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

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Abstract: Development of a huge wind-sailing solar cell raft (SCR) with dimensions of 5×5 km is proposed, which can generate electricity comparable to a 1,000-MW nuclear power plant in low-latitude Pacific Ocean. Solar energy of $8\ \mathrm{k \cdot Wh/m^2/day}$ or more is targeted because the SCR navigates in fine weather 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 data indicate that there are vast open seas in the tropical Pacific Ocean, where the maximum solar energy attains $7\ \mathrm{k \cdot Wh/m^2/day}$ annually on average and conditions of winds, waves, and sea currents are favorable for the solar energy system to operate. Three major technologies for breakthrough to realize this system are discussed from their future perspectives. **DOI: 10.1061/(ASCE)EY.1943-7897.0000088.** *© 2013 American Society of Civil Engineers.*

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Sailing Solar Cell Raft

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

Instead of deserts, Japan faces the vast open seas of the Pacific Ocean, which extend beyond the equator. There is a tremendous potential of solar energy there in a scale incommensurably larger than that in the land area. The marine solar energy can be efficiently utilized by developing gigantic solar cell rafts (SCR) of several $\mathrm{km^2}$.

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

Consider a huge solar cell raft of 5×5 km ($25\ \mathrm{km^2}$ in area) in dimension, as illustrated in Fig. 1. If daily solar energy of $8\ \mathrm{k \cdot Wh/m^2}$ (Wh = watt × hour) and electrical conversion efficiency of 12% [a modest value at present, according to NEDO (New Energy Development Organization) (2009)] are assumed, then the daily generated electricity will be

$$8\ \mathrm{k \cdot Wh/m^2} \times 0.12 \times 25{,}000{,}000\ \mathrm{m^2} = 24{,}000\ \mathrm{MWh} \qquad (1)$$

If this daily electric energy is divided by 24 h, the average power generation is

$$24{,}000\ \mathrm{MWh/24\ h} = 1{,}000\ \mathrm{MW} \qquad (2)$$

indicating that an SCR of this size is comparable to a 1,000 MW nuclear power station in continuous 24-h operation (Kokusho 2010). The daily solar energy of $8\ \mathrm{k \cdot Wh/day}$ or more is targeted as the SCR navigates in the clear regions using weather satellites. The navigation in search of this large energy is possible only on the ocean and offers a great advantage over a land-fixed solar power station.

There are multiple options for transporting the 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 in the form of electricity by battery tankers carrying a 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 and Shimamura 1979), in that hydrogen is produced by the solar heat energy collected by mirrors on rafts staying at fixed locations in tropical seas and transported by hydrogen tankers. This idea was followed by basic studies on associated key technologies (e.g., Endo et al. 1982), but research and development to realize this solar heat energy system have not yet started.

The energy system proposed in this paper, differing from that previously mentioned, is characterized by power generation using widespread solar cell modules covering a gigantic sailing raft by making use of fast-developing solar cell technology in recent years and in the future. Solar cell power generation has a great advantage over solar heat power generation in the ocean, because in the former, the raft can have a larger allowance of rolling and pitching by

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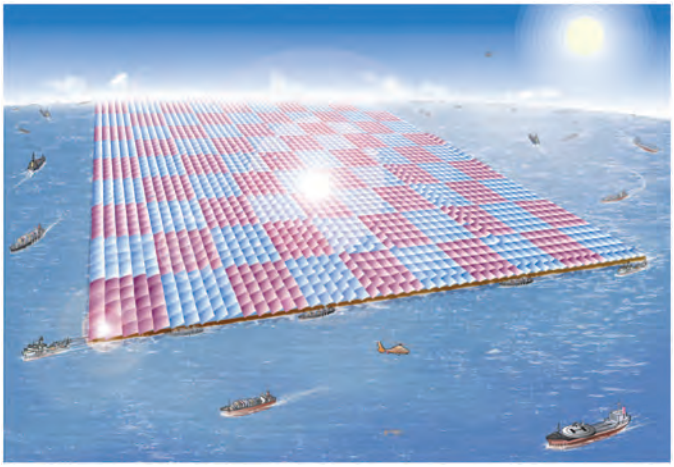

Fig. 1. (Color) Schematic view of sailing solar cell raft in the Pacific Ocean (with permission from Chuo University)

ocean waves than in the latter. In the solar heat system, the raft carrying mirrors has to be stabilized as much as possible to collect solar heat efficiently. Because of this larger allowance in raft movement, it is easier for SCRs to enlarge the raft, and the energy capacity can eventually be as large as a nuclear power station for the sake of better economic performance on a greater scale.

