

# Sailing Solar-Cell Raft Project and Weather/Marine Conditions in Low-Latitude Pacific Ocean

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## Abstract

Development of a huge wind-sailing solar cell raft (SCR) with its ultimate dimension 5 km×5 km is proposed, which can generate electricity, comparable to a 1000 MW nuclear power plant, in low-latitude Pacific Ocean. Sunshine energy of 8 kWh/m<sup>2</sup>/day or more is targeted as SCR navigates in fine weathers using weather satellites. The generated electricity will be transported by battery tankers loaded with a tremendous number of high energy-density batteries. Studies based on available database indicate that there are vast open seas in the tropical Pacific Ocean, where the maximum solar energy attains 7 kWh/m<sup>2</sup>/day on annual average and conditions of wind, wave and sea current are favorable for the solar energy system to operate.

*Key Words:* Low-latitude Pacific Ocean, Sailing raft, Sunray energy, Weather/Marine condition

## SAILING SOLAR CELL RAFT

Japan is a poor country in terms of domestic energy supply, depending 96% of its energy demand on imports from overseas. In a recent few years, the solar cell system is rapidly put into use worldwide in parallel with its innovations in the efficiency and the production technology. Despite its technological advantage, it is generally considered in Japan that the domestic capacity of the solar power generation, unlike desert countries, cannot be so large due to the cloudy and rainy climate and the small land area.

Let us recognize here that, instead of desert, Japan is fronting to vast open seas of the Pacific Ocean, which extend beyond the equator. We should be aware of a tremendous potential of solar energy in a scale incommensurably larger than that in the land area. The marine solar energy will be efficiently utilized by developing gigantic solar cell rafts (SCRs) of several kilometers square in dimension.

