Renewable Energy 80 (2015) 737–745

Contents lists available at ScienceDirect

Renewable Energy

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

Site selection of ocean current power generation from drifter measurements

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ARTICLE INFO

Article history:
Received 8 January 2014
Accepted 2 March 2015
Available online

Keywords:
SVP drifter
Ocean current
Power generation
The East Asia
Kuroshio

ABSTRACT

Site selection of ocean current power generation is usually based on numerical ocean calculation models. In this study however, the selection near the coast of East Asia is optimally from the Surface Velocity Program (SVP) data using the bin average method. Japan, Vietnam, Taiwan, and Philippines have suitable sites for the development of ocean current power generation. In these regions, the average current speeds reach 1.4, 1.2, 1.1, and 1.0 m s^{-1}, respectively. Vietnam has a better bottom topography to develop the current power generation. Taiwan and Philippines also have good conditions to build plants for generating ocean current power. Combined with the four factors of site selection (near coast, shallow seabed, stable flow velocity, and high flow speed), the waters near Vietnam is most suitable for the development of current power generation. Twelve suitable sites, located near coastlines of Vietnam, Japan, Taiwan, and Philippines, are identified for ocean current power generation. After the Kuroshio power plant being successfully operated in Taiwan, more current power plants can be built in these waters.

1. Introduction

Ocean current power is generated from the kinetic energy of ocean currents with less uncertainty than the wind, wave and solar power, and has the high load capacity resulting from the high density of fluid (seawater) [1–3]. Electric power generation from global ocean currents has enormous potential. In 2000, Blue Energy, Inc., estimated that global ocean currents have capacity over 450 GW and represent a market of approximately US$550 billion per annum (assuming purchase price per kWh = US$0.1395) [4]. However, it is noted that devices which extract power from a fluid's momentum (e.g. a tidal turbine or wind turbine) can realistically reach an efficiency up to 50% (the Betz limit is a bit higher, but not by a great deal).

There are many world-wide sites with tidal velocities of 2.5 m s^{-1} and greater. Countries with an exceptionally high resource include the UK, Italy, Philippines, and Japan [4]. But strong tidal currents only last for a short time period, and cannot provide a stable power supply. The strong Florida Current and Gulf Stream move close to the shore of the United States [5,6] in areas of high demand for power [4]. Earlier studies [7,8] indicated that the westward recirculations steadily increase the transport of the Gulf Stream from approximately 30 Sv (1 Sv = 10^6 m^3 s^{-1}) in the Florida Current to approximately 150 Sv at 55°W. The transport is around 20–30 Sv for the Kuroshio near Taiwan, and about 4–10 GW of ocean current power are generated with the flow velocity of 1 m s^{-1} [9].

In Taiwan, the Kuroshio power plant of 30 MW was planned between Taitung and Green Island (~121.43°E, 22.70°N, see Fig. 1) [9]. The estimated annual net income of power plant is 488.58 million NTD (new Taiwan dollar, 1 USD ~ 31 NTD). The payback period is only 6.2 years. The estimated power plant life is 20 years. Thus, the Kuroshio power plant in Taiwan will be operated successfully in the future. Questions arise: Are there other sites or locations in the East Asia suitable for the development of the (Kuroshio) current power generation? If yes, where are these sites? Ocean flow measurement data is an important factor in selecting the site of ocean current power generation. The purpose of this paper is to determine possible sites of current power plant for technical and economic feasibility, and to develop a complete map of strong currents in the East Asia using the Surface Velocity Program (SVP) drifter data of Global Drifter Program (GDP). The GDP is the principle component of the Global Surface Drifting Buoy

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http://dx.doi.org/10.1016/j.renene.2015.03.003

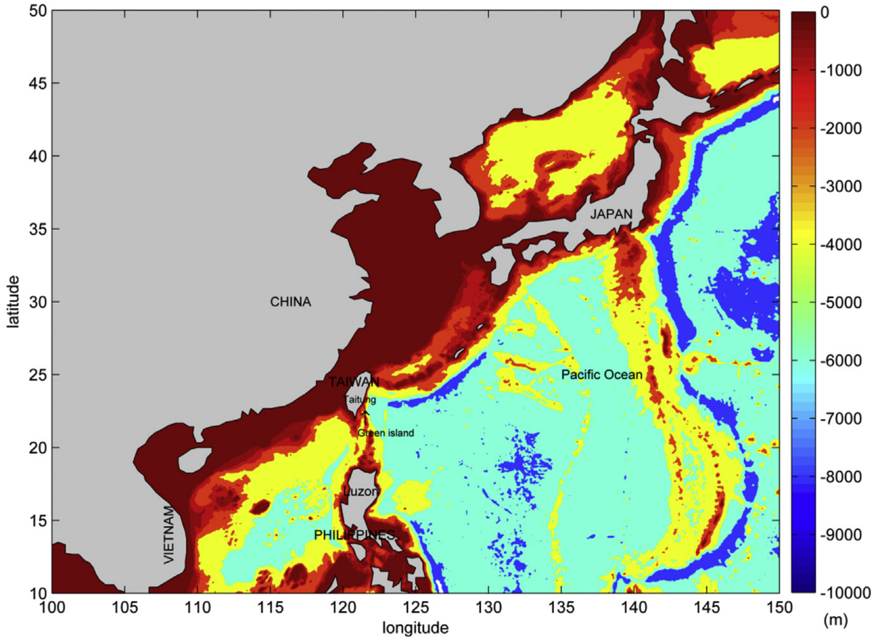

Fig. 1. Geography and bottom topography of the East Asia.