Another big difference from previous similar ideas is that it is always sailing in international 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 solar energy station. Impacts on marine life attributable to covering the sea surface and temporarily stopping sunshine can be minimized by sailing nonstop at slow speed. The sail should be saving energy as much as possible using winds and sea currents. 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 traffic.

The gigantic SCR may be composed of a number of raft units. If the size of a unit is chosen as 100 × 100 m, for instance, 2,500 units are necessary to compose the 5-km square raft. The raft units are interconnected by wires, pressure tubes, and electrical cables, and the sail-cloth 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 navigate together. The mother ships are in charge of controlling the total system, navigation, and solar power generation by adjusting masts 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 during operation.

If such a solar power system is realized, it will immensely help not only Japan, but also other energy-poor countries be less dependent on fossil fuel and fulfill international commitments to reduce CO_2 emission. Furthermore, it will provide opportunities for boosting the economy and nurturing new green business worldwide. As indicated subsequently, vast international open seas with abundant sunshine extend in the north and south hemisphere in the low-latitude Pacific Ocean. Because similar conditions can also be expected in low-latitude Atlantic and Indian Oceans, the global energy potential is big enough for many countries to exploit solar energy for their own use.

Key Technologies to Breakthrough

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 future perspectives are discussed.

Thin Flexible Solar Cell

Widespread sail cloth covered with thin flexible solar cells is essential to realize the proposed raft unit. Among various types of solar cells, a thin film cell made of chemicals composed of copper, indium, gallium, and selenium (CIGS) seems promising because of low material consumption and a potential for high conversion efficiency. A thin film 2 micron thick is enough to absorb the solar radiant energy because of its high absorbing coefficient for the visible ray. A high conversion efficiency seems to last a lifetime for the CIGS type (Niki et al. 2011), though its long-term efficiency has to be tested under actual oceanic environments. The efficiency of a $1-\mathrm{m}^2$ module of the cell is 10–12% at this time, and a higher efficiency seems promising because that of the $1-\mathrm{cm}^2$ 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 time, however, flexible substrate materials are investigated mainly on stainless steel sheet (Niki et al. 2011), and thin-film solar cell modules on flexible textile substrate serving as sail-cloths with high conversion efficiency are yet to be developed. In 20–30 years, however, a great technical advance can be expected to realize seamless solar cell sail-cloth as large as 100 × 100 m with the efficiency much higher than 12%.

High Energy Density Battery

In the movable solar energy system proposed in this paper, the generated energy will be transported in the form of electricity by using high-energy-density rechargeable batteries to avoid energy conversion loss. The battery technology is and will be advancing with the advance of electric vehicles. At this moment, the most advanced battery is the lithium-ion type with energy density of $0.12\ \mathrm{k \cdot Wh/kg}$ (NEDO 2010). According to a road map for the battery technology depicted by the New Energy Development Organization (NEDO 2010) in Japan, the next generation battery with an energy density 6–7 times greater, $0.7\ \mathrm{k \cdot Wh/kg}$, is targeted in 20 years (with the zinc-air battery as one of the promising candidates). Electric cars can run approximately 10 km per $1\ \mathrm{k \cdot Wh}$ of electric energy—hence, a distance of 500 km can be driven by a $50\ \mathrm{k \cdot Wh}$-electricity fully charged in the next generation battery. The mass of the battery will then be $50\ \mathrm{k \cdot Wh}/0.7\ \mathrm{k \cdot Wh/kg} \fallingdotseq 70\ \mathrm{kg}$ (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 $25\ \mathrm{km}^2$ calculated in Eq. (1) is

$$24{,}000\ \mathrm{MWh/day}/50\ \mathrm{k \cdot Wh/piece} = 4.8 \times 10^5\ \mathrm{piece/day} \quad (3)$$

Hence, the weight of the batteries is

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

Today, oil tankers with payloads as heavy as $3\text{–}5 \times 10^6$ kN [called very large crude oil carrier (VLCC)] are in operation commercially. If a battery tanker of the same capacity is constructed, then

$$3\text{–}5 \times 10^6\ \mathrm{kN}/3.4 \times 10^5\ \mathrm{kN/day} \fallingdotseq 10\text{–}15\ \mathrm{days} \quad (5)$$

This indicates that the electricity generated for 10–15 days in the gigantic SCR comparable to a 1,000-MW nuclear power station can be transported by one shuttle of the tanker.