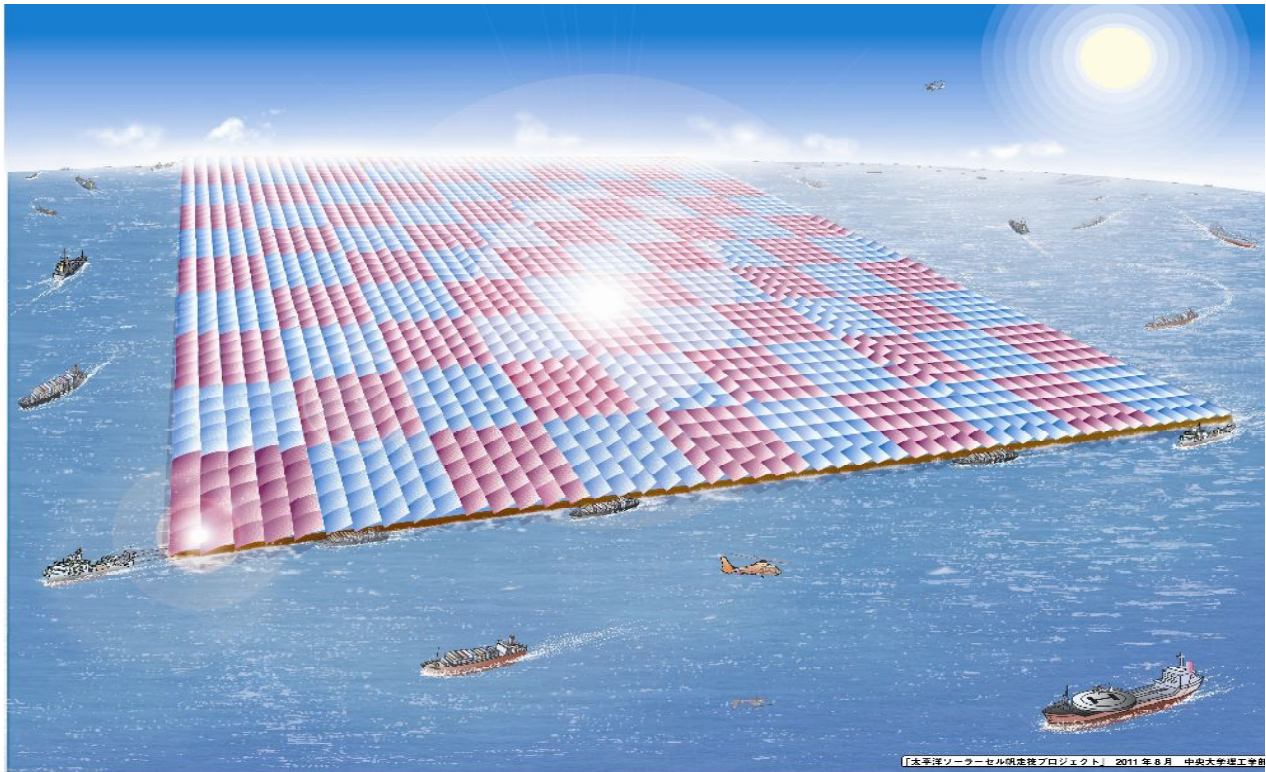


Fig. 1 Schematic view of sailing solar cell raft in the Pacific Ocean (Illustration by Civil & Envir. Eng. Dept, Chuo Univ.)

It is internationally accepted that any vessel can sail the open sea freely for commercial purposes. Although consensus has to be formed among international communities as well as with fishing and shipping industries, it may be said that the navigation in international open seas and hence the power generation during navigation is justified according to the international law. Making the most of the capability of weather satellites, the fleet can schedule a route in advance so as to secure maximum sunshine and favorable weather conditions, realizing high-efficiency solar cell power generation.

Let us imagine a huge solar cell raft of 5 km×5 km (25 km<sup>2</sup> in area) in ultimate dimension when it is realized eventually. If daily solar energy 8 kWh/m<sup>2</sup> (Wh=Watt×hour) and electrical conversion efficiency 12% (a modest value at present) are assumed, then the generated electricity per day will be

$$8 \text{ kWh/m}^2 \times 0.12 \times 25,000,000 \text{ m}^2 = 24,000 \text{ MWh.} \quad (1)$$

If this daily electric energy is divided by 24 hours,

$$24,000 \text{ MWh} / 24\text{h} = 1,000 \text{ MW.} \quad (2)$$

indicating that the SCR of this size can be comparable to a 1,000 MW nuclear power station that is continuous operation in 24-hours (Kokusho 2010). The energy efficiency of 8 kWh/day or more is targeted as the SCR navigate in the clear regions of using weather satellites. The navigation in search of maximum efficiency is possible only on the ocean and a great advantage over a land-fixed power generation.

There may be multiple options for transporting generated electricity to consumers. One is hydrogen gas produced by electrolysis of abundant sea water or its chemical compounds, which will be carried by tankers. Another possibility is to transport the energy directly in the form of electricity by battery tankers carrying tremendous number of high efficiency batteries to avoid the loss in converting the energy.

A similar idea on a marine solar power station was proposed by American and Japanese scholars just after the first oil crisis (Escher et al. 1977, Ohta 1978,), in that hydrogen is produced by the solar heat energy collected on a raft staying at a fixed location in the Pacific Ocean and transported by hydrogen tankers. This idea was followed by basic studies on the associated key technologies (e.g. Endo et al. 1982), but an actual research and development to realize this solar heat energy system have not yet started until today.

The energy system proposed here, differing from that mentioned above, is characterized by power generation using solar cells on a gigantic sailing raft, by making use of fast-developing solar cell technology in recent years and in near future. The energy capacity will eventually be as large as a nuclear power station for the sake of better economic performance in greater scale. Another big difference from previous similar ideas is that it is always sailing in open seas, though slowly, to pursue clear weather and favorable oceanic conditions to receive higher solar energy in calm seas. Its mobility is the greatest advantage of this system over a land-based mega-solar energy station. Impacts on marine lives due to covering sea surface and temporarily stopping sunshine can be minimized by sailing, non-stop though in slow speed. The sail should be energy-saving as much as possible using wind and sea-current. The navigation route is computerized in advance by using weather satellites and other information to maximize the total energy efficiency of the system and minimize impacts on other sea-traffics.

