_{p,f}$
Swansea	73	27	2.16	1.74	1.00	0.53
Cardiff	68	32	2.23	1.99	0.57	0.49
Watchet	69	31	2.35	1.85	0.89	0.20
Colwyn	65	35	2.43	2.16	0.64	0.54
Liverpool	62	38	2.66	2.37	0.67	0.59
Blackpool	73	27	2.62	1.64	1.00	0.36
Solway	64	36	2.56	2.28	0.67	0.57

G. Optimisation and simulation of the tidal lagoon fleet

Once the inputs were generated for each location, 0D numerical simulations modelled the tidal lagoon fleet operation and provide output from which the generated energy and income can be analysed and compared. A summary of these simulations, all of which were applied to each tidal lagoon and ran for 705 tidal cycles of 12.42 hours (roughly one year) from 7am 01/01/2017, is given in Table III. The simulations incorporate pre-generated optimisation files which contained information about the control of hydraulic structures over time as outlined in Section II-E. A fixed control (FC) optimisation file was created which utilised the fixed control parameters displayed in Table II. An energy maximisation (EM) optimisation file was then generated to determine adaptive control parameters by applying the functional Eq. 7 to maximise energy. An income maximisation (IM) optimisation then determined adaptive control parameters to generate maximum income, based on the functional Eq. 8 which utilised the original, unadjusted price signal $p(t)$. The first round of simulations employed these optimisation files to model lagoon energy output and calculate income as shown in in Section II-D, using Eq. 2 with $p(t)$ (OP). The next stage was to run the simulations again with the adjusted price signal $p_{adj}(t)$ (PA). This adopted the hourly energy output of the FC-OP simulation to trigger the price adjustment through Eq. 4. As the optimal control parameters for the FC and EM simulations are not sensitive to changes in the price signal, the generation of a new, unique optimisation file to reflect the adjustment was only required for the IM simulations.

The results displayed in Table IV show the total sum of generated energy $E_{yr,lf}$ and income $I_{yr,lf}$ of all the tidal lagoons along with percentage differences between cases. The -OP cases do not acknowledge any form of lagoon interaction, to either each other or the energy market, whereas the -PA cases utilise a price signal which has been suitably adjusted to the presence of the entire fleet – it is therefore justified to simulate and represent fleet performance in this way.

IV. DISCUSSION

H. Tidal lagoon fleet performance

In the following section, the performance of the tidal lagoon fleet is examined, with an analysis of how the lagoons interact with each other through the energy market providing a diagnosis of the observed trends. Table V summarises results from Harcourt et al. [16], which tabulates the annual energy output and income for a model of the TLP design of the Swansea Bay Lagoon (TLP-SB). Recalculations have been made for the internal percentage changes of income and energy. This allows for inter-study comparison of energy and income gains under different optimisation scenarios, where FCP is equivalent to FC-OP in this study, 2C-BFGS-E is EM-OP and 2C-BFGS-P is IM-OP. In both studies, an increase in energy from the FC-OP case is shown, with a slight decrease between EM-OP and IM-OP cases. This is due to the gains realisable through adopting adaptive control as previously explored [12] [16]. In addition, similarities in income gain are also found, with IM-OP producing a higher income than EM-OP. Both of these relationships between EM-OP and IM-OP are to be expected, as they have been optimised with these goals in mind. However, there are two key differences between the tables. The first is the magnitude of the percentage increases relative to FC-OP in Table IV, which is around twice those displayed in Table V, for both income and energy, with a similar increase in energy in the PA-C case. The other is the combination of the decrease in energy between EM-OP and IM-OP being more pronounced in Table V than in Table IV, and the income gains between the two cases being largely similar in both tables. This could point to the following, respective, conclusions: firstly that in certain locations, adaptive operation becomes a vital tool in ensuring tidal lagoon energy and income maximisation; and secondly, that the TLP-SB lagoon is generating electricity more efficiently than the lagoon fleet in the IM-OP case. Nevertheless, it is likely that discrepancies arise due to scale differences. The results displayed in Table IV represent the totals of a fleet of seven lagoons which vary drastically in tidal and bathymetric conditions, as can be seen in Fig. 4 and Fig. 5. Even the Swansea lagoon of the fleet differs significantly in design from TLP-SB. The conclusions that can therefore be drawn from comparison between the results in Table III and IV are somewhat limited, and further investigation into the nature of these dissimilarities is required as indicated in Section IV-I.