For oil transportation, VLCCs make one shuttle in 40 days between the Persian Gulf and Japan, including loading and unloading, and consume approximately 4,000 kL of heavy oil. This condition is assumed to also be applicable to a battery tanker shuttling between low-latitude Pacific Ocean and Japan, though the batteries, 2–3 times heavier than oil (NEDO 2010), will be much smaller in volume. The electric energy equivalent to 4,000 kL of heavy oil (thermal energy per kL $= 9.7 \times 10^6$ kcal) is calculated as

$$4{,}000\ \text{kL} \times 9.7 \times 10^6\ \text{kcal/kL} \times 1.163 \times 10^{-6}\ \text{MWh/kcal} \times 0.37 = 16.7 \times 10^3\ \text{MWh}$$

where the conversion coefficient from thermal energy to electric energy is taken as 0.37. This transportation energy is approximately 5–7% of the electric energy generated for 10–15 days by the 5×5 km SCR based on Eq. (1), because

$$16.7 \times 10^3\ \text{MWh}/(24{,}000\ \text{MWh/day} \times 10\text{–}15\ \text{days}) = 0.05\text{–}0.07$$

If a battery that is commercially available today, such as the sodium-sulfur battery with an energy density of $0.11\ \text{k} \cdot \text{Wh/kg}$ (higher than $0.035\ \text{k} \cdot \text{Wh/kg}$ for the most popular lead-acid battery) is used for the tanker transportation, the weight of the battery is six times heavier, indicating that the tanker transportation consumes approximately 30–40% of the pay load energy.

It is necessary for the tanker to stay 10–15 days beside the SCR to fully charge the batteries, though this can be much shorter provided that the SCR fleet is equipped with its own batteries. Considering the longer period for the on-site battery charge and the time for the shuttle, 3–4 tankers seem to be necessary to transport the electricity generated by one gigantic SCR comparable to a 1,000-MW nuclear power station. The number of charge/discharge cycles of the batteries is only nine per year ($365/40 \sim 9$); hence, the battery life will not be decided by the cycle-life but by the calendar life—approximately 10 years at this time (NEDO 2010). It may be possible to assume that the high-energy-density battery, unlike today's lead-acid battery, can discharge to nearly zero state of charge (SOC) and recharge to 100% SOC because it will be developed for electric cars. The energy loss by one charge/discharge cycle will be approximately 10% or less, according to NEDO (2010).

Innovative Raft Units

A great number of raft units are needed to realize the raft of 5×5 km. Each raft unit is entirely covered by flexible sail-cloths with solar modules on them. The inclination of the sail-cloths is to be adjusted within a possible range for low-speed/energy-saving wind sail, and also for tracking the sun. It may not be feasible to construct the raft units to be rigid with materials such as steel or reinforced concrete in a home port and tow them together for a long distance. It is therefore essential to create an innovative concept of the raft units that includes floats and masts and is composed of readily foldable pipes and joints made from high-strength/lightweight materials. The floats will be of a semisubmerged type to minimize wave effects. The raft units are interconnected by wires, pressure tubes, and electric cables. In making wind-sail in the sea of operation, floats, masts, and sail-cloths of all raft units will be systematically controlled from the motherships by pressurized air supplied from connected tubes. In starting from a home port, a great number of raft units are folded compactly, towed by motherships, and spread out swiftly after arriving at the sea of operation. The appropriate choice of materials and innovative structural designs of the raft units are essential to make them lightweight, flexible, and durable, and to minimize the construction costs. Pioneering ideas will be needed to develop feasible raft units, considering marine and weather conditions, though the fleet is to navigate in relatively calm seas.

