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Estimating the optimum size of a tidal array at a multi-inlet system considering environmental and performance constraints

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HIGHLIGHTS

- A procedure for the optimisation of tidal array size through surrogate modelling is introduced.
- Array size is defined by means of two design variables: number of rows and number of turbines per row.
- Tidal array is placed in a channel of a multi-inlet costal lagoon with complex feedback mechanisms.
- A numerical model is set-up and validated to assess effects of arrays in hydro- and morphodynamics.
- Multi-objective optimisation models are formulated considering environmental constraints.

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ABSTRACT

This paper investigates the optimum tidal energy converter array density at a tidal inlet by applying surrogate-based optimisation. The SBO procedure comprises problem formulation, design of experiments, numerical simulations, surrogate model construction and constrained optimisation. This study presents an example for the Faro-Olhão Inlet in the Ria Formosa (Portugal), a potential site for tidal in-stream energy extraction. A 35 kW Evopod™ floating tidal energy converter from Oceanflow Energy Ltd. has been used for array size calculations considering two design variables: (1) number of array rows, and (2) number of tidal energy converter per row. Arrays up to 13 rows with 6–11 tidal energy converters each are studied to assess their impacts on array performance, inlets discharges and bathymetry changes. The analysis identified the positive/negative feedbacks between the two design variables in real case complex flow fields under variable bathymetry and channel morphology. The non-uniformity of tidal currents along the array region causes the variability of the resource in each row, as well as makes it difficult to predict the resultant array configuration interactions. Four different multi-objective optimisation models are formulated subject to a set of performance and environmental constraints. Results from the optimisation models imply that the largest array size that meets the environmental constraints is made of 5 rows with 6 tidal energy converter each and an overall capacity factor of 11.6% resulting in an energy production of 1.01 GWh year^{-1}. On the other hand, a higher energy production (1.20 GWh year^{-1}) is achieved by an optimum array configuration, made of 3 rows with 10 tidal energy converters per row, which maximises power output satisfying environmental and performance restrictions. This optimal configuration permits a good level of energy extraction while having a reduced effect on the hydrodynamic functioning of the multi-inlet system. These results prove the suitability and the potential wide use of the surrogate-based optimisation method to define array characteristics that enhance power production and at the same time respect the environmental surrounding conditions.

1. Introduction

Tidal stream energy harvesting consists in extracting part of the kinetic energy from the natural tidal currents to generate electricity. In a coastal lagoon system, the above process can be very productive due to the ebb/flood circulation amplification at the tidal inlets. Tidal

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Energy Converters (TECs) are used for this purpose and, currently, there are numerous types of technologies being proposed and tested at different technology readiness levels with the most advanced devices being at TRLs of 7-8 [1]. Tidal energy has the advantage of being a renewable source of energy with high density, which makes it possible to produce electricity from low flow speeds if compared, for example, with wind energy. One of the advantages of tidal energy with respect to other renewable energy forms is that tides are extremely predictable. It is therefore simple to estimate power production at a particular time, a key aspect to optimise energy distribution systems. For a detailed and complete overview of the tidal energy sector refer to [1].

The tidal energy potential at shallow water estuaries and coastal lagoon systems can be exploited using small-scale TEC devices. Shallow near shores provide economic advantages during TECs deployment and maintenance activities because they are in close vicinity to land, providing advantages in the maintenance and power distribution logistics. These conveniences can translate into opportunities for coastal communities to adopt this form of energy generation and diverse their sustainable and renewable energy matrix. Recent resource assessment studies have shown the potential for tidal energy extraction and/or for device validation of several coastal areas at the UK, Ireland, Spain and Portugal such as the Severn estuary (Wales, UK) [2], Shannon Estuary (Ireland) [3], Rias Baixas (Galicia, Spain) [4] and Ria Formosa (Algarve, Portugal) [5].

On the other hand, there are drawbacks that need to be overcome, mainly related with the coastal environment. Usually, potential regions for energy harvesting are also sensitive natural areas, highly dynamic, with a rich biological diversity and enclose a wide range of uses and stakeholders (e.g. commercial and recreational activities). Any modification introduced into these fragile environments can have the potential to alter the system's equilibrium [6]. The direct consequence of installing and operating a TEC is the alteration of the system's hydrodynamics. As a result of the modification of the hydrodynamic field, other environmental impacts can arise, such as: decrease tidal flooding [6], modify population distribution and dynamics of marine organisms [7], alter water quality [8], increase noise pollution [9], transform marine habitats [10], increase mixing in systems where salinity/temperature gradients are well-defined [10], and affect the transport and deposition of sediments [11]. The effect of TECs on sediment dynamics has been the subject of intense research in the last years by means of numerical modelling. Apart from the study of [11] for São Marcos Bay, Brazil, all of the research focuses on UK (e.g. [12,13]) and France [14] tidal stream energy sites. All studies conclude that TECs presence affect in some extent sediment dynamics, and that the magnitude of the impact depends on tides, the sedimentological characteristics of the site and the amount of energy extracted (i.e. the installed power capacity of the TEC array). Moreover, Robins et al. [12] and Fairley et al. [13] highlight the importance of considering wave shear stresses when assessing morphodynamic impact of tidal turbines. At complex coastal systems, such as multi-inlet coastal lagoons, influences on sediment dynamics will not only be felt on the vicinity of the TEC units but can also affect the global hydrodynamic pattern or the tidal prism of other inlets.

