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Concept Design of Typhoon Power Generation Ship Using System Simulation

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ABSTRACT

A concept of a typhoon power generation ship for utilizing enormous typhoon energy is proposed. This paper developed a system simulator for evaluating and designing the concept of a typhoon power generation ship using typhoon track history. A developed simulator was applied to the case study to design a typhoon power generation ship ship that operated near Japan. The case study showed that the annual power generation of the typhoon power generation ship tends to saturate and become constant earlier when the number of typhoons is small, in contrast to the improvement of power storage capacity. This result indicates that the appropriate size of the typhoon power generation ship exists at the current technology level.

KEY WORDS

Concept design; Typhoon power generation ship; System simulation.

INTRODUCTION

In recent years, demand for renewable energy has increased in Japan to realize a sustainable society. However, the inability to sustainably generate large amounts of renewable energy has become a problem. It is necessary to stabilize the renewable energy supply by increasing and diversifying options other than solar and wind power, which are currently used as the primary renewable energy sources. On the other hand, driven by global warming, disasters caused by typhoons are dramatically increasing in intensity. Japan's national and local governments have worked out a wide range of typhoon preparedness and damage-mitigation measures, yet typhoons remain as grave a threat as ever. However, if that enormous natural energy could be harnessed as an energy resource, it could provide a renewable energy source, contributing to a carbon-neutral society.

To realize this ultimate goal, our group has proposed a future marine movable power generation, storage, and transmission system utilizing typhoon mechanisms and high-accuracy prediction of typhoons. Specifically, we will develop a sailing ship with movable power generation and storage functions that utilize the strong winds of typhoons. Sails catch crosswinds within a typhoon's navigable semicircle and follow the typhoon track. Electric power is generated and stored in the sailing ship by turning a screw propeller underwater. The stored electricity is then transmitted to land by ship. High-precision typhoon forecasting provides high-precision estimates of power generation and risk in advance. Terao (2010) proposed Wind Hunter, one embodiment example of a typhoon power generation ship. Horinouchi and Mitsuyuki (2023) quantified the dynamic effects of large sailing vessels on typhoons. This paper showed that deploying numerous large sailing vessels for hydrogen production, proposed by Ouchi and Henzie (2017), near a typhoon and following it by operating their sails could

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significantly affect the intensity of the target typhoon. Specifically, in one example, assuming a large sailing ship with a sail area of $25,600\,\mathrm{m}^2$ per ship, the intensity of a typhoon could be reduced by $10\,\%$ by deploying 200 large-size sailing ships in a 100 km square around the center of the typhoon and having them follow the target typhoon.

The concept of a typhoon power generation ship has great potential for realizing a sustainable society. However, quantitative assessments with specific operational assumptions must be carried out to make this concept a reality. For example, we should examine whether a typhoon power generation ship can conduct physical operations as assumed in a typhoon. At the same time, we should accurately estimate in advance what kind of operations the typhoon power generation ship should perform, the amount of power generation that can be expected if operations are carried out as assumed, and the appropriate size of the typhoon power generation ship. These issues belong to the problem of designing the concept of a typhoon power generation ship. This paper develops a system simulator for quantitatively evaluating the operation concept of a typhoon power generation ship using typhoon track history data. By using the developed system simulator, this paper examines the appropriate size of the typhoon power generation ship.

PROPOSED METHOD

In this paper, a typhoon power generation ship is called a TPG ship. The operational concept, operation method, and necessary specifications of a typhoon power generation ship are collectively called the TPG ship concept model. The conceptual design and basic plan of the TPG ship are developed by defining its concept and quantitatively evaluating the defined TPG ship concept using a system simulator. Figure 1 shows the proposal to evaluate the TPG ship concept using a developed TPG ship operation simulator.

