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Swansea Bay tidal lagoon annual energy estimation

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ABSTRACT

UK Energy policy is focused on the challenges posed by energy security and climate change, however, efforts to develop a low-carbon economy have overlooked tidal energy a vast and unexploited worldwide resource. Since 1981, UK tidal lagoon schemes have been recommended as an economically and environmentally attractive alternative to tidal barrages. More recently, two proposals for tidal lagoons in Swansea Bay have emerged and there have been several reports documenting the potential to harness significant tidal energy from Swansea Bay using a tidal lagoon. This paper assists in determining a realistic approximation of the energy generation potential in Swansea Bay, a numerical estimation is obtained from a zero dimension, 0D, 'backwards difference' computational model, utilising the latest turbine data available and high-resolution bathymetric data. This paper models the behaviour of the tidal lagoon in dual mode generation, in line with the above proposals. The results of model testing using a variety of fixed and variable parameters are displayed. The ebb mode model with provision for pumping at high tide is then explored further by carrying out optimisations of the starting head, number of turbines and turbine diameter in order to determine the maximum annual energy output from the tidal lagoon.

1. Introduction

Investigations into tidal power require some form of mathematical modelling that utilises a computer simulation of the water flowing in and out of estuaries. The data acquired from this can then be used to study and evaluate several aspects namely:

- The energy output of the tidal lagoon.
- The effects of the lagoon on the water levels in the basin.
- The effects of the lagoon on the seaward water levels.
- Comparison of different methods of operating the lagoon.

River or estuary flow can be simulated by 0D, 1D, 2D or 3D modelling approaches, which increase in complexity. The 1D Saint-Venant equations, more commonly known as the shallow water equations model the response of an incompressible fluid to gravitational and rotational forces in open channel flow, providing average flow velocity and water elevation in each channel section (Randall, 2006). The shallow water equations also apply to a popular 2D modelling approach, in which they are derived by depth integrating the 3D Reynolds Average Navier Stokes equations from the river bed to the free surface (Falconer et al., 2009). The 2D models consist of three equations; the conservation of the volume of water and two representing the conservation of water momentum, which depend on three hydrodynamic variables namely, water depth and the depth averaged velocity components in x and y directions (Bourban et al., 2013). Examples of 2D models include DIVAST from Cardiff University (Brammer et al., 2014), which uses finite volume cell based numeric and SMARTtide from HR Wallingford, which uses finite element cell numeric (Bourban et al., 2013). 2D models assume a hydrostatic pressure distribution (Hervouet, 2007), however due to the need to model pressure terms, particularly on the upstream sides of the impoundment 3D models are usually applied in this near-field zone. The governing equations are the 3D Navier Stokes with the Boussinesq approximation and the incompressible continuity equation. Though computational power has advanced in recent years, 3D modelling remains a complex task, therefore 3D models are usually coupled with 2D models in the far-field zones (Kilanehei et al., 2011).

An 0D model provides a simplified approach to estimating the performance of tidal barrage or lagoon, the model is built on the assumption that a volume of water let into the lagoon will raise the level of the lagoon by an amount equal to the volume let in divided by the area of the lagoon at that moment in time (Aggidis and Benzon, 2013). The model is constructed using MatLab with provisions for the user to vary the input parameters such as number of turbines, head height, turbine diameter, time period, etc. and return the potential power output.

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In order to construct this model knowledge of the tides and bathymetric data for the bay is required. The behaviour of the tides is modelled in terms of an equation that includes the tidal constituents for Swansea Bay. The bathymetry of Swansea Bay is needed in order to determine the height of water within the lagoon. Together these form a vital part of the function of the model, namely that at any point in time the potential energy available from the enclosed body of water can be calculated (Aggidis, 2010). Tidal constituents are available from the United Kingdom Hydrographic Office (UKHO, 2013) and bathymetric data purchased for this research from SeaZone Ltd. (Sea Zone Solutions, 2013). Turbine 'hill charts' for double regulated bulb turbines are used to calculate the flow and power output from a selected turbine at different flow rates and heads. Bulb turbines are employed widely across the world in low-head tidal power schemes, as they are one of the most efficient turbines for low head applications (Schneeberger, 2010). The double-regulated turbine 'hill chart' for this study uses new cutting edge turbine technology made available directly from Andritz Hydro (Aggidis and Feather, 2012). A tidal lagoon is an offshore or partially offshore impoundment that unlike a tidal barrage does not block the estuary it occupies; the technology used is very similar to that found in hydropower schemes, however tidal currents are bi-directional.

Estimating the resource requires a number of assumptions: technical constrains of the device, device efficiency, and effect of resource extraction. Thus there is a large degree of uncertainty. One estimate suggest that the UK holds 50 TW h/year, representing 48% of the European resource (Hammons, 1993), and few sites worldwide are as close to electricity users and the transmission grid as those in the UK. In the 1980s the Department of Energy conducted a number of studies and it was concluded that there are 16 estuaries where tidal barrages should be capable of producing over 44 TW h/year (Department of Energy, 1989). Tidal lagoon schemes in the UK originate from the 1981 Severn Barrage Committee headed by Sir Hermann Bondi (Sustainable Development Commission, 2007). The initial proposal was to dredge the Severn Estuary material against the coast creating bounded enclosures in shallow water only partially blocking the estuary, known as the Russell Lagoon, however these plans were abandoned. In 2004 a report backing the Swansea Bay lagoon was published by Friends of the Earth Wales, proposing this development as an environmentally and economically attractive alternative to the Severn Barrage (Friends of the Earth Cymru, 2004).

Swansea Bay is located in the Bristol Channel on the South Wales coastline, as part of the Severn Estuary it experiences one of the world's largest tidal ranges, often reaching 10 m. In 2004 Tidal Electric Inc. (TEL) announced proposals to build a 5 km^2 tidal lagoon using twenty-four 2.5 MW, 3.3 m diameter turbines. Atkins (2013) report sponsored by TEL estimated costs in the region of £81.5 million (as of 2006), however this was met with scepticism and the Department of Trade and Industry anticipated the cost of the project to be £234 million (Baker, 2006). More recently however, Tidal Lagoon Swansea Bay Plc (TLSB) have submitted a rival bid to develop a lagoon in Swansea Bay, the outline of which is shown in Fig. 1. TLSB are suggesting a much larger 11.5 km^2 structure with sixteen 20 MW, 7 m diameter turbines capable of generating 495 GW h/annum (Case, 2014). Independent consultants Pöyry estimate the capital costs of the TLSB lagoon to be £913 million (Poyry Consultants, 2014). Both companies plan to operate on a dual mode generation.

The Swansea Bay tidal lagoon schemes demonstrate a renewed interest in tidal power, which has long been seen as having significant potential and has many advantages compared to other renewable sources. It is well documented that increasing integration of volatile, unpredictable sources of renewable energy such as wind power and solar power jeopardises the stability of the power grid (Krenn et al., 2013). In order for the grid to remain stable the power generated at any instance has to match demand, therefore it is important that the transmission network contains power sources that are immediately available. Tidal power has an

Fig. 1. Map showing proposed layout of tidal lagoons in Swansea Bay (Case, 2014).