In order to assess the commercial feasibility of a tidal energy project, first, the optimal size and TECs arrangements should be obtained. The drag exerted to the flow by the array depends on blockage, which relates with the number of TEC units and their distribution within the array. High blockage ratios can significantly affect the propagation of the tidal wave, affecting water levels and flow velocities well beyond the location of the tidal array. Therefore, for a given tidal channel, there is an optimum number of TECs to maximise array efficiency at a desired blockage ratio, as investigated by several authors in uniform rectangular channels using one-dimensional theoretical models based on the actuator disk theory [15–19] or by means of semi-analytical methods [20]. However, when it comes to real case scenarios with complex flows the aforementioned models, due to their derivation assumptions, are not able to adequately represent the flow surrounding the tidal arrays. Even less to assess their effects on the complex processes and feedback mechanisms of the whole system [21,22]. For this purpose, numerical modelling of the entire coastal system is a useful tool to simulate case scenarios and predict the effects that energy extraction will have on the overall system's hydrodynamics, as well as on other processes like sediment transport pathways and/or water quality issues.

In the cases where time-consuming numerical simulations are involved, Surrogate-Based Optimisation (SBO) revealed itself as an attractive optimisation technique. In the literature, there are numerous applications of SBO techniques in various fields of knowledge [23]. Recently, SBO methods have been applied to solve the TEC array layout problem in idealised channels aiming to maximise the overall capacity factor of the array subject to economic and geometric constraints [24], as well as to environmental restrictions [25]. The SBO approach consists in approximating a mathematical function, i.e. a surrogate or a metamodel, to existing data or to a function that is expensive (i.e. time-consuming) to evaluate and has no analytical form. Computational simulations are a remarkable example, where an individual run can take hours or even days to complete. The mathematical function provides a response (i.e. dependant variable) as a function of a vector of design parameters (i.e. independent variables), in which its execution computational time is instantaneous. Once a validated surrogate model is built, it can be incorporated into a mathematical optimisation model. Further details on the SBO approach can be obtained in [26].

This paper presents a case study for the complex multi-inlet system of Ria Formosa coastal lagoon (Algarve, Portugal), where the SBO approach is employed to estimate the optimal size of a tidal array for Faro-Olhão Inlet. Several optimisation models are formulated to optimise array characteristics as a function of two design variables, i.e. number of array rows and TECs per row, while ensuring a certain array performance level and minimising detrimental impacts on the lagoon hydrodynamics and morphological processes. As far as the author's know, there has not been yet published any paper where the SBO approach has been used to estimate the optimum size of a tidal array at a potential tidal site.

The remainder of this paper is organized as follows. The paper introduces the main characteristics of the study region (Section 2), describes the methodology approach, including aspects of the tools used, the numerical model set-up and validation, and details the implementation of the SBO method (Section 3), presents the results obtained (Section 4), together with a discussion of these results (Section 5), and presents the main conclusions (Section 6).

2. Site description

The Ria Formosa is a multi-inlet barrier system located in southern Portugal (Fig. 1), comprising five islands and two peninsulas, separated by six tidal inlets, salt marshes, sand flats and a complex network of tidal channels. Two of the inlets are stabilised (Faro-Olhão and Tavira inlets); and the other four are natural (Ancão Armona, Fuseta and Lacém). The tides in the area are semi-diurnal with typical average astronomical ranges of 2.8 m for spring tides and 1.3 m for neap tides. A maximum tidal range of 3.5 m can be reached during equinoctial tides [27,28]. Wave climate in the area is moderate (an offshore annual mean significant wave height, H_s, of ~1 m and peak period, T_p, of 8 s, with storms characterized by $H_s > 3$ m). Approximately 71% of waves approach from the W-SW, with about 23% coming from E-SE [29]. The lagoon is generally well mixed vertically, with no evidence of persistent or widespread haline or thermal stratification [30]. Due to reduced freshwater inputs and elevated tidal exchanges, the salinity values usually close to those observed at adjacent coastal ocean waters [30].

The storm surges in the area are relatively small due to the narrow continental shelf. During extreme storm conditions the surge levels are estimated to reach values close to 0.6 m [27]. For a typical storm with a significant wave height of 4 m the associated storm surge is on the order