The gigantic solar cell raft may be composed of a number of raft units. If the size of the unit is chosen as 100 m × 100 m for instance, 2,500 units are needed to realize the 5 km square raft. The raft units are inter-connected by wires, pressure tubes, and electrical cables and the sailcloth should be designed in a way such that their angles can be controlled to a certain degree for low-speed, energy-saving wind sail.

A fleet consisting of the gigantic solar cell raft, mother ships and work-ships will be navigating together. The mother ships are in charge of total control of the system; navigation and solar power generation; by adjusting sailcloths and floats of all raft units, monitoring the generated electricity and transmitting it to battery tankers. The work-ships are in charge of repair and maintenance of the raft units.

If such a solar power system comes true, it will immensely help not only Japan but also other energy-poor countries be less dependent on fossil fuel and fulfill its international commitment to reduce the CO<sub>2</sub>-emission. Furthermore, it will provide opportunities for boosting economy and nurturing new green business world-wide. As indicated later, vast open sea extends in the north and south hemisphere in the low-latitude Pacific Ocean, vast enough for many countries to exploit solar energy for their own use.

## KEY TECHNOLOGIES TO BREAKTHROUGH

In order to realize the energy system, breakthroughs have to be made in three key technologies; the solar cell, the battery, and the raft unit. In the following, their individual perspectives are described.

### *Thin flexible Solar Cell*

A widespread sailcloth covered with thin flexible solar cells is essential to realize the proposed raft unit. Among various types of solar cells, a thin-film solar cell made of chemicals composed of copper, indium, gallium and selenium (CIGS) seems promising because of low material consumption and a potential for low production cost. A thin film of only 2 micron thick is enough to absorb the solar radiant energy because of its high absorbing coefficient for the visible ray. The current efficiency of 1 square-meter module of the cell is 10-12% yet, and a lot of potential for higher efficiency is still left because that of 1 square-centimeter cell is already as high as 20% (NEDO 2009, Niki et al. 2011). Another important feature of the thin film solar cell is the flexibility of its substrate. At this moment, however, flexible substrate materials are investigated so far mainly on stainless steel sheet (Niki 2011), and thin film solar cell module of high efficiency with flexible sailcloth serving as the substrate is yet to be developed. In 20 to 30 years, however, a lot of technical advances can be expected to realize a seamless solar cell sailcloth as large as 100 m square with the efficiency higher than 12 %.

### *High Energy Density Battery*

In the movable solar energy system proposed here, the generated energy will be transported directly

in the form of electricity by using high energy-density rechargeable batteries to avoid energy conversion loss. The forefront of the battery technology is and will be advancing with electric vehicles. At this moment, the highest energy density available is about 0.1 kWh/kg for the lithium-ion battery. According to a road map for battery technology depicted by New Energy Development Organization (NEDO 2010) in Japan, next generation battery with its energy density 7 times higher, 0.7 kWh/kg, is a target in 20 years (Zinc-Air battery, as one of the promising candidates). Electric cars can run about 10 km per 1 kWh electric energy, hence a distance 500 km can be driven by 50 kWh electricity fully-charged in the next generation battery. Then, the mass of the battery will be  $50 \text{ kWh} / 0.7 \text{ kWh/kg} \doteq 70 \text{ kg}$  (0.7 kN in weight) per piece. When such a battery becomes available, the number of batteries necessary to transport the electricity generated by the gigantic solar cell raft of  $25 \text{ km}^2$  calculated in Eq.(1) is

$$24,000 \text{ MWh/day} / 50 \text{ kWh/piece} = 4.8 \times 10^5 \text{ piece/day} \quad (3)$$

Hence, the weight of the batteries is

$$0.7 \times 4.8 \times 10^5 = 3.4 \times 10^5 \text{ kN/day}. \quad (4)$$

Today, oil tankers as heavy as  $3\text{-}5 \times 10^6 \text{ kN}$  are in operations commercially. If a battery tanker of the same capacity is constructed, then

$$3\text{-}5 \times 10^6 \text{ kN} / 3.4 \times 10^5 \text{ kN/day} \doteq 10\text{-}14 \text{ days} \quad (5)$$

This indicates that the electricity generated for 10 days to 2 weeks in the gigantic solar cell raft of 5 km by 5 km can be transported by one shuttle of the tanker.