Array, a branch of the NOAA Global Ocean Observing System (GOOS) and a scientific project of the Data Buoy Cooperation Panel (DBCP).

2. Data and method

The NOAA Drifter Data Assembly Center (DAC) provides quality controlled data for velocity measurements. Upper ocean current velocities every 6 h can be obtained from the website: http://www.aoml.noaa.gov/phod/dac/dacdata.php (Accessed 25 Nov 2014). A total of 1883 drifters in the northwestern Pacific (10°–50°N, 100°–150°E) during 1985–2009 are used for this study (see Fig. 2). There are 1,029,889 six-hourly velocity observations of SVP drifters in the study area. All drifters had a holey-sock drogue centered at a nominal depth of 15 m. The 6 hourly velocities are obtained via 12 h centered differencing of the kriged positions [10]. The estimated accuracy of the velocity measurements using SVP drifters is 0.01 m s^{-1} with surface winds of 10 m s^{-1} [11].

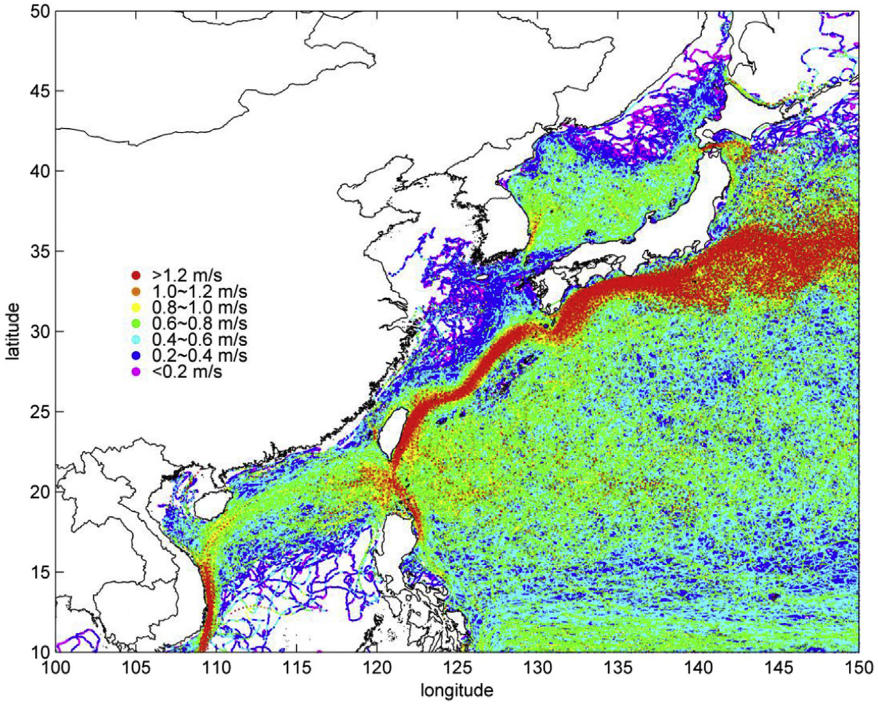

Fig. 2. Locations of drifters with color-coded in accordance with their 6-hourly instantaneous speed.

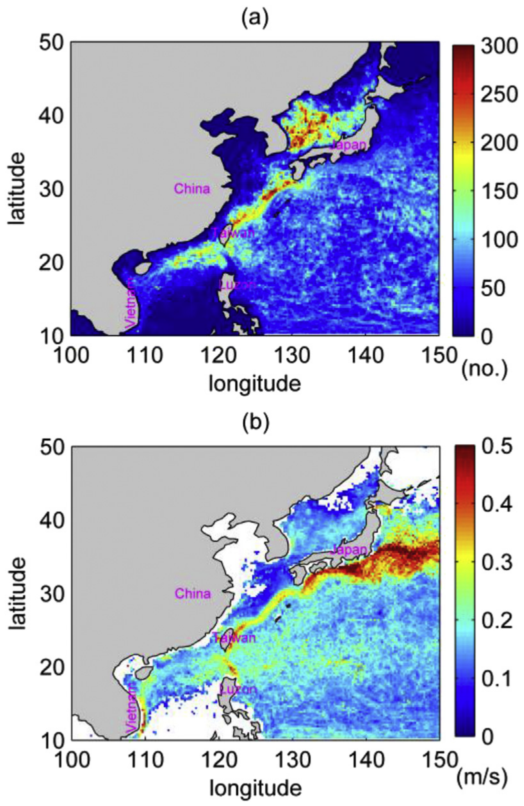

Fig. 3. (a) Numbers of data point in 0.25° × 0.25° bins and (b) their standard deviation (m s^{-1}).

