A FEASIBILITY STUDY OF AN OCEAN POWER PLANT USING A MEGA YACHT SYSTEM

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SUMMARY

An average typhoon has a huge energy of $10^{18}$ J, which is enough for annual Japanese economic activities. Therefore, if we could develop a system that generates electricity from the typhoon, we could obtain clean and abundant energy.

In this research, we propose the concept of a floating power plant designed as a mega sailing yacht with some underwater power generators. This power plant operates using typhoon energy with its sails and the underwater propeller generators that yield electric power, which will be stored by batteries or H$_2$ conversion. Our feasibility study shows that using the 1000 mega yacht fleets, the annual power in Japan can be easily obtained with no CO$_2$ emission. We also compare our concept with the mega-float wind power concept proposed in Japan.

1. INTRODUCTION

It is widely said that the rapid increase in atmospheric CO$_2$ results in global warming and causes serious damage to our environment through various climate changes. A wind power plant is a feasible choice to decrease CO$_2$ emission, and there are many research studies related to mega-float wind power plants in Japan. On the other hand, recently in Japan and also in the USA, several super typhoons and hurricanes hit the mainland, seriously endangering lives and damaging property. However, the average typhoon is a large energy resource with $10^{18}$ J power, which is sufficient for Japanese economic activities. Therefore, if a system that generates electricity from the typhoon can be developed, we will obtain a huge energy resource. If the excessive energy of the typhoon can be safely absorbed, it might not only reduce the disaster of the super typhoon each year, but also result in a new clean power resource.

In this research, we propose a conceptual system of the floating ocean power plant, which consists of a mega sailing yacht and several underwater power generators. The power plant operates using typhoon energy with its sails and pursues optimum operational sea area, and the underwater propeller generators yield electric power that is stored using batteries or H$_2$ conversion. Our feasibility study shows that by operating 1000 mega yacht typhoon hunter fleets, the annual amount of power generated in Japan can be easily generated with no CO$_2$ emission. We propose the concept of a mega yacht floating structure and compare our concept with the mega float wind power plant proposed in Japan.

2. THE TREND IN JAPANESE OFFSHORE WIND POWER PLANT RESEARCH

The primary energy consumption of the world is increasing annually at an exponential rate. Figure 1 shows the prediction curve of primary energy until 2053 referenced by the 1990 level. The hatched areas show the energy amount obtained from each resource and the year they will deplete. As the figure shows, the present energy resources will deplete by 2053, and the last 10 years are only coal, which will cause serious air pollution.
As often said, we need to shift the paradigm related to this problem. The ocean-related power resources are one of the possible solutions. Table 1 shows a comparison of various types of primary energy resources. The most important parameter in our research is whether the resource is renewable. From this viewpoint, it seems that Table 1 suggests the potential of an ocean-related power plant. The marine current or wave is one of the best choices, but neither have been realized commercially. We need to investigate these methods for practical applications. However, as for the present technical development, offshore wind power generators are one of the most effective choices, and some of them are in practical use in some countries (Fig. 2). As Table 1 and Fig. 2 show, a wind power plant needs a big tower with very large blades; therefore, we expect high maintenance cost. Not only do they need high capital cost, but they also often change the landscape scenery. Therefore, the desirable plant site is in most cases a limited area.

However, in the Japanese situation, there are few areas that are suitable for such generators because the Japanese coastlines are generally intricate and have very steep landscape and underwater structures. As a result, the concept of offshore wind power plants proposed in Japan are almost always assumed to be situated in deep water.

### Table 1. Comparison between primary energy resources

<table>
<thead>
<tr>
<th>Resource</th>
<th>Enviromental Impact</th>
<th>Low capital cost</th>
<th>Low running cost</th>
<th>Predictable</th>
<th>Modular</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Nuclear</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Wind</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Solar</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Hydro</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Wave/MarineCurrent</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
</tbody>
</table>

Fig. 1. Prediction of primary energy consumption.

Figures 3–5 illustrate such proposed concepts under investigation in various institutions. All concepts have a moored structure and the research is focused on the dynamical system analysis of the base structure in waves. Although each proposed structural concept has its own advantages, a common difficulty exists in the construction and installation cost of the offshore platform.
and the mooring system in deep sea.

Fig. 4. Basin experiment of National Maritime Research Institute Japan.

Fig. 5. Conceptual sketch of deep water wind power generators proposed by the University of Tokyo.

Fig. 6. A conceptual design of Mobile mega offshore base power plant.

Table 2. Principal dimensions of the mobile mega floating wind power plant.