### *Innovative Raft Units*

As mentioned previously, a great number of raft units are needed to realize the solar energy system with the capacity comparable to a 1000 MW nuclear power station. It may not be feasible to construct such a great number of units to be rigid with materials such as steel or reinforced concrete in a home port and tow them together in a long distance. It is therefore essential to create an innovative concept of the raft unit, which includes floats and masts, readily foldable and made of high-strength/lightweight materials and sailcloth with thin flexible solar cells. The floats will be a semi-submerged type to minimize wave effects. The raft units are inter-connected by wires, pressure tubes, and electrical cables and the masts and sailcloth should be controlled for low-speed, energy-saving wind sail to a certain degree and also for tracking the sun for efficient power generation as far as possible. A great number of raft units folded compactly and towed by

mother-ships starting from a home port will spread out swiftly as soon as the SCR-fleet arrives at the sea of operation. Appropriate choice of materials and innovative structural designs of the raft units are essential to make them lightweight, flexible and highly durable, and to minimize the construction costs. No doubt that pioneering ideas will be needed to develop feasible raft, considering marine and weather conditions though the fleet is to navigate in relatively calm seas.

## WEATHER/OCEANIC CONDITIONS IN LOW-LATITUDE PACIFIC OCEAN

In order to know how tough or favorable the weather and oceanic conditions in the low-latitude Pacific Ocean for the proposed SCR-fleet, pertinent data accessible through Internet at this moment have been collected here.

### *Sunshine*

According to a world-wide sunshine energy map already available (WMO 1981), the annually-averaged solar energy per day is 5-6 kWh/m<sup>2</sup> maximum in the low-latitude Pacific Ocean. Because, this map is very crude covering the whole world by a single map, a map more focused on the low-latitude Pacific has been depicted here using the NASA data (NASA 2008). In the original database, data points at every 1 km mesh all around the globe (90° north to 90° south and 180° east to 180° west) are available in a huge file of 5 MB. Out of that, a low-latitude band of 30° north to 30° south and from 130° east to 90° west has been focused. Fig. 2 indicates the distribution of