3. Site selection

3.1. Four factors of site selection

Four factors related to the site selection of ocean current power generation [9] are (1) near coast, (2) shallow seabed, (3) stable flow velocity, and (4) high flow speed, respectively. Near-shore or shallow-water facilities require less cost of construction and maintenance. High and stable flow speeds can provide the great and steady power in comparison tidal current power generation (short period strong currents). The distance from shore (L) can be calculated from the coastline data of *NOAA National Geophysical Data Center* (*NGDC*). The depth (D) data can also be obtained from the NOAA/NGDC. The drifter locations and velocities can be downloaded online at the NOAA/DAC website. The ensemble of the individual drifter locations is plotted in Fig. 2 with color coded in accordance with the local instantaneous speed. The strongest current of the Northwestern Pacific is the Kuroshio. Formed from branching of the North Equatorial Current, the Kuroshio is intensified east of Luzon and Taiwan [12]. Fig. 3 shows the numbers of data point in 0.25° × 0.25° bins and their standard deviation. The ensemble mean current speed (Fig. 4) and velocity vectors (Fig. 5) are computed using the bin average method [13,14] in 0.25° × 0.25° bins and is shown only for bins with more than 7 observations. The Kuroshio axis is along the east coast of Luzon, Taiwan and Japan. Drifter-measured velocities (U) are often greater than 1.2 m s^{-1} in the Kuroshio axis (Fig. 2). Besides Kuroshio, there is a strong current with a velocity of 1.2 m s^{-1} in the South China Sea along the coast of Vietnam. Fig. 4 shows the average speeds of strong currents near Japan, Vietnam, Taiwan, and Philippines, reaching 1.4, 1.2, 1.1, and 1.0 m s^{-1}, respectively. A complete map of strong ocean currents is obtained from 25 years (1985–2009) of direct velocity measurements for the site selection of ocean current power generation in the East Asia. Thus, Japan, Vietnam, Taiwan, and Philippines (Figs. 4 and 5) have a good condition ($U > 1.0$ m s^{-1}) for developing the ocean current power generation.

Percentages of current speed greater than 1 m s^{-1} (i.e., percentage of good quality of power supply) in 0.25° × 0.25° bins (Fig. 6) can reach 55–80% (~13.2–19.2 h/day) in some locations near Japan, Taiwan, Vietnam, and Philippines. Fig. 7 shows the seasonal variation of current speeds with the mean current speeds in winter half-year (from October to March) and in summer half-year (from April to September). The locations of strong currents along the east coast of Luzon, Taiwan and Japan are almost the same

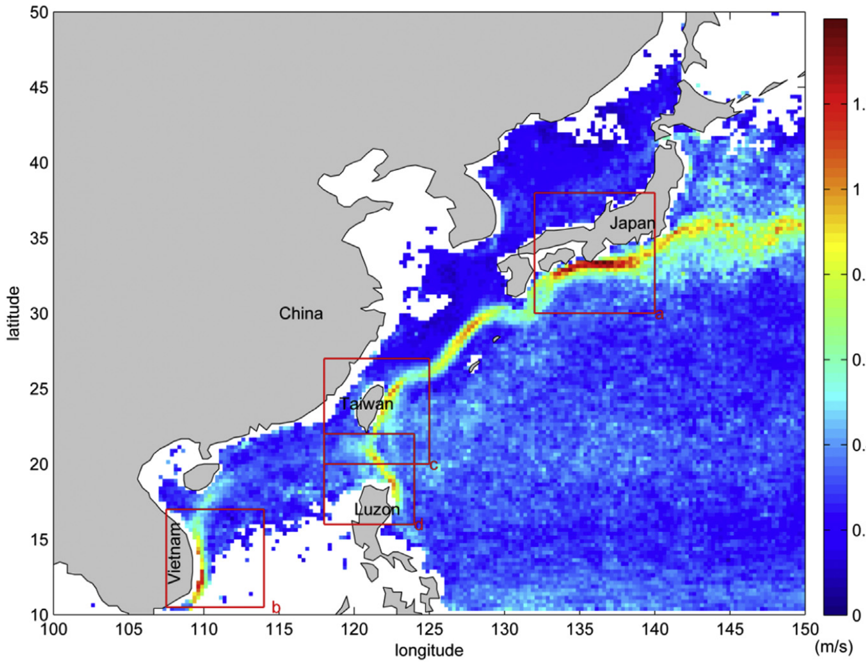

Fig. 4. Averaged drifter speeds (unit: m s^{-1}) in 0.25° × 0.25° bins.

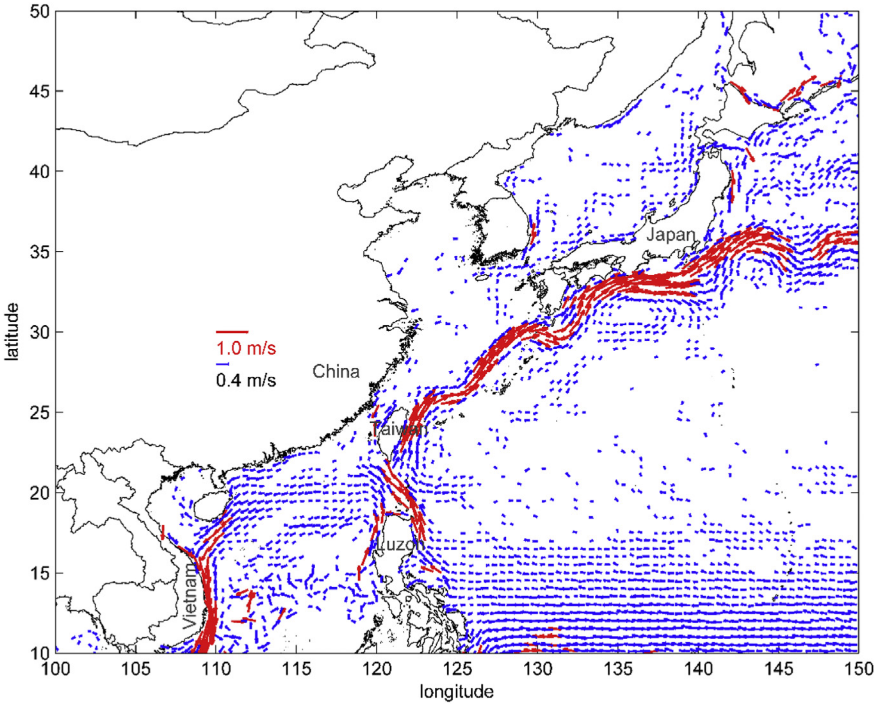

Fig. 5. Averaged drifter velocities. Speeds higher and lower than 0.4 m s^{-1} are shown in red and blue, respectively.

in winter half-year as in summer half-year. But, the mean current speeds are 0.1–0.2 m s^{-1} greater in summer half-year than in winter half-year. Thus the power plant will generate more electricity in summer half-year. The observed current data near Vietnam is less in summer half-year, but strong currents (>1.0 m s^{-1}) were measured along the east coast of Vietnam in both winter and summer half-years.

