Renewable Energy 118 (2018) 814–824

Contents lists available at ScienceDirect

Renewable Energy

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

Numerical investigation of wave energy resources and hotspots in the surrounding waters of Taiwan

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A R T I C L E I N F O

Article history:
Received 3 August 2017
Received in revised form
7 November 2017
Accepted 26 November 2017

Keywords:
Wind wave model
Taiwan waters
Wave hindcast
Wave power
Wave energy output

A B S T R A C T

A state-of-the-art, third-generation, spectral wind wave model was implemented for the surrounding waters of Taiwan. The model was driven by 10-m winds above sea level from ERA-Interim reanalysis data. Medium-term (ten-year) hindcasts covering the period from 2007 to 2016 were conducted to assess the wave power resources in Taiwanese waters. The lowest monthly mean wave power density occurs in May and June, while the most energetic month is December. The sea area with the highest wave power density was observed near Lanyu. Four energetic areas located off the northern coast (H1), the southeastern coast (H2 and H3), and the southern coast (H4) of Taiwan serve as the appropriate sites (hotspots) for deploying wave energy converters. The annual mean wave power densities over ten years are approximately 8.72 kW/m, 10.97 kW/m, 13.72 kW/m, and 13.02 kW/m for H1, H2, H3, and H4, respectively. The annual total wave energy outputs were estimated to be 48.80 MWh/m, 76.59 MWh/m, 94.20 MWh/m, and 92.56 MWh/m at H1, H2, H3, and H4, respectively. The wave power is primarily driven by the northeast monsoon and the bulk of the wave energy appears to be generated by local wind waves in the surrounding waters of Taiwan.

1. Introduction

Renewable energy has continually attracted attention all over the world, and due to global warming, it is becoming an increasingly important issue. The exploitation of natural renewable energy is an urgent need for reducing the emissions of greenhouse gases [1]. Many natural energy sources, including wind, solar, geothermal, and marine energy, are considered potential candidates for dependable and renewable sources of energy because of their minimal environmental impact [2]. The renewable marine power resources, in the form of tides, tidal currents, sea temperature (thermal energy), and waves are particularly attractive energy sources for many island countries [3], since they usually suffer from a scarcity of fossil fuels but could have easy access to a large amount of marine energy [4]. Wave energy is regarded as an enormous source of renewable energy with negligible environmental impact and the high energy density and is experiencing increasing interest and development [5–8].

Wave energy potential assessments have been carried out for the Canary Islands, Madeira, and the Azores in the Atlantic Ocean [9–12], Hawaii and Taiwan in the Pacific Ocean [13,14], Fuerte Island in the Caribbean Sea [15], and Sardinia and Menorca in the Mediterranean Sea [16,17,18].

Since Ref. [19] assessed the wave energy potential along European coasts based on a European Wave Energy Atlas created by coarse numerical simulations, the employment of the wind wave numerical model to estimate ocean wave power has been widely used on both regional [20–23] and global scales [24–27]. The third-generation spectral wind wave models are capable of describing the complex sea states and are very reliable tools for wave forecasting, wave hindcasting, and wave climate study [28]. Therefore, a state-of-the-art third-generation, spectral, high-resolution wind wave model based on unstructured meshes was implemented for the waters surrounding Taiwan in this study. Medium-term (ten-year) hindcasts of the wave parameters associated with the calculation of wave power were conducted using the wind wave model. The spatial distribution maps of annual and monthly mean wave

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https://doi.org/10.1016/j.renene.2017.11.080
0960-1481/

power were created to clarify the inter-annual and inter-month variations in mean wave power and to identify appropriate locations (hotspots) for deploying the wave energy converters in Taiwanese waters.

The island of Taiwan is located just off the southeastern coast of mainland China (as shown in Fig. 1), covering an area of 36,197 km^2 and with a population of 23.5 million people in 2017. According to the statistical data provided by the Ministry of Economic Affairs, Taiwan, the annual total electricity generating capacity was 264.1 billion kWh in 2016, in which fuel-fired power accounted for 82% (216.56 billion kWh), nuclear power accounted for 12% (31.69 billion kWh), hydroelectric power accounted for 1.2% (3.17 billion kWh), and renewable power accounted for 4.8% (12.68 billion kWh). With regard to the renewable energy, only wind power and solar power are currently utilized in Taiwan. The exploitation of energy resources in the ocean, for instance tides, tidal currents, sea temperature (thermal energy), and waves, are necessary complements to the scarcity of natural energy resources because they are renewable and do not contribute to atmospheric pollution.