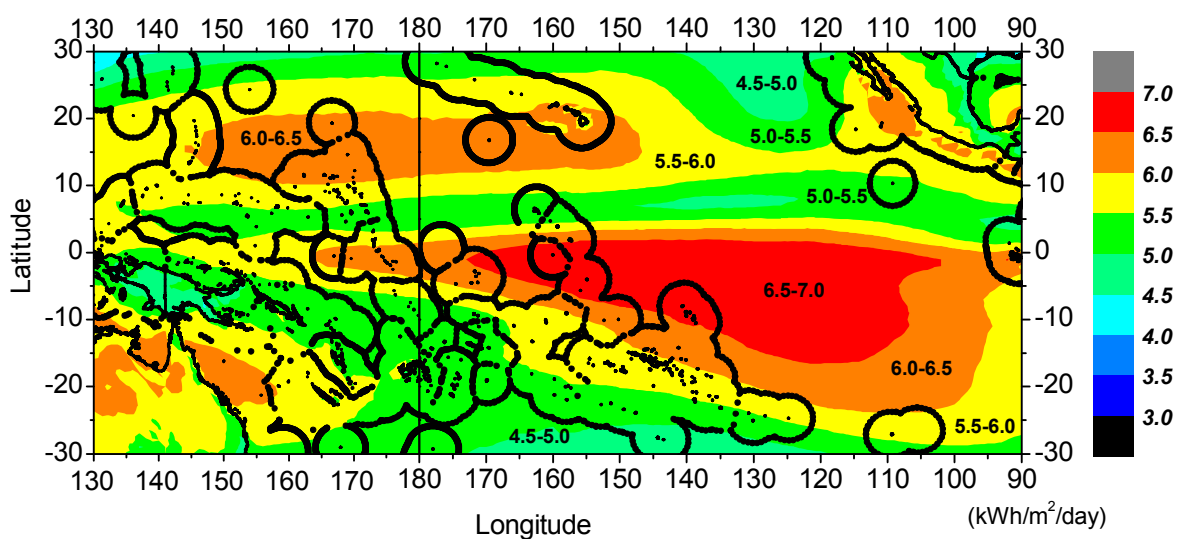


Fig.2 Distribution of annually averaged daily sunshine energy on horizontal plane in low-latitude Pacific Ocean depicted in every 1 km mesh from NASA data (Unit: kWh/m<sup>2</sup>/day).

annually averaged daily sunshine energy on 1 m<sup>2</sup> horizontal plane (kWh/m<sup>2</sup>/day) in the low-latitude band. As depicted, the map covers the area from New-Guinea in the east to Galapagos Islands (Ecuador) in the west along the equator. It is noted that there is a vast sea with the energy 6.5 – 7.0 kWh/m<sup>2</sup>/day expanding from 0° to 15° south and from 170° east to 110° west. Seas with the energy larger than 6.0 kWh/m<sup>2</sup>/day can be located in greater areas in both north and south of the equator.

The thick roundish lines in the map representing EEZ (Exclusive Economic Zone) occupy wide areas with high sunshine energy. It seems unreasonable to restrict the utilization of the solar energy in EEZ, because the solar energy is never lost by exploitation unlike mineral or fishery resources. Even if international consensus that EEZ is not the restriction for free sailing of SCR cannot be reached, however, there will still be left a vast area greater than Australian continent with the energy higher than 6.0 kWh/m<sup>2</sup>/day. It should be stressed here again that the energy shown in Fig. 2 is the annual average. Thus, it seems quite realistic that the daily energy higher than 8.0 kWh/m<sup>2</sup>/day as assumed in calculating the energy capacity in Eq.(1) can be attained by SCRs by pursuing stronger sunshine crossing the equator throughout the year.

### *Winds*

Fig.3 shows wind speed in the same low-latitude Pacific Ocean depicted by the present authors based on the NASA database (NASA 2008). The wind speed in m/s is the annually averaged value at 10m high from the sea-surface. It is seen that the average wind speed spans 3 to 7 m/s, relatively lower than that in higher latitudes.

Fig. 4 is a chart of wind directions/speed provided by Japan Meteorological Agency in January and July in North Pacific Ocean (JMA 2003). In the band 10°N-20°N, east or north-east wind blows all

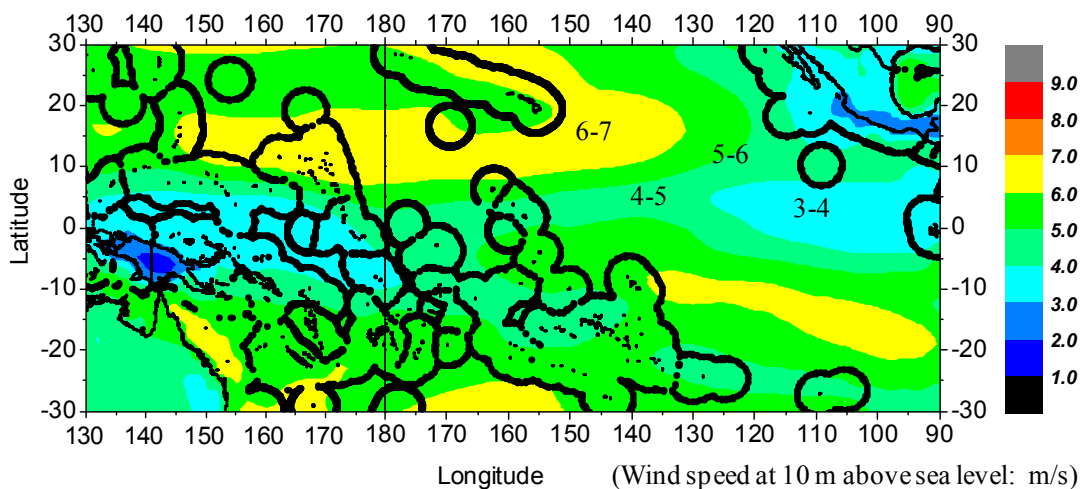


Fig.3 Distribution of annually averaged wind speed in low-latitude Pacific Ocean depicted in every 1 km mesh from NASA data (Scalar average in m/s)

