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National geodatabase of ocean current power resource in USA

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ABSTRACT

Ocean currents represent an alternative source of clean energy given their inherent reliability, persistence and sustainability. The general ocean circulation is characterized by large rotating ocean gyres resulting in rapid ocean currents along the western boundaries because of the Coriolis Effect. The Gulf Stream system is formed by the western boundary current of the North Atlantic Ocean flowing along the east coast of the United States, and is of particular interest as a potential energy resource for the United States. This study presents a national database of ocean current kinetic energy resource derived from seven years of numerical model simulations to help advance awareness and market penetration for ocean current energy. A web based GIS interface is provided for dissemination of the national energy resource data: http://www.oceancurrentpower.gatech.edu/. The website includes GIS layers of computed monthly and yearly mean ocean current speed and associated power density along the coastlines of the United States, as well as joint and marginal probability histograms for current velocities at a variable horizontal resolution of 4–7 km. Various tools are provided for viewing, identifying, filtering and downloading the data from this website. The Gulf Stream system, especially the Florida Current, concentrates the highest kinetic power density ($>2000\ \mathrm{W/m^2}$). The majority of the kinetic power and its variability are only present in relatively shallow water given the strong correlation with the surface wind stress. The kinetic energy flux in the Florida Current is estimated over 30 years to provide temporal variability of the undisturbed kinetic energy with high statistical significance. Available power of approximately 5 GW associated with the undisturbed natural flow condition from the Gulf Stream system is predicted based on hypothetical turbine parameters. Successful development of renewable energy generation requires further studies to account for more precise technical, economic and environmental constraints.

Contents

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1. Introduction

There is a growing interest in renewable energy around the world. Concerns about environmental pollution and climate change are among the driving forces for seeking affordable and environmentally friendly energy alternatives [1]. The decrease in fossil fuel reserves makes renewable energy attractive to both the government and the industry as the importance of renewable energy is increasingly recognized. In the past three decades global energy consumption almost doubled [2], while some predict the global fossil fuel reserves may be exhausted within a century [3]. Some countries are also seeking energy independence by reducing fossil fuel imports from foreign regions and developing domestic alternatives of clean energy. Renewable energy has great benefits compared to fossil fuels, including environmental improvement, fuel diversity, and national security if supplies cover a significant portion of the country's energy demands. Furthermore, the investment into the renewable energy industry will most likely be spent on materials and infrastructure rather than on energy imports, thereby spurring local economies through the creation of jobs [4,5].

The world's oceans cover more than 70% of the earth's surface and are a promising reservoir of alternative energy resources. Energy production from the ocean presently constitutes a negligible portion of our daily energy supply, while the worldwide electricity produced by ocean based devices is predicted to reach more than 7% by 2050 [6]. In countries with ocean access, coastal areas concentrate a wealth of natural and economic resources and are typically among the most developed areas in a country. Renewable energy from coastal and offshore regions is well positioned to supply countries' most populated areas if efficient harvesting is feasible.

Ocean currents are the continuous flow of ocean water in certain directions, and can vary greatly in terms of dominating driving forces, spatial locations, temporal and spatial scales. Fast moving ocean currents are rich in hydrokinetic energy. Since water is about 800 times denser than air, ocean currents of about 1/9 the wind speed carry comparable kinetic power density to wind. The major driving forces for large scale currents (on the order of 1000 km length-scale) are wind stress, and temperature and salinity differences (or associated density differences). Besides, meso-scale (on the order of 100 km length-scale) ocean currents can also be driven by tides, river discharge and pressure gradients (generated by sea surface slope setup from coastal long waves, for example). Among these forces, only the astronomical tidal forcing is deterministic, and thus allows for accurate forecasting. Tidal forcing, however, has a negligible contribution on the Gulf Stream ocean current system [7,8]. Therefore, this study only examines the non-deterministic forces, among which the most important are wind and density differences, and uses a probabilistic approach to define the ocean currents.

Surface ocean currents are generally wind driven and develop their typical clockwise spirals in the northern hemisphere and counter-clockwise rotation in the southern hemisphere because of the imposed wind stresses. The Gulf Stream system exemplifies wind driven currents in the northern hemisphere intensified at the western boundary of the Atlantic Ocean because of the Coriolis effect. Beginning in the Caribbean and ending in the northern North Atlantic, the Gulf Stream is one of the world's most intensely studied ocean current systems. On average, the Gulf Stream is approximately 90 km wide and 1000 m deep. The current speed is fastest near the surface with the maximum speed typically exceeding 2 m/s [9–11]. The Gulf Stream system's time scales vary from seasonal (stronger in the fall and weaker in the winter) to weekly [12–14]. Stronger meandering occurs primarily downstream of Cape Hatteras, North Carolina.

An ocean current energy converter extracts and converts the mechanical energy of the current into a transmittable energy form such as electricity. A variety of conversion devices have been proposed or are currently under active development. Such devices include water turbines similar to scaled wind turbines driving a generator via a gearbox, and oscillating hydrofoils driving a hydraulic motor. The available in-stream kinetic power per unit area, or power density P_{stream} from ocean currents, is calculated using the following equation:

$$P_{stream} = \frac{1}{2}\rho V^3 \quad (1)$$

where ρ is the density of water and V is the magnitude of the current velocity. This equation represents the power available at the individual device level.

The total power extraction potential from ocean currents, however, does not simply correspond to the superposition of individual power densities from multiple devices. The dynamics of ocean circulation and accumulative effects of converters need to be considered. A number of ocean current energy assessments have been performed in the past to evaluate the power potential of the Gulf Stream system. The earliest systematic studies date back to the 1970s. A research project named “Coriolis Program” predicted that an amount of about 10 GW of hydrokinetic power could be extracted from the Gulf Stream using turbines [15]. A more conservative prediction suggested an amount of up to 1 GW of kinetic energy can be extracted from the Gulf Stream by turbine arrays without seriously disrupting climatic conditions [16]. However neither study elucidated on the details of their resource estimates. A recent study by Duerr and Dhanak [17] considered a fraction of the undisturbed kinetic power density in the Gulf Stream as equivalent to the available power potential. They estimated approximately 20–25 GW of available hydrokinetic power in the Florida Current based on the computer model Hybrid Coordinate Ocean Model (HYCOM) data. Duerr and Dhanak [17] further stated that the power potential reduces to 1–4 GW if some operational constraints are applied. Yang et al. [18] concluded that kinetic power extraction potential from ocean currents should not be considered equivalent to the undisturbed power density, and the accumulative effect of power extraction on the flow itself needs to be considered. By using a simplified ocean circulation model and including the cumulative effect from power extraction, Yang et al. [19] estimated the upper limit of the theoretical power potential from the Florida Current portion of the Gulf Stream system to be approximately 5 GW for average flow conditions.

The present study provides the characterization of ocean currents along the coasts of the United States from a probabilistic perspective with an emphasis on the energetic Gulf Stream system. A GIS database with a web interface disseminates data to interested parties and the general public. The kinetic energy flux is considered a primary indicator of the kinetic energy reserve, and therefore 30 years of kinetic energy flux time series are predicted and used to provide estimates of the temporal