Weather/Oceanic Conditions in Low-Latitude Pacific Ocean

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 the Internet have been collected.

Sunshine

According to a worldwide sunshine energy map already available [World Meteorological Organization (WMO) 1981], the annually-averaged solar energy per day is $5\text{–}6\ \text{k} \cdot \text{Wh/m}^2$ maximum in the low-latitude Pacific Ocean. Because this map is very crude, a more detailed map focused on the low-latitude Pacific has been depicted here using National Aeronautics and Space Administration (NASA) data (NASA 2008). In the original database, data sets on solar energy and meteorology observed during 21 years (July 1983–June 2005) at every 1 degree mesh all around the globe (90° north to 90° south and 180° east to 180° west) are available.

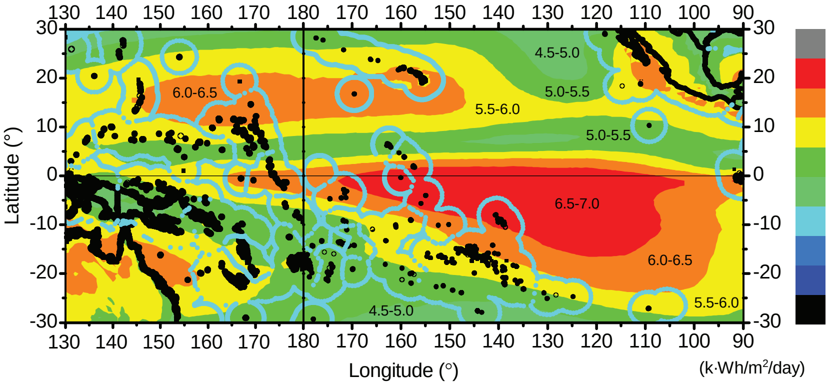

Fig. 2. (Color) Distribution of annually averaged daily sunshine energy on a horizontal plane in low-latitude Pacific Ocean depicted from NASA (2008) data (unit: $\text{k} \cdot \text{Wh/m}^2\text{/day}$)

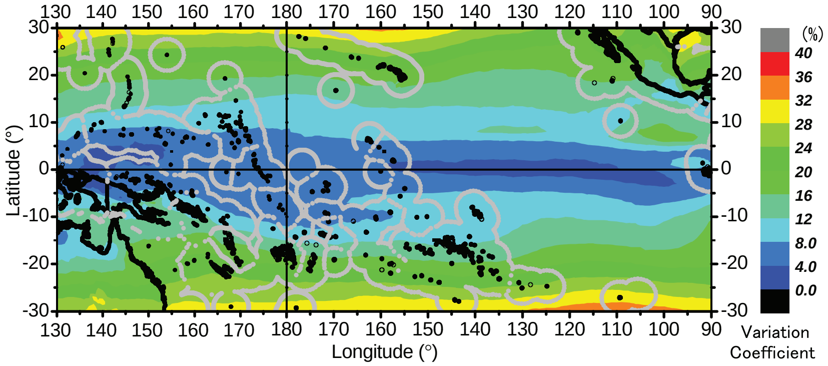

Fig. 3. (Color) Variation coefficient of annually averaged daily sunshine energy on a horizontal plane in low-latitude Pacific Ocean depicted from NASA (2008) data

From that, a low-latitude band of 30° north to 30° south and 130° east to 90° west has been cut out. Fig. 2 indicates the distribution of annually averaged daily sunshine energy on a 1 m^2 horizontal plane ($k \cdot Wh/m^2/day$). The map covers the area from New Guinea in the west to the Galapagos Islands (Ecuador) in the east along the equator. There are vast seas with solar energy of 6.5–7.0 $k \cdot Wh/m^2/day$ extending from 0° to 15° south and from 170° east to 110° west. The solar energy in this region is larger than that in the desert in the Australian continent shown in the left end of the map. Seas with solar energy larger than 6.0 $k \cdot Wh/m^2/day$ can be located in greater areas both north and south of the equator.

The thick blue lines in the map represent exclusive economic zones (EEZ) that occupy wide areas with high sunshine energy. It seems unreasonable to restrict free utilization of the solar energy inside EEZs, because the solar energy is never lost by exploitation unlike mineral or fishery resources. Even if international consensus cannot be reached that EEZs should be open to free sailing of SCRs, there are still open seas wider than the Australian continent with solar energy greater than 6.0 $k \cdot Wh/m^2/day$, which is the annual average.