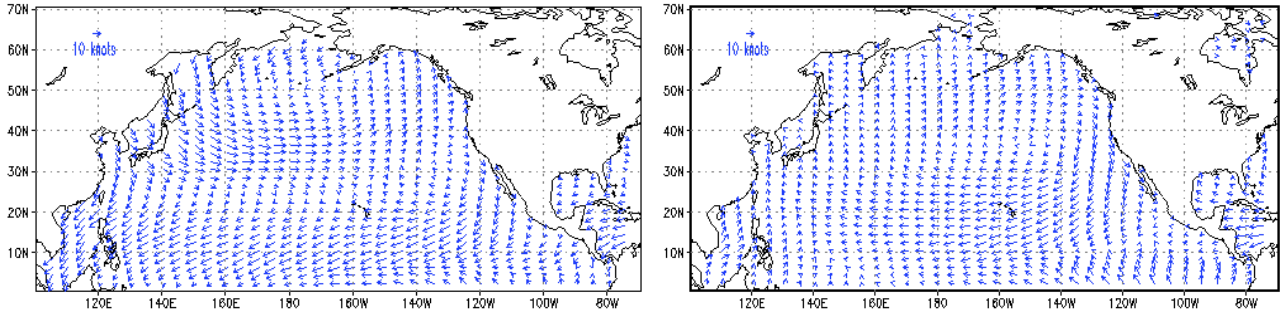


Fig.4 Wind directions and speeds in North-Hemisphere Pacific Ocean (Vector average, Left: January, Right: July).

around the year. In the vicinity of Japan, the wind changes seasonally; north-west wind changing west wind offshore blows very strongly in winter while south wind prevails in summer.

The strongest wind in the west part of North Pacific is caused by typhoons. The most dangerous part is north of 15°N and west of 150°E, where most of them pass with strong energy. It is necessary to avoid the typhoon season for the SCR-fleet to cross the dangerous sea around Japan to and from the SCR operation area.

### *Ocean Waves*

Fig. 5 shows a chart for ocean wave heights (significant wave heights) in the northern hemisphere Pacific Ocean in February and September provided by JMA (JMA 2003). In general, the waves, highest in high latitudes near the Bering Strait, tend to be lower in lower latitudes and the lowest in tropical seas near the equator, smaller than 1 m all around the year.

In the vicinity of Japan, atmospheric depressions, frequently passing through and getting stronger, generate high waves in the north-west Pacific in winter, represented by February here. The waves propagate south, making waves higher than 2m as far as Hawaii. Even in February, however, wave

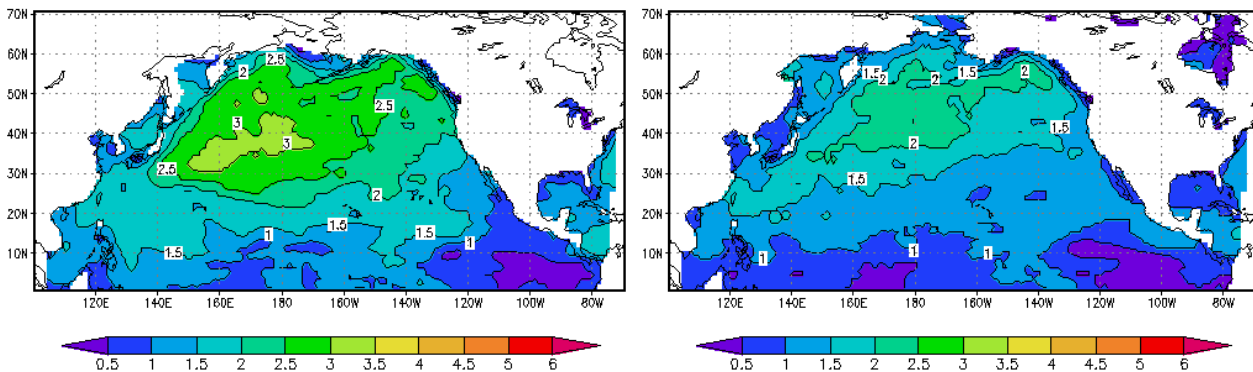


Fig.5 Wave height distribution in North-Hemisphere Pacific Ocean (Left: February, Right: September)(JMA 2003)