<table>
<thead>
<tr>
<th>LOA</th>
<th>2 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breadth</td>
<td>70 m</td>
</tr>
<tr>
<td>Steel Weight</td>
<td>114,600 tf</td>
</tr>
<tr>
<td>Displacement</td>
<td>199,000 tf</td>
</tr>
<tr>
<td>Wind turbine</td>
<td>11×5MW</td>
</tr>
</tbody>
</table>

3. TYPHOON AS ENERGY RESOURCE

The Japanese definition of the typhoon is a tropical cyclone whose wind speed is more than 17.2 m/s. About 30 typhoons are born every year, and three or four of them attack Japan, which lead to disasters. The diameter ranges from 200 km to 800 km, and the wind speed of the biggest one is more than 50 m/s.

The average typhoon has an energy of about $1.0 \times 10^{18}$ J. It is almost equal to 10,000 times the energy of the
On the other hand, the Japanese primary energy supply in the fiscal year 2003 was reported as $2.29 \times 10^{19}$ J ($545,165 \times 10^{10}$ kcal), which corresponds to 0.5 billion tf crude oil. This is 23 times the amount of typhoon energy. In addition, the total generated electricity in the fiscal year 2004 was reported as 1028 TWh, which corresponds to about 22% of the typhoon energy.

Ideally, if we can utilize 1% of the energy in each typhoon in a year, we can cover all power requirements. Since typhoons are born only in the summer season, this concept is weak as an annual stable supply of commercial electricity; however, considering the rapid progress in storage devices and diversification of power application, the potential of a typhoon as a power resource cannot be ignored. Moreover, the low pressure strong wind phenomena is measured near the Japanese coastline even in the spring season, and this high wind energy resource can be used by the system.

4. THE MEGA YACHT POWER PLANT

4.1 THE CONCEPT

The basic idea of the mega yacht power plant is a combination of a sailing yacht and some water turbine generators. Since an offshore wind power plant converts the wind energy directly into commercial electricity, the selected plant site should be where the wind direction and speed are suitable for power generation. The site selection is important to maintain a good operation rate and to achieve competitive electricity cost. As for the floating platform, the site selection is more important, but this type of plant has a heavy upper deck structure because of equipment such as a propeller and generator. The high center of gravity structure degrades the responses in waves and requires additional strength for the underwater structures and mooring equipment. This will decrease the operation rate and increase the total cost.

On the other hand, we developed an idea of a new current energy plant system, as shown in Fig. 8. Applying the contra-rotating pod driven generator, current or tidal flow could be efficiently used as energy resources. However, this system needs a fixed platform and its efficiency depends on the current condition, as is the case with the wind power generators.

Our aim is to improve the weak points of the fixed offshore wind power plants and the fixed marine current generators. The wind power is first converted into water current through the ship’s advanced speed and the relative flow is converted into electricity using several water turbines. Our design has low COG and is steady enough to have all the wave oscillation modes compared with the platforms shown in Figs. 4–6. Moreover, we will be able to use the wind power more effectively because of the huge ship mass, which is the law of inertia, and our design will not be affected by wind direction and speed changes.
4.2 FEASIBILITY STUDY BASED ON A CONCEPTUAL MODEL

4.2.1 A simple check of the downsizing effect due to the medium change

Next, we conduct a basic feasibility study of our mega yacht system. First, to see the downsizing effect of our proposed system, which uses sea water instead of air as flow medium, we compare our model with the mobile mega-float type power plant mentioned in Section 2. Our main aim is to generate the same energy using the water propeller generator instead of the air turbine of the mobile mega-float. To simplify,

\[ \frac{A_A}{A_W} = 100 \equiv A_R \]

The mega-float wind power plant has 11 huge air turbines with a rotor radius of 120 m. However, if we want to absorb the same amount of flow energy, our conceptual plant needs only one rotor and the diameter will be 40 m. This is a very simple comparison and further investigation is needed; however, it still shows the possibility of dramatic reduction in both the rotor size and generator number, which will be advantageous for various aspects such as construction cost and operation control.

4.2.2 Principal dimensions

Next, we consider the principal dimensions from the viewpoint of sailing performance. As for the sailing system, beam sea condition is superior to the other condition because it provides the system with less heeling angle and higher advance speed. We consider the beam sea case as the first step. The lift force generated by the total sails is given as

\[ L = \frac{1}{2} \rho_A S_S v_{Ap}^2 C_L \]

Here, \( L \) is lift force, \( \rho_A \) is density of air, \( S_S \) is the total sail area, \( v_{Ap} \) is the apparent speed of the sail, and \( C_L \) is the lift force coefficient. We set \( C_L \) as 2.0; this means that we use high performance sail configuration and foil section.