The next stage is to look at the effect of applying the price adjustment on the results. The use of shared

TABLE III
DETAILS OF THE DIFFERENT SIMULATIONS AND OPTIMISATION SCENARIOS THAT WERE CONSIDERED FOR THE SEVEN LAGOONS.

Simulation	Optimisation objective	Operation control	Price signal	Optimisation file: Unique	Optimisation file: Shared	For the simulation of: Individual lagoons	For the simulation of: Lagoon fleet
FC-OP	Energy	Fixed	Original		✓	✓	✓
FC-PA	Energy	Fixed	Adjusted to lagoon fleet		✓		✓
EM-OP	Energy	Adaptive	Original		✓	✓	✓
EM-PA	Energy	Adaptive	Adjusted to lagoon fleet		✓		✓
IM-OP	Income	Adaptive	Original	✓		✓	✓
IM-PA	Income	Adaptive	Adjusted to lagoon fleet	✓			✓

TABLE IV
ENERGY AND INCOME RESULTS FOR THE LAGOON FLEET FROM 7AM 01/01/2017 TO 7AM 01/01/2018. THE DIFFERENT OPTIMISATION CASES ARE FIXED CONTROL (FC), ENERGY MAXIMISATION UNDER ADAPTIVE CONTROL (EM) AND INCOME MAXIMISATION, ALSO UNDER ADAPTIVE CONTROL (IM), USING THE ORIGINAL PRICE SIGNAL (OP) AND PRICE SIGNAL ADJUSTMENT (PA).

Simulation	-OP	$E_{yr,lf}$ (MWh) -PA-C	%Δ -OP → -PA-C
FC-	14,863,257	14,863,257	0.00%
EM-	18,804,682	18,804,682	0.00%
IM-	18,623,884	18,483,376	-0.75%
%Δ FC- → EM-	26.52%	26.52%	
%Δ FC- → IM-	25.30%	24.36%	
%Δ EM- → IM-	-0.96%	-1.71%	
	-OP	$I_{yr,lf}$ (£) -PA-C	%Δ -OP → -PA-C
FC-	673,038,644	537,676,137	-20.11%
EM-	844,922,063	718,375,395	-14.98%
IM-	881,051,539	769,335,935	-12.68%
%Δ FC- → EM-	25.54%	33.61%	
%Δ FC- → IM-	30.91%	43.09%	
%Δ EM- → IM-	4.28%	7.09%	

%Δ A → B indicates that the displayed value shows the percentage increase from A to B

TABLE V
ENERGY AND INCOME RESULTS TAKEN FROM TABLE 4 IN [16], WHICH USED SIMILAR OPTIMISATION CASES FOR THE TLP DESIGN OF SWANSEA BAY LAGOON.

Optimisation	$E_{yr,l}$ (MWh)	$I_{yr,l}$ (£)
FC-OP	558,448	25,049,732
EM-OP	630,308	27,858,573
IM-OP	611,417	29,155,484
%Δ FC-OP → EM-OP	12.87%	11.21%
%Δ FC-OP → IM-OP	9.49%	16.39%
%Δ EM-OP → IM-OP	-3.00%	4.66%

%Δ A → B indicates that the displayed value shows the percentage increase from A to B