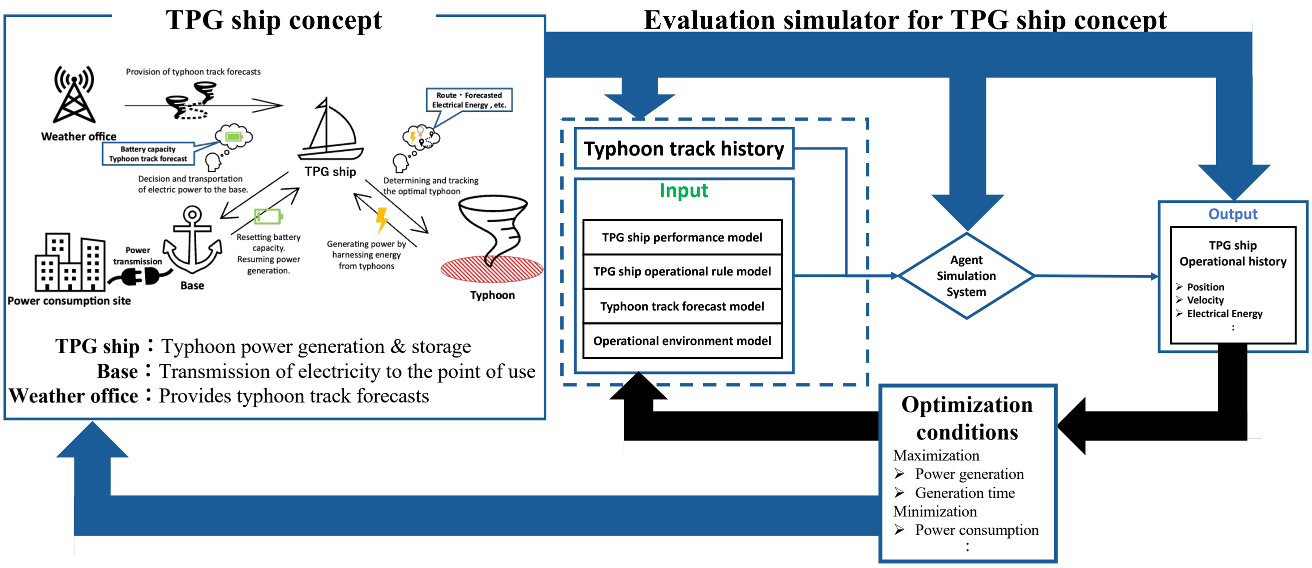

Figure 1: Overview of the proposed method

The TPG ship operation simulator must be able to reflect not only the ship body but also related technologies for power generation and storage and weather information as parameters. It also needs to be able to evaluate the impact of parameter changes on the TPG ship. An optimized TPG ship model is explored by continuously selecting and evaluating the TPG ship model based on the optimization conditions established, such as the maximization of power generation. We can quantitatively evaluate the TPG ship concept based on the required power generation targets and other issues.

TPG ship concept model

The TPG ship concept model consists of the operational concept, operation method, and necessary specifications of a target TPG ship. Figure 2 shows the operational concept of the TPG ship. In the proposed model, TPG ships can operate stably under typhoon conditions, generating and storing electricity. When sailing under typhoons, the TPG ship is propelled only by wind propulsion. When sailing in other conditions, the TPG ship is propelled using both wind and electricity propulsion stored on board. When sailing during power generation, even if the typhoon speed is slower than the TPG ship, this ship can keep the ship service speed by zigzag maneuvering under the typhoon. TPG ships can obtain accurate real-time typhoon track forecast information from the weather office. During periods when there are no typhoons in the surrounding area, the TPG ship waits in a predefined area. A base for accumulating the energy acquired by the TPG ship shall already be in place, and the base shall transport the energy to the use site by a different method from that of the TPG ship. The TPG ship must call at its base and manage its capacity before its storage capacity is full. The modeling of the TPG ship concept focuses only on the power generation from typhoons. Therefore, the entire supply chain, including transportation to the utilization sites, is not considered. The scope of the proposed model is limited to the transportation to the base, whose place is pre-determined.

