Renewable and Sustainable Energy Reviews 34 (2014) 98–109

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

# Energy of marine currents in the Strait of Gibraltar and its potential as a renewable energy resource

María Concepción Calero Quesada*, Jesús García Lafuente, José Carlos Sánchez Garrido, Simone Sammartino, Javier Delgado

*Physical Oceanography Group, University of Málaga, Spain*

ARTICLE INFO

*Article history:*
Received 18 October 2013
Received in revised form
11 February 2014
Accepted 18 February 2014
Available online 21 March 2014

*Keywords:*
Strait of Gibraltar
Energy fluxes
Tidal energy
Unidirectional currents

ABSTRACT

A non-hydrostatic hydrodynamic model of the Strait of Gibraltar with high spatial and temporal resolution has been used to assess suitable areas for energy extraction from marine currents. The model shows great spatial variability of the available energy flux, ranging from 200 W $m^{-2}$ to more than 1800 W $m^{-2}$. In addition to the mean energy flux, other properties and characteristics of the flow such as permanence and direction of the currents, vertical shear or occurrence of unwanted high frequency internal waves have been merged into an index that is used in this work as a proxy for the suitability of a given place to install a power plant. This index highlights two zones gathering the required conditions: the subsurface layer of the eastern half of the strait and the near-bottom layer of Espartel sill at the westernmost gateway of the strait.



**Contents**



* Correspondence to: Campus Teatinos s/n, 29071 Málaga, Spain. Tel.: +34 952 132 849.

http://dx.doi.org/10.1016/j.rser.2014.02.038
1364-0321/

## 1. Introduction

Renewable marine energy can be obtained from wind waves and swell, tides, ocean currents and from ocean salinity and temperature gradients. Many different devices are employed at this aim, such as the direct-drive converters that transform the wave mechanical energy in electrical power, the hydrokinetic turbines that convert the kinetic energy of the moving mass of water into electricity in the case of marine currents, or the thermal oceanic plant, producing energy by the thermic differences between deep and surface waters [1]. Ocean contains a large amount of unexploited clean renewable energy resources that can play a significant role in the future of worldwide energy portfolios. This kind of energy will supply future electrical energy needs in the world: the U.S. Electric Power Research Institute (EPRI) and the National Renewable Energy Laboratory (NREL) estimate that the total potential of all the combined ocean renewable energies in United States currently exceeds the national electric energy needs. A total of 13 GW of new hydrokinetic technologies could be deployed by 2025, supplying at least the 10% of the USA electrical needs [2]. Wave and tidal current energy could potentially supply the 15% of the UK's electricity needs [3] and wave energy is likely to have a significant role in Australia electric policy with the highest capacity expected (449 GW from 2023 to 2032) [4].

Several technologies and devices are currently operating with different efficiency depending on the available energy and the device performance and maintenance [1]. The exploitation of renewable energy from ocean waves is widely developed in several countries as Australia, Americas, Portugal, South Africa, parts of Scandinavia, United Kingdom [3], and Ireland [5]. Wind waves energy extraction has different technologies [6] and modes of operation [7] with high energy potential (of the order of TW/yr). Some of the most interesting ongoing projects are the Pelamis Wave Power (PWP) in Portugal (2.25 MW), in Orkney (3 MW) and Cronwall (5 MW) in UK [8].

### 1.1. Tidal energy resource

Marine currents carry a huge deal of energy, too, but this technology is currently under pilot phase or research projects [9]. Some of the most suitable places to extract this type of energy are Ireland, the Amazon River, the English Channel, the Strait of Gibraltar [10], Fiji Island [11], the Strait of Messina [12], the southern coast of Iran [13] or South Korea [14]. Most of the plants are already functioning, as the case of the coast of Welsh (UK) with its 8 MW, while others are currently being completed, as the one in Korea that will supply 300 MW by 2015 [8]. In some places the extraction of marine energy can be combined by two types of energy, as the case of wave and tidal mixed systems in UK [15].