heights are 1.5 m or lower in the south of 20° N and 1m or lower near the equator.

In summer, represented by September here, areas with wave heights 2 m or lower expands up to the north 40° N, except in the vicinity of Japan, where typhoons often passing there tend to generate high waves. Waves are 1.5 m or lower in the south of 25° N, and lower than 1.0 m or even lower than 0.5 m in the south of 10° N. Although no data are available at this moment on the wave heights in the southern hemisphere, a symmetrical pattern of wave heights may be estimated generally, with calm seas in low latitude.

### Sea-Currents

Fig. 6 illustrates the flows of sea-current in the Pacific Ocean (National Geospatial Intelligence Agency 2002). In the north hemisphere, the most remarkable is the clock-wise flow of a large scale. It is composed of North Equatorial Current flowing west in low latitude sea, Kuroshio flowing north-east near Japan and then Kuroshio Extension heading east, North Pacific Current reaching the west coast of USA, and California Current heading south to circulate again.

The large-scale circular currents make inner vortexes at two locations; south of Japan and near Hawaii. The former is formed by a diverted current from Kurishio Extension before passing by the Hawaii Islands. The latter vortex, located inside the large-scale current in the eastern part of Pacific Ocean, is known as a place where drifted materials from Japan tend to accumulate. Another group

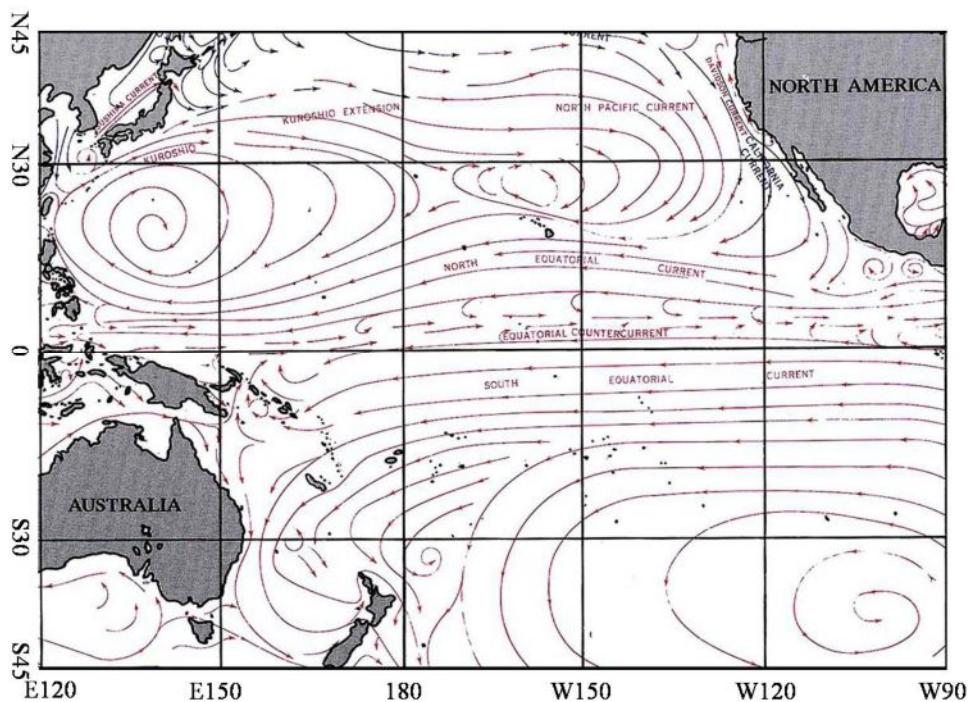


Fig.6 Sea current in the central part of Pacific Ocean <sup>12)</sup>

of sea-currents is found near the equator; North Equatorial Current and South Equatorial Current, both heading west, and Equatorial Counter Current between the two, heading east along the equator.