optimisation file in the FC and EM cases results in identical energy output when adjusting the price signal. A decrease is noted between the IM-OP and IM-PA cases, and a cause of this is explored further in Section IV-J. The more notable changes in the PA cases are present in the lagoon fleet income. As expected, incurring a penalty on price consistently leads to a decrease in income. What is more remarkable, is the decrease in income loss from the FC and EC scenarios to the IM scenario. Calculating the average hourly price in the OP and PA simulations yields values of £45.31 and £39.77, respectively, a change of -12.22%. The percentage change values for the IM case are only slightly lower, which suggests that the effect of adjusting the price signal has a direct effect on the income from the IM optimisation. However, it could be argued that the level of losses incurred when implementing the price signal are inconsequential, as the aim of applying the price signal adjustment is to provide a more realistic representation of the tidal lagoon fleet's interaction with the DAM. In that case, valuable findings with regards to the price adjustment implementation lie in the net increase in income between optimisation scenarios. These show a vastly increased income from the FC case to the EM and IM cases, and a greater increase between EM and IM cases than there was in the OP results and in Table IV [16]. Both these trends highlight the benefits of forecasting – by modelling the interaction of the lagoon fleet with the DAM, adaptive control parameters in the IM-PA case are altered in a way that is sensitive to the presence of the other lagoons, and can maximise income accordingly. In addition, there is an even higher drop between the energy in the EM-PA to IM-PA (-1.17%) than there is in the equivalent OP simulations (-0.96%), indicating a more economically efficient generation of energy in the IM-PA case.

I. Variability in individual tidal lagoon performance

We now examine the performance of individual tidal lagoons to analyse how they affect some of the trends in fleet performance discussed in the previous section, and the comparison with the work of Harcourt et al. [16]. An initial observation is the inherent variability of the site conditions between schemes. Differences in tidal conditions, which can be observed in Table I and Fig. 4, and bathymetric conditions, as seen in Fig. 5, result in significant intertidal variations between schemes. These site-specific variations manifest themselves when schemes are optimised, particularly as so many aspects of lagoon design and operation here are idealised. This can be seen in Table II which indicates the spread of hydraulic structure setup and control parameters under the FC optimisation. Analysis of

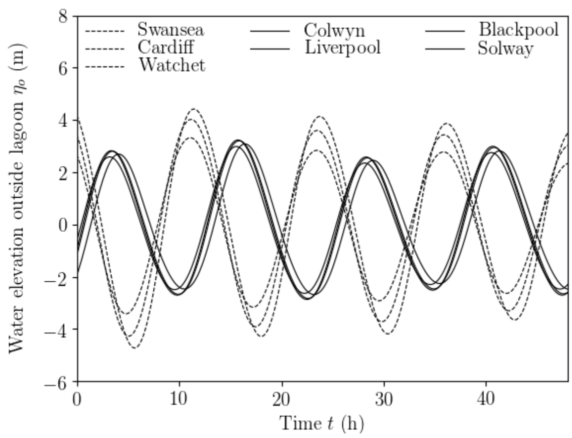

Fig. 6. Snapshot of the water elevation at the seven lagoon locations, at a monitor point just outside the lagoon wall.

the individual performance of the lagoons between optimisation cases demonstrates this further. Results indicate increases in energy output between FC-OP to EM-OP ranging from 19-39% and increases in income between FC-OP to IM-OP from 21-44%. Lagoon income gains are even more pronounced when the price signal adjustment is implemented in the -PA cases, with an income increase of 63% present between IM-OP and IM-PA in the Watchet lagoon. These variations serve to demonstrate the unpredictability of the scale of impact on lagoon income that constraining aspects of operation imposes. Tidal lagoons are advantageous in that the dynamic factors which affect their performance can be modelled and predicted for years in advance. Combining this with the drastic variations present between potential sites for lagoon construction emphasises the need for flexibility, where possible, in operating and building with the local conditions in mind.

Furthermore, despite the large range of energy and income gains displayed when implementing adaptive operation in this study, the increases are all higher than those observed in Table V [16]. This is attributed to factors of the lagoon layout that are idealised in this study, such as the placement, area and shape of the embankment, being optimised to fixed control parameters in the design of the TLP-SB lagoon. By maximising the potential of the fixed cycle operation through the optimal design of such factors, the impact of adaptive operation is therefore more limited. Applying this theory to the lagoons in this study, the exact placement of the embankment in each location could be altered to harness the maximum income potential through an adaptive operation scenario. With the further addition of a cost element component, this manner of spatial optimisation could have the potential to boost lagoon income to an even greater extent.

