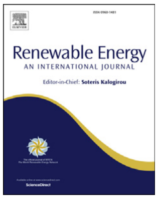
Renewable Energy 101 (2017) 603–616

Contents lists available at ScienceDirect

Renewable Energy

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



# Assessing the influence of sea level rise on tidal power output and tidal energy dissipation near a channel

Wei-Bo Chen [a], Wen-Cheng Liu [b, c, *]

[a] National Science and Technology Center for Disaster Reduction, New Taipei City 23143, Taiwan
[b] Department of Civil and Disaster Prevention Engineering, National United University, Miaoli 36063, Taiwan
[c] National Applied Research Laboratories, Taiwan Typhoon and Flood Research Institute, Taipei 1009, Taiwan

## ARTICLE INFO

*Article history:*
Received 30 March 2016
Received in revised form
10 September 2016
Accepted 14 September 2016

*Keywords:*
Sea level rise
Unstructured-grid
Depth-averaged numerical model
Tidal energy dissipation
Tidal power output
Penghu channel

## ABSTRACT

The influence of sea level rise on tidal power output and tidal energy dissipation is investigated by means of numerical simulations. The hydrodynamics in the Taiwan Strait were simulated using a new unstructured-grid, depth-averaged numerical model. Eight tidal constituents ($M_2$, $S_2$, $N_2$, $K_2$, $K_1$, $O_1$, $P_1$, and $Q_1$) were used to specify the open boundary conditions to drive the model. The observed data, including the time-series water level and tidal current, were used to validate the numerical model. The model results were in reasonable agreement with the measured data. The values of root mean square error (RMSE) for water level and tidal current are in the ranges of 0.06–0.19 m and 0.12–0.20 m/s, respectively. Moreover, the modeling amplitudes for eight tidal constituents determined using the present model were also similar to those determined using the regional inverse tidal model. The model predicted results indicated that the Penghu Channel is an appropriate location for deploying a tidal power plant because of its deep water (>100 m) and fast tidal current (>1.5 m/s). Furthermore, four sea level rise (SLR) scenarios were adopted to investigate the influence of SLR on tidal energy dissipation and tidal power output in the Penghu Channel. The simulation results showed that the total tidal energy dissipation was 11.23 GW for the baseline condition and increased corresponding to different SLR scenarios. The mean tidal power output was 42.15 MW when the additional turbine friction coefficient was set to 0.225. The extractable tidal energy increased by 1.62 MW, 2.09 MW, 2.63 MW, and 3.52 MW for SLR values of 0.87 m, 1.11 m, 1.40 m, and 1.90 m, respectively. We found that sea level rise increased tidal energy dissipation and energy output in the Penghu Channel.

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## 1. Introduction

The increased attention on global warming and the dependence on fossil fuels have stimulated interest in using renewable resources to achieve sustainable power production. Ocean and tidal currents are obvious carriers of large amounts of energy. Over the years, academia and industry have expended considerable efforts to find better ways to generate electricity from this source [1].

Renewable energy sources are both unreliable and intermittent, creating problems in power delivery and affecting the economic viability of projects. Tidal currents are recognized as a resource that can be exploited for sustainable generation of electric power. The high load factors resulting from the fluid properties and the predictable resource characteristics make tidal currents particularly attractive for power generation. These two factors make electricity generation from tidal currents much more appealing compared to other renewable energy sources. Furthermore, with a suitably chosen limited rated power of each device, tidal currents offer a relatively high capacity factor [2], which is important for the economic viability of any renewable energy project [3].

Due to increasing greenhouse gas emissions, global warming is expected to be more intense during the next century [4]. This warming will very likely influence natural processes and human activities. Sea level rise due to climate change is a serious threat to countries with heavy concentrations of population and economic activity in coastal regions. It will cause flooding of coastal areas, erosion of sandy beaches, and the destruction of harbor constructions. However, the potential influence of sea level rise on tidal energy at specific locations remains unclear.

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[*] Corresponding author. Department of Civil and Disaster Prevention Engineering, National United University, Miaoli 36063, Taiwan.
*E-mail address:* wcliu@nuu.edu.tw (W.-C. Liu).

http://dx.doi.org/10.1016/j.renene.2016.09.024
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Many researchers have studied how much tidal energy can be extracted from a specific site with a certain characteristic geometry, for example, in a simple uniform channel [5], a channel with a varying cross section linking two large water bodies [1,6,7], a channel connecting a bay to a large basin [8,9], or sites where the flow is less restricted such as the accelerated flow around headlands [10–15]. Recently, a few reports have started to focus on investigating the impact of sea level rise on the tidal energy distribution using numerical models [16,17].

The Penghu Islands have a population of about 100,000. The Magong city among the Penghu Island is the largest city, the largest port, and the only one airport (shown in Fig. 1a). The Chienshan Power Plant is not the only major power plant in Penghu Island but also the largest diesel fuel-fired power plant in Taiwan. The total capacity of power generation is 140 MW. Chienshan Fish Port is the nearest port to the Chienshan Power Plant, and therefore plays a role in shipping fuel material for power plant. According to hydrographic data measured by Wang and Chern [18] and Xiao and Cai [19], the northward flow is the major inflow entering the Taiwan Strait. The Penghu Channel is a funnel-shaped depth channel located between Penghu Islands and the Island of Taiwan. It is about 40 km wide and 100 m deep to the north, and 80 km and 200 m deep to the south and there is a persistent northward subtidal flow in Penghu Channel throughout a year [20].