Thus, based on the weather/oceanic conditions in the low-latitude Pacific Ocean available at this moment, it may be judged that the energy-saving sailing of the gigantic SCR using wind and sea-currents combined can be possible in low-latitude calm seas crossing the equator pursuing stronger sunshine all around the year.

## STEPS FOR REALIZING SCR

The initial step in the SCR-fleet project is to pick up several pertinent issues associated with the energy system; for example, marine environments, fishing, sea-traffics and international maritime laws including EEZ. These problems have to be scrutinized from different viewpoints to find out directions toward their solutions. An international group of specialists from diverted disciplines should be involved in this step; ocean meteorology, ocean environment, fishing, ship building, marine engineering, international law, etc.

In the next step, the composition of the fleet and its dimension/specification has to be decided. Then the raft units, the core parts of the system are substantiated in terms of materials, structures and functions by conducting trial designs, simplified structural analyses and model tests. Then, the feasibility of the system thus outlined will be assessed from technical and economical viewpoints. The assessment should be premised on general conditions in 20 to 30 years ahead when this energy system is to be realized; such as basic energy cost, efficiency and production cost of thin flexible solar cell, energy density of batteries, transportation cost of electricity by battery tankers, etc. Essential problems associated with the feasibility will also be discussed; such as the degradation rate of raft units by ultra-violet ray and other effects as well as in-operation maintenance of a great number of solar cell units, etc. together with their potential solutions.

Based on the studies above, the upper bounds of the total cost and its break-down into major compositions will be quantified for the energy system to be economically feasible. The obtained upper bounds will provide targets in the following research and development on solar cells, batteries, raft units and other major components. In parallel with such R & D efforts, it is essential to form a consensus in international organizations such as United Nations on an exploitation of reusable natural energy in open seas not only in Pacific Ocean but also Atlantic and Indian Oceans all over the world. Thus the project should be implemented not only nationally but also internationally from an early stage by forming a world-wide consortium.

If such a solar power system comes true, it will immensely help human-beings be less dependent on fossil fuels and fulfill international commitments to reduce the CO<sub>2</sub>-emission. Furthermore, it will provide opportunities for nurturing new green business through new types of R & D and boosting economy in many countries.

The solar energy reaching the earth is so great that one hour sunshine actually amounts to the annual energy use of human-beings. The technical and economic hurdles will be high for efficiently gathering the low-density natural energy in the vast unused open sea to use as sustainable primary energy source, whereas the significance of realizing it is immeasurable. Japan, a maritime nation with little natural resources, should take the initiative in cooperation with other countries in trying to reach this goal.

## SUMMARY

- 1) A huge wind-sailing solar cell raft (SCR) of 25 km<sup>2</sup> (5 km×5 km) in ultimate dimension is proposed, here. The capacity can be comparable to 1000 MW nuclear power station, 24-hours in operation, if daily sunshine energy 8 kWh/m<sup>2</sup> and electrical conversion efficiency 12% are assumed.
- 2) Three major technical breakthroughs to realize the SCR; thin flexible solar cell, high energy-density battery and innovative raft unit, have been discussed with their future perspectives.
- 3) Studies on weather and marine conditions in the low-latitude Pacific Ocean based on database available have revealed that the vast seas expand with annually averaged daily sunshine energy nearly 7 kWh/m<sup>2</sup>, hence the energy 8 kWh/m<sup>2</sup> or higher can be attained by the raft pursuing optimum sunshine throughout the year crossing the equator. Winds, ocean waves and sea-currents seem to be favorable for the energy system in the low-latitude seas.
- 4) A road map has been proposed to realize the energy system in 20-30 years ahead by international cooperation.

## ACKNOWLEDGMENTS

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