3.2. Index I

In the recent study [4], the mid-water energy production units (EPUs) with a retention–transmission cable system will lie 6–37 km offshore of southeast Florida in about 100–500 m of water. In Taiwan, the anchor system for the deep water of more than 500 m is also being developed for Kuroshio power plant near

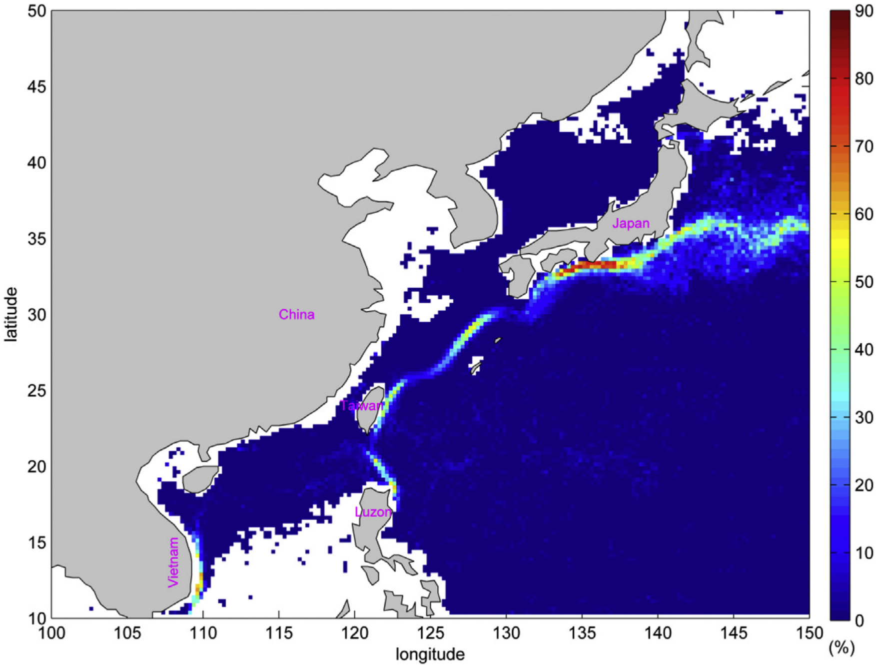

Fig. 6. Percentages of current speed greater than 1 m s^{-1} in 0.25° × 0.25° bins.

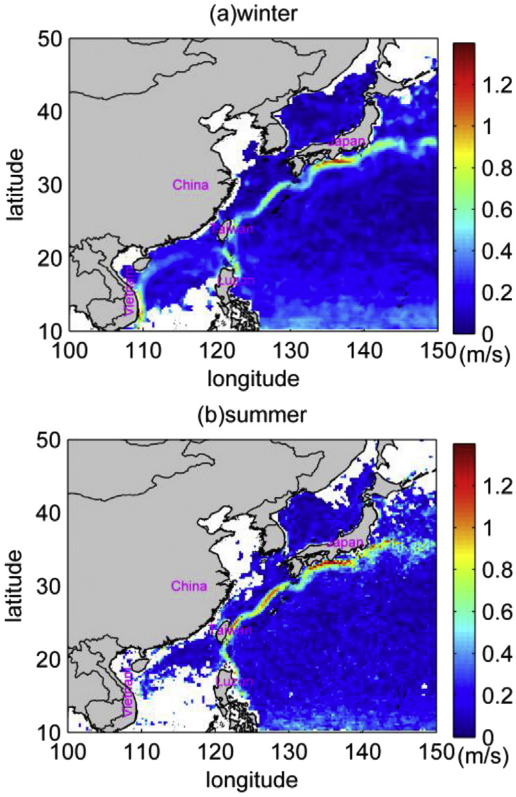

Fig. 7. Averaged drifter speeds (unit: m s^{-1}) (a) in winter half-year and (b) in summer half-year.

Taitung [9]. The sea depth near Taitung is often more than 500 m. Thus the anchor chain length must be over a thousand meter. The relay platform is a flexible structure floating in the deep sea [15]. Existing turbines with vertical axis may be suitable for the Kuroshio plant [9]. Because its construction and maintenance cost is lowest for deep-sea engineering. Thus turbine generators and anchor system for the deep water may be able to work successfully in the next few years. In order to objectively consider four factors of site selection, an index I related to the site selecting of current power generation is designed as

$$I = \sum_{i=1}^{4} I_i w_i, \tag{1}$$

$$I_1 = [1 - (L/50\ \text{km})], \quad I_2 = [1 + (D/1000\ \text{m})],$$
$$I_3 = P/100\%, \quad I_4 = U/1.4\ \text{m s}^{-1}.$$