There are different energy conversion systems in MCTs: rotating devices and reciprocating devices. The extraction of energy from ocean currents by rotating devices has the same physical basis as the extraction from wind and a similar technology. These are named marine current turbines (MCTs). The generated power is directly proportional to the fluid density and the cube of the speed. In places suitable for the extraction of marine energy, ocean currents are typically one order magnitude less than wind speed, but the sea water density is about three orders of magnitude greater than the air density and, therefore, the power generated is of the same order of magnitude in both environments.

MCTs can have two different configurations: the axial turbines, the most frequently employed, where the axis rotates horizontally parallel to the current stream and, with a special configuration of the blades (variable pitch) can operate in opposite flows, and the cross-flow turbines where the main axis is vertical and the blades are perpendicular to the main stream, being able to operate with flow from any direction [4,9].

An intense work of design and optimization is currently being developed in this field. While all hydrokinetic devices operate on the same conversions principles regardless of their areas of applications, a set of subtle differences may appear in terms of design and operational features of the farms. These include: design of the turbine (size, directionality and placement), operation (flow characteristics, water density, control resource and prediction) and end-use (grid-connectivity) [16]. Many studies indicate different types of turbines, for instance, the Evopod tested in Ireland or the Gorlov in USA, or the most promising, Delta Stream Turbine or the Neptune Tidal Stream Device (2.4 MW of capacity) [10].

Several test models claim a superior performance of MCTs located in marine channels than others installed in open flows, the latter being more similar to windmills, resulting in an increase of both average and peak power coefficient [17]. In general MCTs present more technical limitations than wind turbines: the closer proximity of the sea surface and the seafloor [18], the damages on the turbine blades caused by cavitation [18] and other effects related to the higher density of sea water with respect to the air. In many cases it results in the failure of the device, such as the blade fracture on the Open-Hydro 16-m installed in the Bay of Fundy or the Atlantis AR1000 [19]. Once the rotor is in motion, the blade section starts to experience a relative component of tidal current velocity at various angles of attack depending of the blade parameters [20]. For all these reasons, the presence of a strong current and the persistence of a flow in a site are not sufficient conditions to ensure its suitability for the installation of a turbine farm [21].

Besides the optimal design of the MCTs or their components, the hydrodynamic interactions between turbines may have significant impact in the efficiency of the devices and the electrical power output decays considerably. The two most important control variables for energy cost are the farm size and the turbine distribution in a farm [22]. Different models are used to find the optimal configuration of tidal turbine farms, by the solution of an optimization problem [23]. On the other hand, there are different types of devices that operate in specific conditions and prototypes still under development, whose technical characteristics can be adapted to ocean currents. For instance, the Northeast Normal University in China, developed a floating horizontal axis turbine provided with a flex shaft with a vertically arranged generator designed to avoid some disadvantages of horizontal axis turbine, such as needing pitch adjusting and efficiency dropping in reverse flow [24]. In Ria de Arousa, Spain, a parametric approach based on four performance parameters was proposed to compare two types of turbines, the Evopod and the Gorlov. It was found that the Evopod achieves greater site-specific turbine efficiency and energy output whereas the Gorlov turbine presents higher availability and capacity factors or, in other words, more operation hours and equivalent hours per year, essentially due to its lower cut-in velocity and power rating [25].

### 1.2. Marine currents in the Strait of Gibraltar

The Strait of Gibraltar holds areas where ocean currents are strong, around a velocity of 2 m $s^{-1}$ [26,27] compared with 3 m $s^{-1}$ in the Strait of Messina [12] or about 2 m $s^{-1}$ in Ireland [28], which makes it suitable to install power marine farms. The strait is the scenario of a two-way exchange of marked spatial variability induced by interaction of the flow with the several topographic constraints as Tarifa Narrows (TN hereinafter), Camarinal Sill (CS) and Espartel Sill (ES) shown in Fig. 1 [29–32]. Atlantic water, less saline and warmer, flows at the surface into the Mediterranean while a Mediterranean undercurrent, saltier and