Fig. 3 is a map of the same extent as Fig. 2, showing the coefficient of variation (COV) of monthly averaged solar energies based on the same NASA data sets. The COV tends to increase quite systematically and continuously with increasing latitudes in both north and south hemispheres (lower than 8–12% within 10°, and approximately 30% at 30° north and south). Therefore, it seems quite realistic that the daily energy greater than 8.0 $k \cdot Wh/m^2/day$, 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. 4 shows a wind speed map in the same low-latitude Pacific Ocean developed based on the NASA database (NASA 2008). The wind speed in m/s is the annually averaged value at 10 m higher than the sea surface. It is seen that the average wind speed spans 3–7 m/s, relatively lower than that in higher latitudes. The COV of the monthly averaged wind speed, also available in the same database, is less than 35% in all the areas shown in Fig. 4.

Fig. 5 is a chart of wind directions/speed published by the Japan Meteorological Agency (JMA 2003) in January and July in the north Pacific Ocean. In the band 10°N–20°N, east or northeast winds blow all year. In the vicinity of Japan, the wind changes seasonally; northwest wind changing to west wind offshore blows very strongly in winter, whereas south wind prevails in summer.

The strongest wind in the western part of the north Pacific is caused by typhoons. The most dangerous region is north of 15°N and west of 150°E, where many of them pass with stronger energies. It is necessary to avoid the typhoon season for the SCR fleet to cross the dangerous sea around Japan to and from the seas of operation.

Ocean Waves

Fig. 6 shows a chart for ocean wave heights (significant wave heights) in the northern hemisphere part of the Pacific Ocean in February and September, published by JMA (2003). In general, the waves, highest in the high latitudes near the Bering Strait, tend to be lower in the lower latitudes and the lowest in tropical seas near the equator—less than 1 m all year.

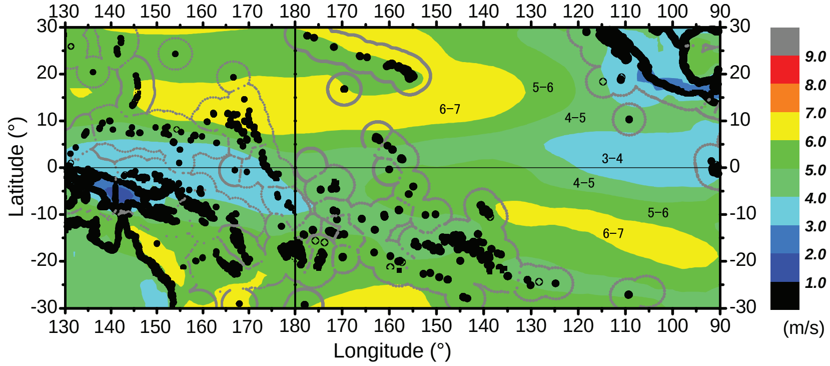

Fig. 4. (Color) Distribution of annually averaged wind speed (10 m above sea level) in low-latitude Pacific Ocean depicted from NASA (2008) data (scalar average in m/s)