The total resistance force is the sum of the drag force of the sail and that of the underwater structure, which consists of the hull and water turbines and the apparent drag force caused by the energy consumption due to the electric power generation. In the next equation, we did not consider the sail drag force because we can absorb this effect by reducing the \( C_L \) value. Considering the latter two terms, we can obtain the total resistance force, which is equal to the lift force of the sail,
\[
R = \frac{1}{2} \rho_w S_p v_w^2 C_{DP} + \frac{1}{2} \rho_w S_H v_w^2 C_{DH} \\
= \frac{1}{2} \rho_w v_w^2 (S_p C_{DP} + S_H C_{DH})
\]
(5)

where \( R \) is resistance force, \( \rho_w \) is the density of water, \( S_p \) is the total water turbine area, \( v_w \) is the apparent speed of water, \( C_{DP} \) is the drag coefficient of a water turbine, \( S_H \) is the total hull area, and \( C_{DH} \) is the drag coefficient of the hull.

In the steady state, the L/R ratio must be one; therefore,
\[
\frac{L}{R} = \frac{\rho_p v_w^2 + v_A^2}{\rho_w v_w^2 (S_p C_{DP} + S_H C_{DH})} = 1
\]
(6)

Here, we must determine the hull area. Therefore, we selected the ship projected area \( S_H \) \( \text{m}^2 \) so that the displacement becomes the same as the mega-float in Section 2. The length of the hull is assumed to be 300 m considering the present tanker size or ship building facilities. In addition, the propeller projected area \( S_p \) \( \text{m}^2 \) is determined with the 40 m diameter as mentioned in 4.2.1. Therefore,
\[
S_H = 10 \times 20 \times 2 = 400
\]
\[
S_p = \pi r^2 \approx 1200
\]
(7)

Though the precise value must be investigated further, we assumed the \( C_p \) and \( C_D \) values as 0.3. This mega yacht system requires a sail area \( S_A \) of 4800 m\(^2\). If we use the square of one main sail, the height is 300 m and the breadth is 180 m. This size is quite difficult to handle, and the low aspect ratio reduces sail performance. Therefore, we designed the principal dimensions as shown in Figs. 9 and 10 corresponding to the two types of sail layout.

The concept shown in Fig. 9 is designed to suppress the heel angle. The concept shown in Fig. 10 will experience more heel angle, but the maneuverability will be improved compared to that in Fig. 9. In the following consideration, we use the Fig. 10 concept as the first feasibility study model.

4.2.3 A basic parametric study

Next, we conduct a parameter survey. Figure 11 shows hull speed vs. resistance force curve. The wind speed is assumed and fixed as 14 m/s in this case. The turbine curve decreases with an increase in the hull speed because the generated power is assumed to be constant and the power is proportional to the cube of the water speed as shown in Eq. (3). Thus, the diameter of the turbine propeller becomes smaller when the water speed increases. On the other hand, the hull resistance increases in proportion to the square of the water speed. As a result, the total resistance has an optimum point around the
water speed of 7 m/s to 9 m/s.

Figure 12 shows advance speed vs. sail area. The wind speed is the same. Using Eqs. (6) and (7) and by changing the advance speed, we calculated the desired sail area. Here, the optimum condition exists around the water speed of 9 m/s to 11 m/s. This optimum point has little difference compared to the result of Fig. 11. We should further investigate the relationship between these optimum points.

The advance speed is obtained by the wind force so that high speed performance is possible, and high sailing performance improves upwind sailing efficiency. The efficiency improvement of the system could sustain long-term operation in the gale area.

The use of underwater turbines as power generators has characteristics, such as lower center of gravity, more unified flow field, smaller turbine size, and reduced number of electricity turbines.

Compared to the mega-float power plant, this system has the merits of higher speed and maneuver performance, which improves tracing of the optimum wind area. This positioning capability guarantees stay in a limited small area.

The merits of small hull size are the utilization of the existing naval architecture technology, such as the hull structure and materials, and reduction in planning and building times.

The cost merits that we can expect are the low development cost by applying existing ship building technology and using existing ship yards for construction; less steel weight means extended producer responsibility (EPR) reduction.

On the contrary, demerits are that the huge sails are difficult to construct and control, and there are many problems to be solved, such as cascade foils interaction,
total structural analysis, and optimization. We should investigate these problems further.

Figure 13 shows an image of the future conceptual model which we are planning to investigate.

5. CONCLUSIONS

In this paper, we present a new concept of a natural energy absorption system. We are concerned about the increase in the number of world wide disasters due to super typhoons of increasing size and number. If we safely absorb such huge natural energy and reduce the violence of the natural wind powers, we will live more safely with a clean and cooler earth. Our target is to utilize strong wind energy sources, such as typhoons, cyclones, and hurricanes, which we have not yet utilized. Some basic considerations were presented and compared with the mobile mega-float power plant that was investigated by the Japanese research project and two types of conceptual models are proposed. Basic calculation shows that our concept has potential for downsizing or cost reduction of the system as well as improvement in maneuverability and operation. However, there are many problems to be solved to realize this system, for which we should continue investigation.

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