Here, P is the percentage of current speed greater than 1 m s^{-1}; U is the current speed. The choice of constants ($L = 50$ km, $D = 1000$ m, and $U = 1.4$ m s^{-1}) is based on the aforementioned studies [4,9] and a maximum of mean speeds in Fig. 4. Each of these indices was weighted to reflect their impact on revenue, capital costs, and maintenance costs, etc. According to the recent study [9], the plant engineering of a 30 MW pilot plant needs a total investment fund of 2.3 billion NTD. The operation expenses, include maintenance costs, personnel costs, insurance, etc., is 0.12 billion NTD dollars a year. If the plant life is 20 years, the operation expenses of 20 years is 2.4 billion NTD. Thus the capital and maintenance costs of 20 years are about 4.7 billion NTD. The sales income of a 30 MW plant is 30,000 kW × 20 (years) × 365 (day/year) × 24 (h/day) × 0.7 (assuming capacity = 70%) × 2.8 (NTD/kWh, purchase price per kWh = 2.8 NTD) = 10.3 billion NTD [9]. Thus, percentages of expenditure and income were 31% (4.7 billion NTD) and 69% (10.3 billion NTD), respectively. I_1 and I_2 reflect their impact on expenditure. I_3 and I_4 reflect their impact on revenue. Hence w_1 and w_2 are set to be 15.5%, then w_3 and w_4 are set to be 34.5%. Each index of site selection ranged from 0 to 1. The variations of I_1, I_2, I_3, and I_4 are shown in Fig. 8. The variation of the index I is shown in Fig. 9. The higher the index value is, the more suitable the site of ocean current power generation selects. The recent study [9] suggests the four

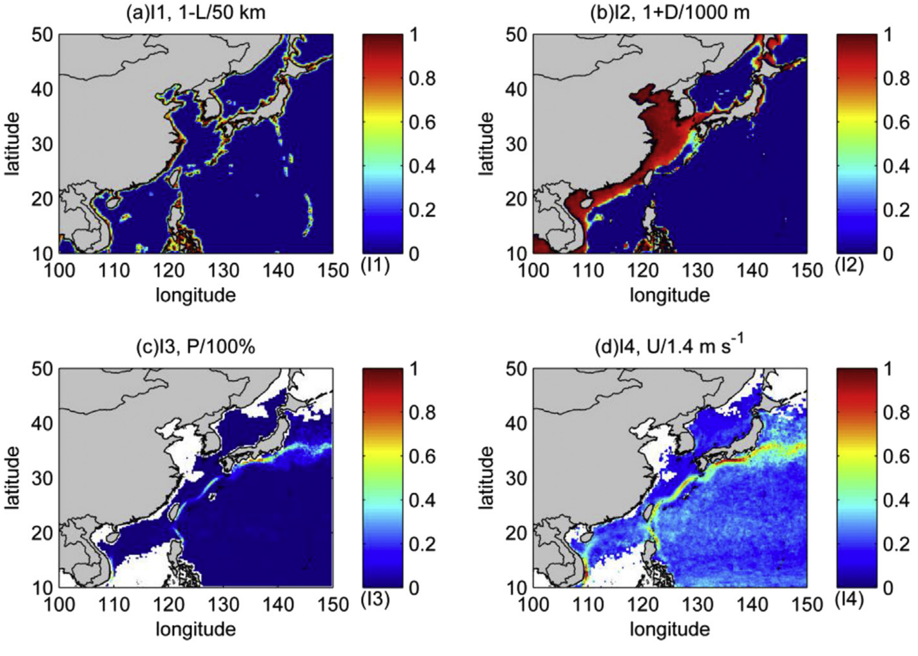

Fig. 8. Distributions of index I_1, I_2, I_3, and I_4 in the East Asia.

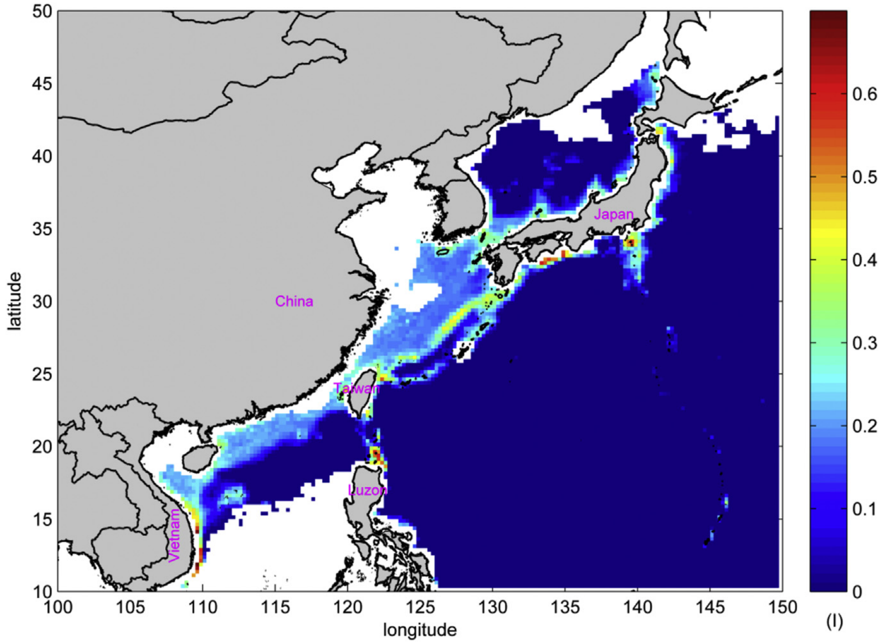

Fig. 9. Distribution of index *I* in the East Asia.