The objective of this paper is to investigate the influence of sea level rise on tidal stream energy resources around the Penghu Islands and on tidal energy dissipation in the Penghu Channel using a refined three-dimensional hydrodynamic model. The model was validated with the observed water level and tidal current to ensure the model's capability. The model was then used to calculate the distributions of current and tidal energy dissipation and to evaluate the tidal stream energy and the tidal energy dissipation in the Penghu Channel subject to different sea level rise scenarios.

## 2. Methodology

### 2.1. Sea level rise projection

Changes in sea level occur over a broad range of temporal and spatial scales with many contributing factors, making it an integral measure of climate change [21,22]. The primary contributors to contemporary sea level change are the expansion of the ocean as it warms and the transfer of water currently stored on land to the ocean, particularly from land ice (glaciers and ice sheets) [23]. Observed sea level rise (SLR) rates vary greatly depending on the time period studied. For example, Church and White [24] reported that the average global rate of sea level rise was 1.7 mm yr$^{-1}$. In the last decade, an accelerated rate of 3.1 mm yr$^{-1}$ was observed [25]. IPCC estimates of SLR over the 21st century suggest an average rate of 1.8–5.9 mm yr$^{-1}$ [26]. The SLR of 0.2–2 m estimated for the year 2100 may have a large impact on regional tides [27,28]. Other research incorporates uncertainty in future estimates, suggesting that during previous natural de-glaciations, higher rates of 16 mm yr$^{-1}$ have occurred [29], and for the next century, the SLR is suggested to be 15–20 mm yr$^{-1}$ [30,31].

The purpose of this study is to identify the response of tidal energy at a specific site to potential future SLR based on hypothetical increases of mean sea level. However, the projections of SLR for the 21st century vary widely, ranging from several centimeters to more than a meter. According to different reports from literature, we selected four relative sea level rise scenarios over the next century, as shown in Table 1. The SLR rates for scenarios SLR087, SLR111, SLR140, and SLR190 represent 0.87, 1.11, 1.40, and 1.90 mm yr$^{-1}$, respectively.

### 2.2. Hydrodynamic model

A new unstructured-grid hydrodynamic model, the semi-implicit cross-scale hydroscience integrated system model (SCHISM) [32], has been used to simulate the hydrodynamics, including the water level and tidal current, for the Taiwan Strait. SCHISM is a modeling system that is an evolution of the original SELFE model [33]. Similar to the SELFE model, SCHISM is based on unstructured grids and is designed for simulating hydrodynamics in the ocean, coast, and river with its two-dimensional barotropic version. A highly efficient, parallel computing, robust and accurate semi-implicit finite-element/finite-volume method with an Eulerian-Lagrangian algorithm is implemented in SCHISM to solve Reynolds-averaged Navier-Stokes equations with the transport of heat, salt and tracers. The wetting and drying scheme is also naturally incorporated into the model. Due to the highly flexible framework of the models, SELFE and SCHISM have been widely used for solving cross-scale problems: general circulation [34], storm surges [35], tsunami hazards [36], water quality [37], oil spills [38], sediment transport [39], biogeochemistry [40,41], and physical processes of coupled tidal and non-tidal basins [42].

Since the feature of circulation at surface is quite similar to that at bottom in the Taiwan Strait during the period of spring (from March to May) [43], a two-dimensional version of SCHISM, SCHISM 2D, is employed in the present study. The governing equations of SCHISM 2D with hydrostatic form and Boussinesq approximation in the Cartesian coordinate system are given as:

$$\frac{\partial \eta}{\partial t}+\frac{\partial uH}{\partial x}+\frac{\partial vH}{\partial y}=0 \tag{1}$$

$$\frac{Du}{Dt}=fv-\frac{\partial}{\partial x}\left\{g\left(\eta-\alpha\widehat{\psi}\right)+\frac{P_A}{\rho}\right\}+\frac{\tau_{sx}-\tau_{bx}}{\rho H} \tag{2}$$

$$\frac{Dv}{Dt}=-fu-\frac{\partial}{\partial y}\left\{g\left(\eta-\alpha\widehat{\psi}\right)+\frac{P_A}{\rho}\right\}+\frac{\tau_{sy}-\tau_{by}}{\rho H} \tag{3}$$

where $\eta(x,y,t)$ is the free-surface elevation; $u(x,y,t)$ and $v(x,y,t)$ are the horizontal velocity in the $x$ and $y$ directions, respectively; $f$ is the Coriolis factor; g is the acceleration due to gravity; $\widehat{\psi}$ is the earth's tidal potential; $\alpha$ is the effective earth elasticity factor; $\rho$ is the density of water; $P_A(x,y,t)$ is the atmospheric pressure at the free surface; $\tau_{sx}$ and $\tau_{sy}$ are the wind shear stresses in the $x$ and $y$ directions, respectively; $\tau_{bx}$ and $\tau_{by}$ are the bottom shear stresses in the $x$ and $y$ directions, respectively; and $H=\eta+h$, where $h(x,y)$ is the bathymetric depth. The formulas of the bottom shear stresses are as follows:

$$\tau_{bx}=\rho C_d\sqrt{u^2+v^2}\,u \tag{4a}$$

$$\tau_{by}=\rho C_d\sqrt{u^2+v^2}\,v \tag{4b}$$

where $C_d$ is the bottom drag coefficient, which can be parameterized using the Manning formulation:

$$C_d=gn^2\Big/H^{1/3} \tag{5}$$

where $n$ is Manning's roughness coefficient. SCHISM 2D uses this hybrid bottom friction formulation to represent the bottom shear stress. This approach provides a depth-dependent bottom drag coefficient to allow large values for shallow areas and smaller values for deeper areas.

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