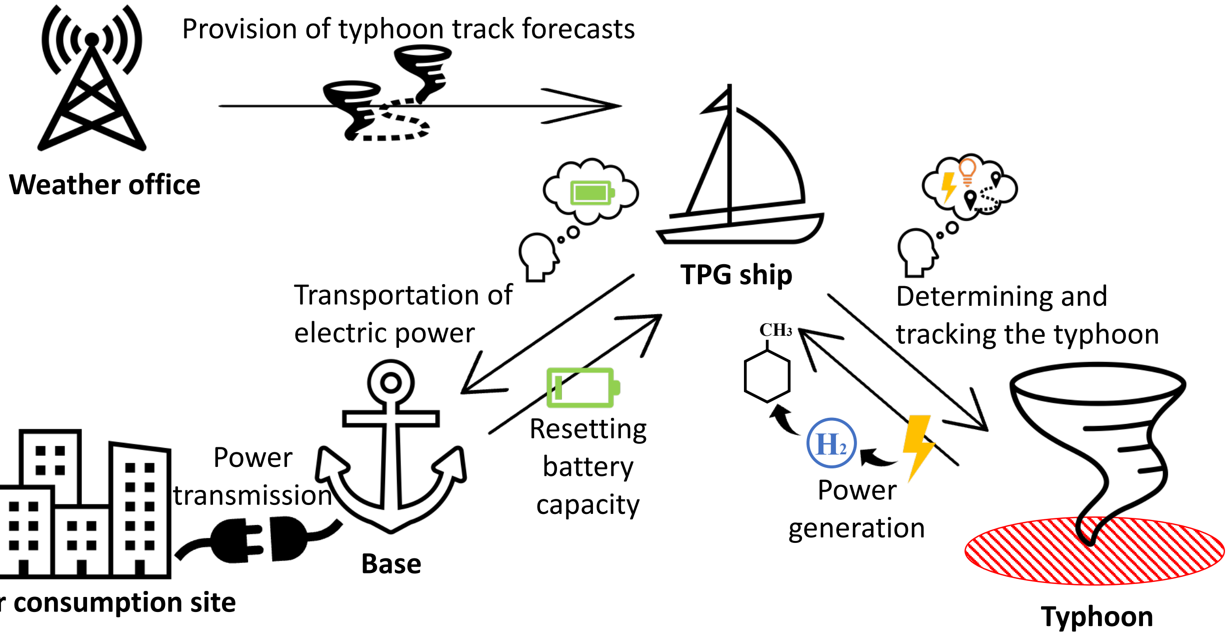

Figure 2: TPG ship operation concept

Developed TPG ship operation simulator

This paper has developed the TPG ship operation simulator as an agent-simulation system. The inputs consist of four models: the TPG ship performance model, the TPG ship operational rule model, the typhoon forecast model, and the operation environment model. This simulator conducts the agent simulation using these inputs and typhoon track history.

The TPG ship performance model defines the specification of functions, including power generation, power storage, wind propulsion, and electricity propulsion. The power generation function generates electricity when the TPG ship is propelled under typhoons. The power storage function stores the generated electricity or hydrogen converted from the generated electricity. The wind propulsion function uses winds to propel the TPG ship. The electricity propulsion function is a function in which the TPG ship is propelled by using the electric power stored on board. The TPG ship operational rule model reflects how the TPG ship operates, corresponding to the environment. The TPG ship operational rule model is defined as an agent rule in the developed simulator. The typhoon forecast model defines the period and accuracy of typhoon track forecast. The operation environment model defines the position of the base and standby of the TPG ship.

The output of the TPG ship operation simulator includes the position, speed, power generation amount, and power generation time of the TPG ship at each time. Figure 3 shows one of the examples of the developed interface for visualizing the output of the TPG ship operation simulator. Figure 3 depicts a typhoon ship departing from a standby position to track, capture, and generate power from a typhoon. By specifying the period to be visualized, the behavior of the TPG ship in the simulator can be understood in detail and intuitively.