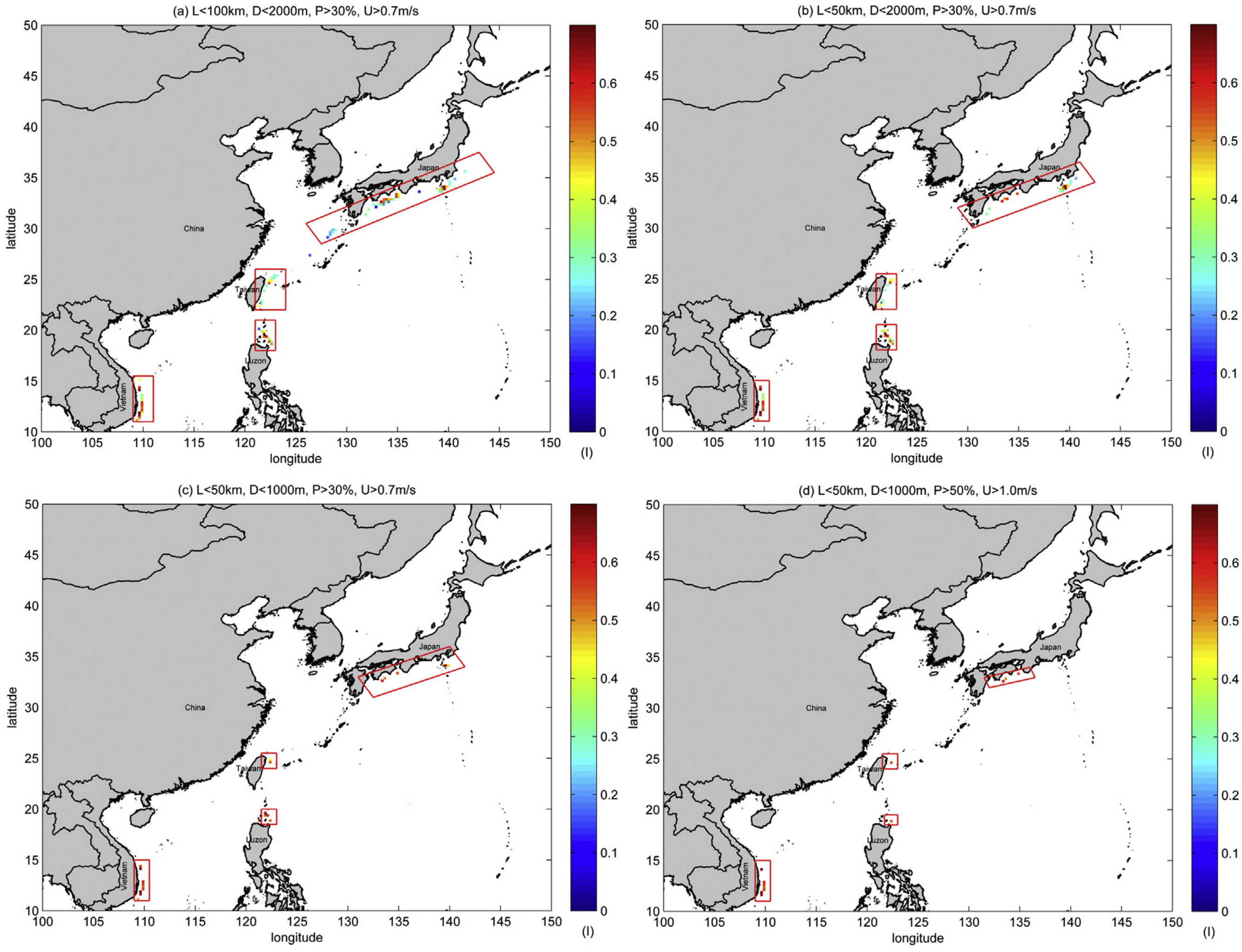

Fig. 10. Selected sites in conditions of (a) $L < 100$ km, $D < 2000$ m, $P > 30\%$, $U > 0.7$ m s^{-1}, (b) $L < 50$ km, $D < 2000$ m, $P > 30\%$, $U > 0.7$ m s^{-1}, (c) $L < 50$ km, $D < 1000$ m, $P > 30\%$, $U > 0.7$ m s^{-1}, and (d) $L < 50$ km, $D < 1000$ m, $P > 50\%$, $U > 1.0$ m s^{-1}.

Table 1
Twelve suitable locations ($L < 50$ km, $D < 1000$ m, $P > 50\%$, and $U > 1$ m s^{-1}) for development of ocean current power generation.

Site	Location	Distance, L (km)	Depth, D (m)	Percentage, P (%)	Speed, U (m s^{-1})
V1 (Vietnam)	109.50°E, 14.00°N	19 km	−160 m	55% (>1 m s^{-1})	1.05 m s^{-1}
V2 (Vietnam)	109.75°E, 12.75°N	33 km	−960 m	62%	1.26 m s^{-1}
V3 (Vietnam)	109.75°E, 12.50°N	33 km	−890 m	60%	1.20 m s^{-1}
V4 (Vietnam)	109.75°E, 12.25°N	39 km	−790 m	51%	1.20 m s^{-1}
V5 (Vietnam)	109.75°E, 12.00°N	46 km	−680 m	58%	1.25 m s^{-1}
V6 (Vietnam)	109.50°E, 11.75°N	28 km	−120 m	63%	1.23 m s^{-1}
V7 (Vietnam)	109.50°E, 11.50°N	38 km	−100 m	58%	1.12 m s^{-1}
J1 (Japan)	134.75°E, 33.25°N	41 km	−850 m	64%	1.15 m s^{-1}
J2 (Japan)	133.50°E, 32.75°N	41 km	−710 m	54%	1.05 m s^{-1}
J3 (Japan)	133.25°E, 33.50°N	38 km	−560 m	64%	1.13 m s^{-1}
T1 (Taiwan)	122.25°E, 24.50°N	29 km	−650 m	50%	1.01 m s^{-1}
P1(Philippines)	122.25°E, 18.75°N	23 km	−960 m	55%	1.05 m s^{-1}