J. Interaction with the energy market

In the absence of 2D hydrodynamic modelling of the tidal lagoons, the only manner in which the simulations represent any interaction between schemes is through the change in price signal present in the IM-PA cases. Although the previous section demonstrated the significant variations present in the results of the seven tidal lagoons, this section divides them into two distinct groups: Swansea, Cardiff and Watchet – the lagoons in the Bristol Channel (BC), and Colwyn, Liverpool, Blackpool and Solway – the lagoons in the Irish Sea north of Wales (IS). These two groups are separated by their performance. The income of individual BC lagoons using OP are all higher than the income of the IS lagoons, with their combined income being 1.5% lower despite being comprised of one lagoon less. Once the price signal adjustment is applied the BC lagoons generate 17.3% more income. Another notable distinction is made between the operation of these two groups when observing the tidal signal present in the seven lagoon locations, as shown in Fig. 6. This 48 hour interval demonstrates that BC and IS lagoons are significantly out of phase with each other, with peaks of maximum and minimum elevation being roughly four hours apart. This phase difference is then translated into the price signal adjustment through Eq. 4, with the reduction in price being proportional to the energy output of the FC simulations. The key characteristic of the FC simulations is the continuity of operation between cycles. Table II indicates relative consistency in control periods among the lagoons, with the variations present not large enough to significantly shift the four hour phase difference shown in Fig. 6. The phase difference is therefore sufficiently preserved during lagoon operation in the FC simulation as to be conveyed in the price signal adjustment. The effect of this can be observed in Fig. 7. This time series offers a glimpse at the volatility of the price signal under various scenarios, and the combined energy output of the two lagoon groups in the FC simulations which prompts these changes. The phase difference in the energy output of the two groups is preserved, with the implementation of their peaks alternating evenly over time. As a result, one group of lagoons will often be pumping while the other group is generating. This limits the reduction in price when one group is generating, observed by the line representing all the lagoons frequently having a higher price than when just one of the groups is considered.

The grouping of tidal lagoons in this manner and its effect on the price signal goes further towards explaining some of the trends explored in section IV-H. Firstly, the drop in generated energy from IM-OP to IM-PA is a sum of energy gains in BC lagoons and energy losses in IS lagoons. Also, the scale of the income drop between IM-OP and IM-PA, -12.68%, was directly linked to the average -12.22% change present between the original and adjusted price signal. The reality is that this, again, is a summation of the disparities between the two lagoon groups, with the BC lagoons showing a change of less than -7% and the IS lagoons all showing a drop of over -15%. The cause of this is the ratio between the energy output of the individual lagoons under a given optimisation scenario and the energy output of its groups in the FC-OP scenario. The similarities between energy output of the groups in FC-OP (BC generates just 4.3% less one one lagoon fewer)

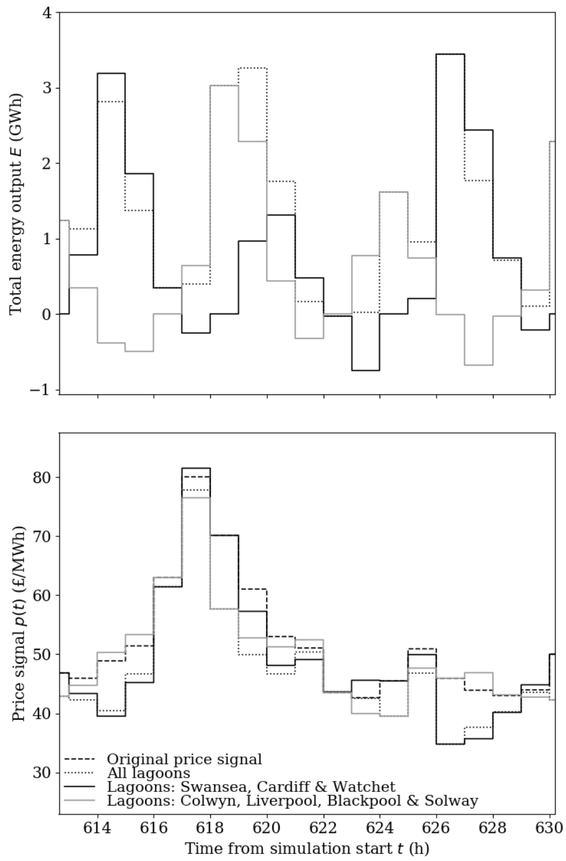

Fig. 7. Time series comparing combined, hourly lagoon energy outputs during the fixed control (FC) simulation and the resulting price signal adjustment.