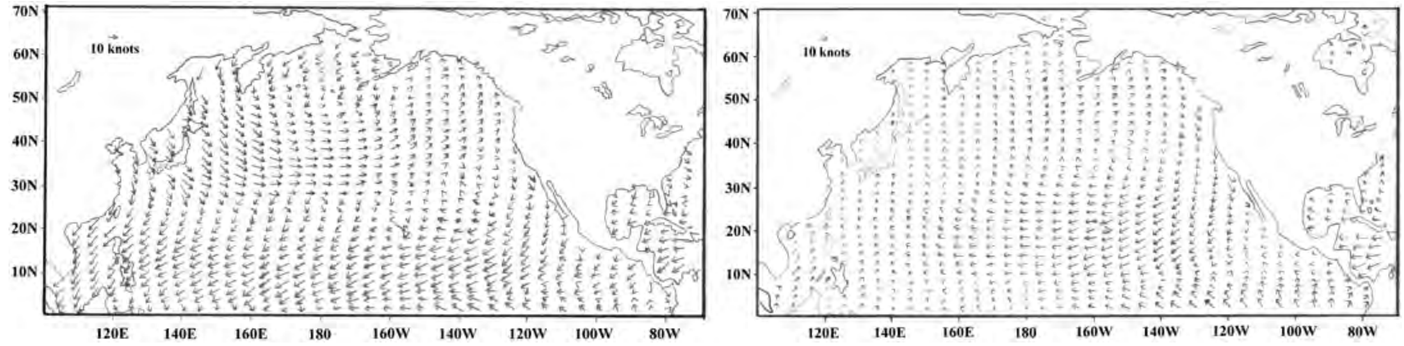

Fig. 5. Wind directions and speeds in northern hemisphere Pacific Ocean (vector average, left: January, right: July) (reprinted with permission from JMA 2003)

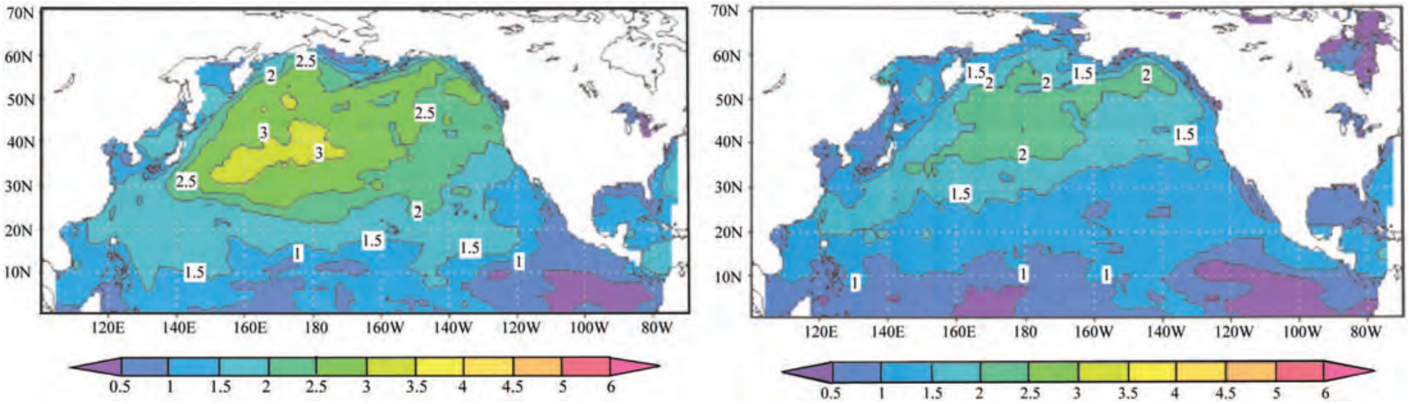

Fig. 6. (Color) Wave height distribution in northern hemisphere Pacific Ocean (left: February, right: September) (reprinted with permission from JMA 2003)

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 2 m as far as Hawaii. Even in February, however, wave heights are 1.5 m or lower in the seas south of 20°N and 1 m or lower near the equator.

In summer, represented by September, areas with wave heights 2 m or lower expand up to the north 40°N, except in the vicinity of Japan, where typhoons frequently passing through tend to generate high waves. Waves are 1.5 m or lower in the seas south of 25°N, and lower than 1.0 m or even lower than 0.5 m 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 the low latitudes.

Sea Currents

Fig. 7 illustrates the flows of sea current in the Pacific Ocean (National Geospatial Intelligence Agency 2002). In the northern hemisphere, most remarkable is the clockwise flow in a large scale. It is composed of the North Equatorial Current flowing west in low latitude sea, the Kuroshio Current flowing northeast near Japan, the Kuroshio Extension heading east, the North Pacific Current reaching the west coast of the USA, and the California Current heading south to circulate again.

The large-scale circular currents cause inner vortices at two locations: south of Japan and near Hawaii. The former is formed by a diverted current from the Kuroshio Extension before passing by the Hawaiian Islands. The latter vortex, located in the eastern part of the Pacific Ocean, is known as a place where flotsam from Japan tends to accumulate. Another group of sea currents is found near the equator: the North Equatorial Current and the South Equatorial Current, both heading west, and the Equatorial Counter Current between the two, heading east along the equator. The maximum current speed is 0.3–0.5 m/s—much slower than the wind speed, though it is another important driving energy for the energy-saving navigation.