factors of site selection in priority order: (1) near coast (I_1), (2) shallow seabed (I_2), (3) stable flow velocity (I_3), and (4) high flow speed (I_4). Thus the ranges of four factors (or four indexes, I_1–I_4) were limited to select suitable sites of ocean current power generation in the following paragraph. Firstly, 76 sites, which meet initial conditions ($L < 100$ km ($I_1 > -1$), $D < 2000$ m ($I_2 > -1$), $P > 30\%$ ($I_3 > 0.3$), and $U > 0.7$ m s^{-1} ($I_4 > 0.5$)), and their I values are shown in Fig. 10a. These sites located in the east of Vietnam, northeast of Luzon, east of Taiwan and south of Japan (in red boxes of Fig. 10a, in the web version). The site of Kuroshio power plant near Green Island in the recent study [9] is also selected in these conditions. If L is reduced to 50 km ($L < 50$ km; $I_1 > 0$), the selected sites become less in amount (46 sites), as shown in Fig. 10b. Shorter L will significantly reduce engineering and maintenance costs. The site of Kuroshio power plant near Green Island is still one of selected sites. If D is reduced from 2000 m to 1000 m ($D < 1000$ m; $I_2 > 0$), only 21 sites are selected, as shown in Fig. 10c. Selecting a site in shallower waters will greatly increase the chances of successful operation, because developing an anchor system for the shallower water is easier. As $D < 1000$ m, the site of Kuroshio power plant near Green Island is not selected. Finally, if P and U are increased to 50% and 1 m s^{-1} ($I_3 > 0.5$, and $I_4 > 0.714$), respectively, income and power generation of plant will greatly increase. In Fig. 10d, the most suitable sites are selected for the development of ocean current power generation in the East Asia. There are 12 sites are selected according to the conditions of $L < 50$ km, $D < 1000$ m, $P > 50\%$, and $U > 1.0$ m s^{-1}. The information of the 12 sites is listed in Table 1. There are seven sites (V1–V7) near Vietnam, three sites (J1–J3) near Japan, and 2 sites near Taiwan (T1) and Philippines (P1). Their index I values are 0.539–0.726 (V1–V7, Vietnam), 0.518–0.607 (J1–J3, Japan), 0.540 (T1, Taiwan), and 0.538 (P1, Philippines), respectively. This suggests that the most suitable region to develop the ocean current power generation is the shallow coastal water near Vietnam, and then is followed by Japan, Taiwan and the Philippines. The detail descriptions for each index are listed in Table 2.

In order to show clearly the correct position of 12 sites with strong currents, enlargements of mean current speed from Fig. 4 with the isobaths near Japan, Taiwan, Vietnam, and Philippines, respectively, are plotted in Fig. 11. Sites V1 (109.5°E, 14.0°N), V6 (109.5°E, 11.75°N) and V7 (109.5°E, 11.5°N) are selected approximately 30 km east of Vietnam on the shelf (Table 1 and Fig. 11a). Water depths at V1, V6, and V7 are only 160, 120, and 100 m, respectively (see Table 1). The three sites have higher I_2 values (0.84, 0.88, and 0.90), which are much greater than those of other sites. Then, V6, V1, and V7 have three highest I values (see Table 2). Thus the shallow seabed ($D < 200$ m) is an important parameter to influence the choice Vietnam over the others. Mid-water EPUs can work in approximately 100–500 m of water in recent study [4]. Thus it is easier to build a current power plant near Vietnam in the future. Sites V2–V5 are selected about 40 km east of Vietnam with the current speeds of about 1.2 m s^{-1} (U), and depths (D) of 700–900 m (see Table 1, and Fig. 11a). At these sites, there are stronger current speeds and deeper depths. Approximately 60% of observed speeds are greater than 1 m s^{-1} at these sites. Sites J1, J2, and J3 are selected about 40 km south of Shikoku, Japan with the U of 1.1 m s^{-1}, and D of 560–850 m (Fig. 11b). Site T1 is selected about 29 km east of Yilan, Taiwan (122.25°E, 24.5°N) with an average current speed of 1.0 m s^{-1} on the slope ($D \sim 650$ m) (Fig. 11c). About 50% of all measured currents speeds are greater than 1 m s^{-1}. Finally, site P1 near Philippines is selected about 30 km northeast of Palaui Island (122.5°E, 18.75°N) with an average current speed of 1.0 m s^{-1} (Fig. 11d). Approximately 55% of all observed speeds are greater than 1 m s^{-1}. Sites T1 and P1

Table 2
Index I for selecting the site of ocean current power generation.

