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Device interactions in reducing the cost of tidal stream energy

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ABSTRACT

The levelised cost of energy takes into account the lifetime generated energy and the costs associated with a project. The objective of this work is to investigate the effects of device interactions on the energy output and, therefore, on the levelised cost of energy of a tidal stream project, by means of numerical modelling. For this purpose, a case study is considered: Lynmouth (North Devon, UK), an area in the Bristol Channel in which the first tidal stream turbine was installed – a testimony of its potential as a tidal energy site. A state-of-the-art hydrodynamics model is implemented on a high-resolution computational grid, which allows the demarcation of the individual devices. The modification to the energy output resulting from interaction between turbines within the tidal farm is thus resolved for each individual turbine. The results indicate that significant changes in the levelised cost of energy values, of up to £0.221 kW h^{-1}, occur due to the aforementioned modifications, which should not be disregarded if the cost of tidal stream energy is to be minimised.

1. Introduction

Tidal stream energy is called to play a major role in meeting future energy needs due to its advantages relative to other renewable energies; inter alia, predictability, stability and high load factor [1]. The interest of the tidal stream resource has driven intense research during the last decades, which has mainly centred on resource assessments and technological advances [2]. Concerning the assessments of the tidal resource, they allowed the quantification of the potential energy production in a number of promising tidal stream areas worldwide, including sites around headlands, straits between islands or enclosed bodies of water, such as estuaries [3]. In previous works, different methodologies were applied, including numerical modelling and direct flow measurements [4]. Having quantified the available energy resource, the final decision concerning a future tidal stream installation at a potential site is subject to several practical constraints, such as the existence of tidal asymmetry, i.e. differences between flood and ebb phases of the tidal cycle. These differences can affect the performance of tidal stream converters and can serve as a criterion to decide if bi-directional turbines should be preferred, as discussed by Neill et al. [5] with reference to Orkney (Northern Scotland). The relationship between tidal flow and bathymetry constitutes another aspect that cannot be disregarded: shear stress and topographic features can influence tidal hydrodynamics, and in some cases induce flow obstruction or recirculation [6]. Finally, the proximity to a grid connection point and the final consumer minimises the loses due to energy transmission. A recent work showed how the electricity needs of a port in Ria de Ribadeo (NW Spain) could be fulfilled through tidal stream energy production [7]. As regards the technological advances, they allowed the development of a range of tidal stream energy converters, including [8]: reciprocating and rotating principle converters, vertical- and horizontal-axis turbines, as well as floating and bottom-fixed devices. As a result, the tidal energy industry is growing rapidly, with commercial designs, such as the SeaGen turbine [9]. However, so far none of the existing designs has gained universal acceptance (as in the case of e.g. the three-bladed horizontal-axis wind turbine [10]). Rather, a number of analyses on different designs are being conducted with a view to determining which characteristics can maximise the power output of converters [11]. It is not only the performance of these converters that is of importance, but also their survivability under extreme conditions, since they are to be deployed in harsh environments [12]. The potential impacts of tidal stream energy are also being investigated, and indeed quantifying – and minimising – them is a requirement for tidal stream energy to be sustainable [13]. These studies are helping designers to establish a basis on which prototypes can be successfully deployed in real environments [14]. Although there is no doubt that it is technically feasible to

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Nomenclature and units

Roman symbols

A	turbine aperture (m^2)
c	salinity or temperature (transported substance)
C_D	drag coefficient
C_p	power coefficient
C_T	thrust coefficient
C_{2D}	Chézy coefficient
d	local water depth (m)
D_h	horizontal eddy diffusivity ($m^2\,s^{-1}$)
F_x	*x* component of the flow retarding force per unit volume (N)
F_y	*y* component of the flow retarding force per unit volume (N)
f	Coriolis parameter
g	gravitational acceleration ($m\,s^{-2}$)
M_x	*x* component of the momentum generated by an external force (N m)
M_y	*y* component of the momentum generated by an external force (N m)
n	Manning coefficient
P_t	tidal stream available power (W)
Q	intensity of mass sources per unit area ($m^2\,s^{-1}$)
r	discount rate
R	source term per unit area
t	time (years)
t_i	time instant
T	project lifetime
U	vertically integrated eastward component of the flow velocity ($m\,s^{-1}$)
V	vertically integrated northward component of the flow velocity ($m\,s^{-1}$)
V_c	volume of control