allow for simple direct comparisons of these ratios. The BC lagoons, which individually generate more, exhibit a higher ratio, so the reduction in price when they generate is smaller in proportion to their energy output, and therefore income, than the IS lagoons. Even though the price signal adjustment is affected by the FC simulation only, operation is still tied to the tidal signal in the EM and IM simulations, thus maintaining these effects to an extent. This manifests itself in the trends outlined above, in addition to the percentage difference of income between the BC and IS lagoons shifting from -1.5% to 17.3% when the price adjustment is implemented.

In terms of overall tidal lagoon fleet performance, the effect of hindering price signal reduction serves to benefit the lagoon fleet in the IM-PA scenario. With the limitation of the increase of price volatility caused by the inherent phase difference of the two lagoon groups being translated from the FC simulations, peaks in the price signal are largely preserved. IM-PA simulations allow all lagoons to target the spikes in the price signal, where practical, without risk of collectively diminishing it. Within the lagoon fleet, the effects of this are shown through the previously discussed large income increases from both the FC-PA and EM-PA to the IM-PA simulations. The great economic benefits of coupling price forecasting with income optimisation are demonstrated, the implications of which have the potential to go beyond the operation of just the fleet. The presence of less predictable renewable energy sources in the DAM in other countries, such as wind and solar, has previously had the effect of greatly magnifying price signal volatility due to the concentrated and simultaneous nature of their generation [35]. As previously argued by Harcourt et al. in relation to the presence of a single lagoon [16], a fleet of well-placed tidal lagoons could go even further by offering a more stable alternative to such renewable schemes, and a more environmentally friendly alternative to the open cycle gas turbines and nuclear generators which also trade in the UK DAM [36].

However, the lagoon fleet in this scheme benefits from a system in which its actual energy output is not reflected in the price signal adjustment in the EM-PA and IM-PA cases. The algorithm herein is advantageous to the lagoon fleet as the DAM forecasts the generation of the FC-OP simulation, thus allowing the adaptive control parameters in the EM-PA and IM-PA optimisations to avoid periods when the price has been reduced the most. A more reactive response to tidal lagoon generation in the price adjustment could serve to hinder the benefits of income optimisation of the fleet, but would be an even more realistic approach. Further work to implement this is required.

V. Conclusions

This paper highlights the benefits of modelling and optimising multiple tidal lagoons as a fleet to maximise income. A methodology is applied to optimise operation by exploiting the flexibility of the hydraulic structure control parameters and calculating income through interaction with the day-ahead energy market. Results of tidal lagoon fleet performance show that by considering the presence of other lagoons in the fleet, individual lagoons are able to adjust their control parameters as to maximise collective income. A diagnosis behind some of the trends is attributed to the inherent phase difference present when subdividing the considered lagoons into two groups: within the Bristol Channel and to the north of Wales in the Irish Sea. The phase difference serves to restrict an increase in price signal reduction in the energy market, thus limiting the losses which occur when the price is adjusted. Furthermore, idealising numerous aspects of lagoon design offers a glimpse at the variability in individual site conditions, emphasising the importance of exploiting the flexible and predictable nature of tidal energy schemes when designing and operating them.

The results presented here open up number of different avenues for further research. Coupling the current 0D model with a 2D or 3D hydrodynamic model of the domain including lagoons would better represent the operation of the tidal lagoon fleet. In addition, a metric for capital costs combined with spatial optimisation could serve to increase exploitation of the high variability of site conditions present in the lagoon fleet and paint a clearer picture of their optimal implementation. Finally, an update on the price adjustment algorithm could be made to better represent the day-ahead energy market's responsiveness to the lagoon fleet under adaptive operation when maximising income.

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