No.	Site	I_1 [$1 - L/50$ km]	I_2 [$1 + D/1000$ m]	I_3 [$P/100\%$]	I_4 [$U/1.4$ m s^{-1}]	I
1	V6	0.44	0.88	0.63	0.88	0.726
2	V1	0.62	0.84	0.55	0.75	0.675
3	V7	0.24	0.90	0.58	0.80	0.653
4	J3	0.25	0.44	0.64	0.81	0.607
5	V2	0.34	0.04	0.62	0.90	0.583
6	V3	0.34	0.11	0.60	0.86	0.574
7	V5	0.09	0.32	0.58	0.89	0.571
8	J1	0.18	0.15	0.64	0.82	0.555
9	T1	0.42	0.35	0.50	0.72	0.540
10	V4	0.22	0.21	0.51	0.86	0.539
11	P1	0.54	0.04	0.55	0.75	0.538
12	J2	0.18	0.29	0.54	0.75	0.518

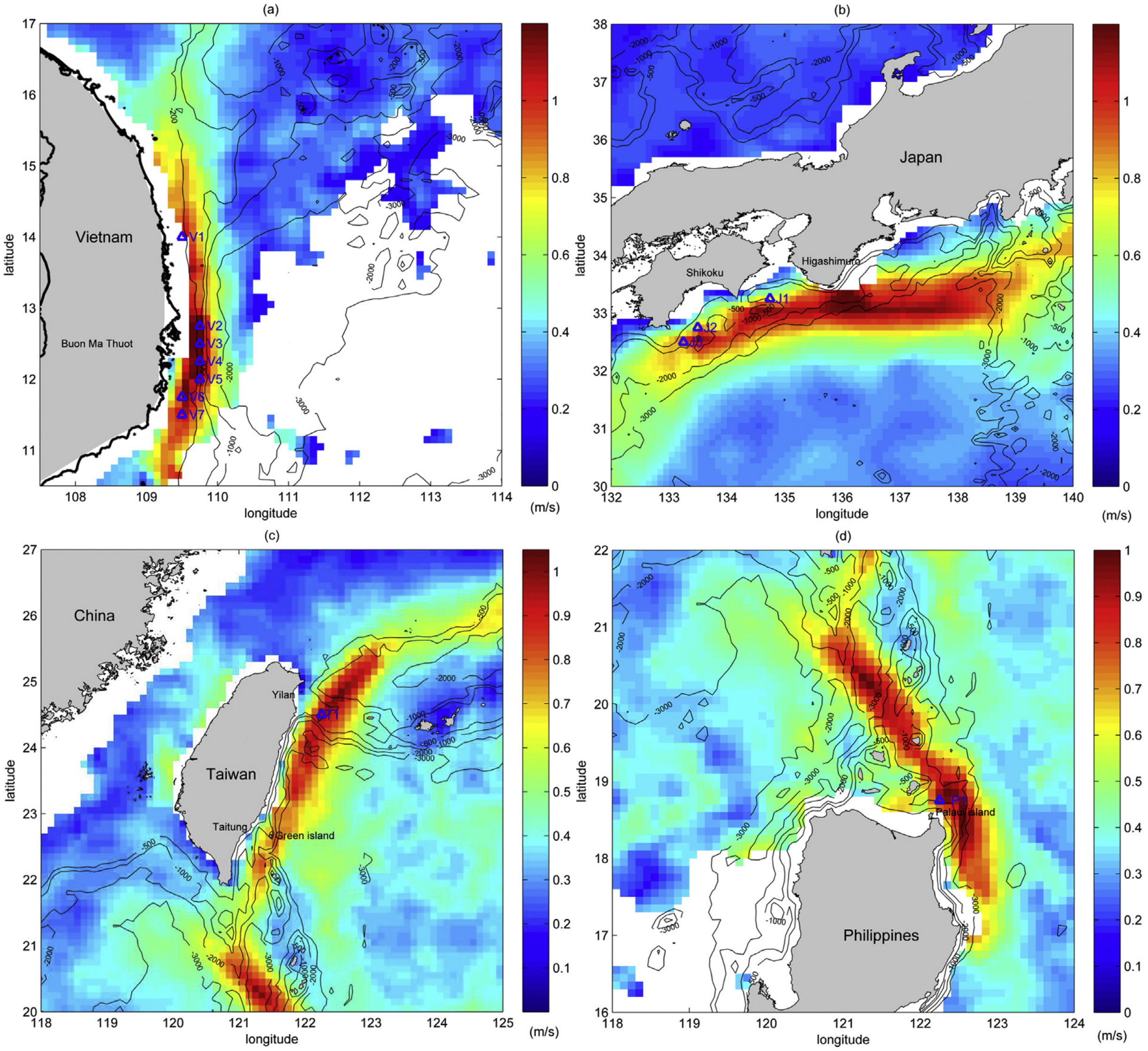

Fig. 11. Enlargement of bin-averaged speed (a) east of Vietnam, (b) south of Japan, (c) east of Taiwan, and (d) northeast of Philippines. The contour line is an isobath (unit: m).

located in the Kuroshio axis (see Fig. 11c and d). In Taiwan, the Kuroshio power generation was planned to build in the waters between Taitung and Green Island [9]. After the Kuroshio power plant is operated successfully in the near future, more current power plants can be built in the 12 suitable sites near Vietnam, Japan, Taiwan, and Philippines.

4. Summary

The charts of mean current speeds and 12 suitable sites in the East Asia are provided for the development of ocean current power generation from analyzing the SVP drifter current data (1985–2009). In the future, current power plants can be built in the regions of Vietnam, Japan, Taiwan, and Philippines. The United Nations Intergovernmental Panel on Climate Change (IPCC) has released its synthesis report, which can be obtained from http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_LONGERREPORT.pdf (Accessed 10 Dec 2014). The report warns that greenhouse gas levels are at their highest in at least 800,000 years, and continued emission of greenhouse gases will cause irreversible impacts for people and ecosystems. The application of ocean current power generation will help to reduce greenhouse gas emissions.

Acknowledgments

This research was completed with Grants from the Ministry of Science and Technology of Taiwan, Republic of China (MOST 102-2611-M-110-010-MY3). Peter C. Chu was supported by the Naval Oceanographic Office. We are grateful for the comments of anonymous reviewers.

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