Greek symbols

ζ	water level (m)
η	efficiency
λ_d	first order decay process
ρ_0	water reference density ($kg\,m^{-3}$)
ρ'	anomaly density ($kg\,m^{-3}$)
ρ	seawater density ($kg\,m^{-3}$)
τ_b	shear stress at the bottom ($N\,m^{-2}$)
τ_s	shear stress at the surface ($N\,m^{-2}$)
υ_h	kinematic horizontal eddy viscosity ($m^2\,s^{-1}$)

Abbreviations

AEP	annual energy production
CAPEX	capital expenditures
LCOE	levelised cost of energy
OPEX	operational expenditures
TST	tidal stream turbine

extract energy from tidal currents, only a few tidal stream projects are now operating at a commercial scale [15]. Having observed also proactive public attitudes and positive externalities towards this renewable [16], the primary reason for the scarcity of commercial plants is that the cost of generation from the tidal stream resource, the so-called levelised cost of energy (LCOE), is typically higher than that from traditional sources (coal, natural gas, etc.) [17]. On these grounds, it is crucial to understand the parameters affecting this cost so as to provide a framework of potential areas of reduction [18].

Estimating the LCOE for a tidal stream farm requires information on the expected energy output from the farm and the costs involved in the construction, operation and maintenance of the tidal stream installation [19]. Although the information on the capital and operational cost-values of tidal stream devices is limited due to the technological stage of development, the sensitiveness of their values is well known [20]. In this regard, several areas can contribute to lower the capital and operational costs of tidal stream farms [21]. They include technological innovation, which can lead to improve the performance, efficiency and reliability of tidal stream energy converters; as well as economies of scale [22]. The innovation process should be aligned with policy strategies, including the public subsidisation of this energy [23].

The relationship between the variations of energy output and the LCOE is an aspect that has received less attention. Previous works analysed how the hydrodynamic interactions between tidal stream turbines placed at a real tidal site could modify the flow patterns, such as the transient and residual flows [24]. The alteration of the hydrodynamics has inevitably an effect on the energy available for conversion, and hence, the energy production [25]. In addition, the work of Ahmadian et al. [26] investigated the relationship between the aforementioned modifications with the shape of a tidal stream farm, whereas Neil et al. [27] and Robins et al. [28] focused on the potential effects on sedimentary processes. Notwithstanding, the numerical modelling of the performance of a tidal stream turbine (used in most of the previous studies) has not been applied to the LCOE calculation so far, and this is the main objective of the present work.

Lynmouth, on the North Devon coast, constitutes an excellent tidal stream site (Fig. 1). The nearby grid connection point at Lynton and the research facilities of the South West Marine Energy Park [29] are testimony to the potential of this site for tidal stream energy exploitation. Indeed, Lynmouth has been recently included as a new tidal stream energy demonstration zone to be managed by the Wave Hub [30] and the South West Marine Energy Park [31]. This decision based on the experience acquired during 2003, when Lynmouth was the scenario of the world's first tidal current installation to be deployed in a working environment [32] (the 300 kW tidal stream turbine "Seaflow" of Marine Current Turbines). Lynmouth stands out for tidal streams over 2.25 $m\,s^{-1}$ in conjunction with water depths in the range 15–25 m, which make it an ideal location for the deployment of the majority of first generation tidal energy converters. As a case study, a high resolution model of Lynmouth is implemented and successfully validated in order to simulate the operation of a tidal farm. The resolution of the model allows the demarcation of individual devices on the grid. The LCOE for each device is examined in two scenarios: without (baseline) and with the tidal stream farm. A comparison between the different estimates is presented, showing a maximum LCOE variation of £0.221 $kW\,h^{-1}$. As explained below, different values of LCOE are found for each single tidal stream device, ranging from £0.556 $kW\,h^{-1}$ to £0.663 $kW\,h^{-1}$ for the baseline case; and from £0.714 $kW\,h^{-1}$ to £0.828 $kW\,h^{-1}$ for the farm case. These ranges suggest that the effects on the LCOE are associated with the specific position of the tidal stream converter within the farm – which indicates the need for the optimisation of the tidal stream farm.