The primary objectives of this study are as follows: (1) implement the third-generation spectral high-resolution wind wave model for Taiwanese waters; (2) validate the wind wave model with available measured data; (3) create spatial distribution maps of annual and monthly average wave power; (4) locate the wave power hotspots in Taiwanese waters; (5) clarify the wave energy characterization at each hotspot; and (6) assess the annual total wave energy output at each hotspot.

2. Data and methodology

2.1. Wind forcing data

The wind forcing data used to drive the wind wave model was the wind field 10 m above sea level produced by ERA-Interim and was acquired from the European Center for Medium-Range Weather Forecasts (ECMWF) public datasets. ERA-Interim is the latest global atmospheric reanalysis and is normally updated once per month with a delay of two months [29]. The 10-m U and V wind components were extracted from ERA-Interim reanalysis with a temporal resolution of 6 h (four analysis fields per day, at 00:00, 06:00, 12:00and 18:00 UTC) and a spatial resolution of $0.125^o \times 0.125^o$ and were converted to the unstructured grids of the wind wave model.

2.2. Wind wave model

The state-of-the-art, third-generation, spectral wind wave model III (WWM-III) was adopted for ten-year wave parameter hindcasts in this study. WWM-III was derived from wind wave model II (WWM-II) and developed by Ref. [30] and Ref. [31]. The governing equation of WWM-III is the wave action equation and is given in Ref. [32] as

$$\frac{\partial N}{\partial t} + \frac{\partial (C_{gx} N)}{\partial x} + \frac{\partial (C_{gy} N)}{\partial y} + \frac{\partial (C_\sigma N)}{\partial \sigma} + \frac{\partial (C_\theta N)}{\partial \theta} = \frac{S_{tot}}{\sigma} \tag{1}$$

where N is the wave action, C_{gx} and C_{gy} are the wave group velocity in the x, y direction, u and v are the horizontal velocity in the x, y direction, σ is the wave relative angular frequency, θ is the wave direction, C_σ and C_θ are the propagation velocity in σ, θ space, and S_{tot} is the sum of the source terms for wave variance. The maximum wave direction in WWM-III is 360°, and this measure is discretized into 36 bins. The low- and high-frequency limits of the discrete wave period are 0.03 and 1.0, respectively, and are divided into 36 bins. The bottom friction is set equal to 0.067 based on the formulation of JONSWAP [33]. The wave breaking in shallow water area is computed in WWM-III using the method presented by Ref. [34] with a constant wave breaking coefficient of 0.78.

2.3. Wave power assessment

The extractable wave power per unit of the wave crest length can be calculated through the spectral output of WWM-III and is given in kW per meter as below:

$$P = \rho g \int_0^{2\pi} \int_0^{\infty} c_g(\sigma, d) S(\sigma, \theta) d\sigma d\theta \tag{2}$$

where $S(\sigma, \theta)$ is the directional wave variance density spectrum, $c_g(\sigma, \theta)$ is the wave group velocity, ρ is the density of seawater, g is the acceleration due to gravity, and d is the water depth. In deep water conditions ($d > 0.5 \times$ wavelength), Equation (2) can be simplified to

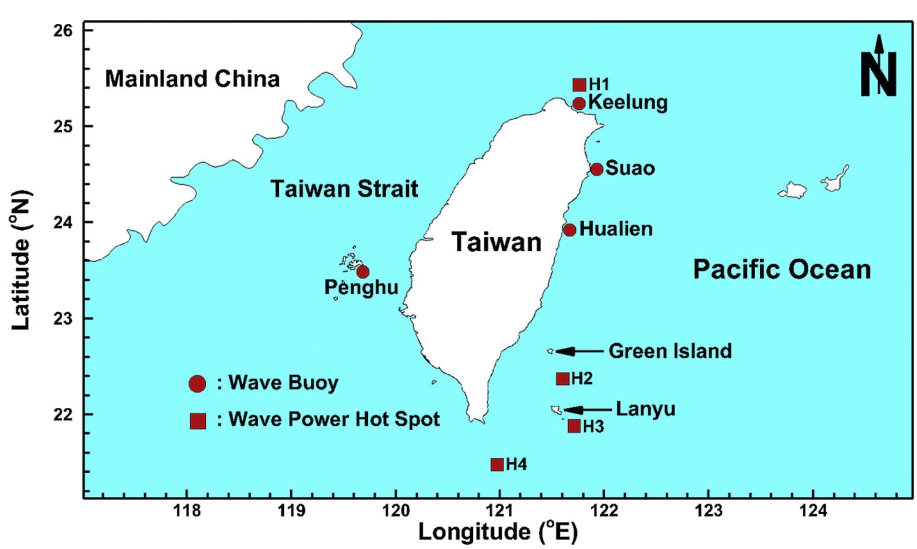

Fig. 1. Location of the study area and wave buoy. The cyan area represents the ocean, while white areas are land.