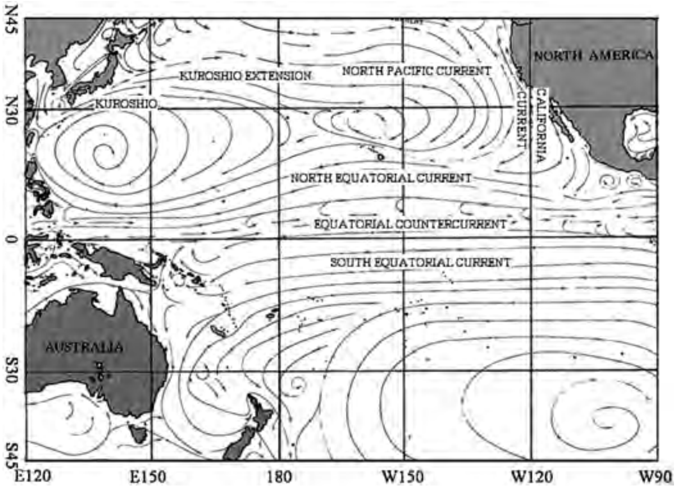

Fig. 7. Sea current in the central part of Pacific Ocean (National Geospatial Intelligence Agency 2002)

All the data on solar energy, wind speed, and wave heights shown previously are average values on an annual or monthly basis, and the peak values, to be used in designing the SCR, are not known at this time. Hence, long-term on-site observations to decide the design peak values are essential before starting the Research and Development Phase (R and D) of this energy system. In the meantime, however, based on the weather/oceanic conditions in the low-latitude Pacific Ocean available at this time, 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 sunshine stronger than $8.0\ \mathrm{k \cdot Wh/m^2/day}$ all year.

Steps for Realizing SCR

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

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 based on wave/wind conditions available at this time. Then, the feasibility of the system thus outlined will be assessed from technical and economical viewpoints. The assessment should be premised on conditions 20–30 years in the future, 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, and transportation cost of electricity by battery tankers. Other problems associated with the feasibility will also be discussed, such as the degradation rate of raft units by ultraviolet rays and other effects and in-operation maintenance of a great number of solar cell units with their potential solutions.

Based on the aforementioned studies, the upper bounds of the total cost and its breakdown into major components will be quantified for the energy system to be economically feasible. The obtained upper bounds will provide targets in the following R and D on solar cells, batteries, raft units, and other major components. In parallel with such R and D efforts, it is essential to form a consensus in international organizations such as the United Nations on an exploitation of renewable natural energy in open seas, not only in the Pacific Ocean, but all over the world. Thus, the project should be implemented not only nationally, but also internationally, from the early stage by forming a worldwide 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 CO_2 emissions. Furthermore, it will provide opportunities for nurturing new green business through new types of R and D and boosting the economy in many countries.

The solar energy reaching the earth is so great that 1 h of sunshine amounts to the annual energy use of all human beings. The technical and economical hurdles will be high for efficiently gathering the low-density natural energy in the vast unused open sea to utilize as a 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 SCR of $25\ \mathrm{km^2}$ (5×5 km) in its ultimate dimension was proposed. The capacity can be comparable to a 1,000-MW nuclear power station in 24-h operation, if daily sunshine energy $8\ \mathrm{k \cdot Wh/m^2}$ and electrical conversion efficiency of 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 from their future perspectives.
3. Studies on weather and marine conditions in the low-latitude Pacific Ocean based on available database have revealed that vast seas are expanding with annually averaged daily sunshine energy of 6–7 $\mathrm{k \cdot Wh/m^2}$; hence, the energy $8\ \mathrm{k \cdot Wh/m^2}$ or greater can be attained by the mobile SCRs pursuing optimum sunshine throughout the year crossing the equator. Winds, ocean waves, and sea currents seem to be favorable for the energy system to make energy-saving sail and operate in the low-latitude seas.
4. Several steps have been proposed to realize the energy system in 20–30 years by international cooperation.

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