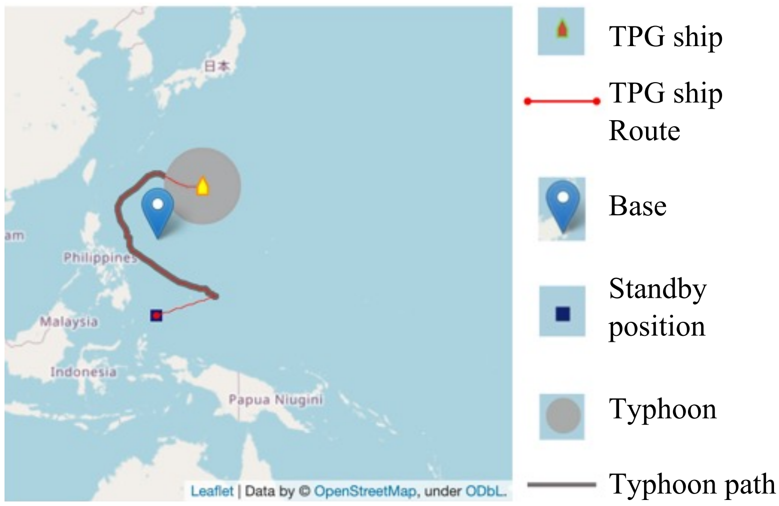

Figure 3: Interface for visualizing the result of TPG ship operation simulator

CASE STUDY

A primary design study of a TPG ship was conducted using the proposed method. Specifically, we performed sensitivity analysis on a simplified performance model of a TPG ship in which the specifications of the power generation function were set as fixed, and other performance functions of the TPG ship were automatically defined according to the storage capacity settings. This paper analyzed how the annual power generation of the typhoon power generation ship changes when the storage capacity setting is changed.

Problem setting

TPG Ship performance model

The TPG ship performance model defines the specification of functions, including power generation, power storage, wind propulsion, and electricity propulsion. In this case study, the specifications for the power generation function were fixed, and the specifications for the power storage function were adopted as the parameters for sensitivity analysis. The specifications of the wind propulsion and electric propulsion functions were calculated automatically from the power storage function's specifications by adopting a simple TPG specification model.

The specifications of the power generation function were set based on the studies conducted during the conceptual phase of this research. Specifically, the rated output of a TPG ship under a typhoon P_{output} is set to 0.138 GW, and this specification is assumed to remain fixed as long as the ship is within 100km of the typhoon's center. It is assumed that the TPG ship cannot generate power outside the typhoon area. The specification of the power storage function can be entered into the developed simulator in units of 1 GWh. This case study will employ the organic hydride method to model the power storage function. The organic hydride method is a method in which electricity is converted to hydrogen and then added to toluene, an organic compound, for storage. The efficiency of converting the energy of the hydrogen produced by this method into electricity was set to 80 % by adopting the direct MCH method (Matsuoka et al. (2018), Kobayashi et al. (2021)) and in anticipation of future technological innovation. In other words, a 0.138GW TPG ship can store 0.110 GWh of electricity as MCH for one hour of power generation. The wind and electric propulsion function specifications are defined according to the deadweight ton (DWT). This case study uses a simple TPG specification model that transforms the deadweight ton to 379 tons per one GWh of power storage capacity, considering the physical properties of toluene, MCH and a ship hull similar to a tanker. Equation (1) shows the formula for calculating the energy output required for a deadweight ton of TPG ship hull to sail at speed V, which was adopted in this case study. This case study adopts $K = 2.2$, considering that the hull form of a TPG ship is similar to that of a tanker. Since the TPG ship is assumed to be a catamaran, Equation (1) divides the deadweight ton by two and multiplies by two at the end to calculate the energy output for two ship hulls that each ship hull has half deadweight ton.

$$P_{hull} = K \times \left(\frac{\mathrm{DWT}}{2}\right)^{\frac{2}{3}} \times V^3 \times 2 \tag{1}$$

The required energy output for the additional items other than the ship hull is calculated using Equation (2). For this simplified study, P_{add} is calculated as the energy output equivalent to 1 % of the rated output P_{output} at the service speed $V_{service}$ of the TPG ship. The required energy output for wind propulsion P_{wind} for speed V is always assumed to be 10 % of P_{hull} at service speed $V_{service}$. The energy output required for electric propulsion P_e is calculated from these three elements, as shown in Equation (3). Note that when the TPG ship generates electricity under a typhoon, it is assumed that $P_e = 0$, i.e., the TPG ship can sail at assumed service speed $V_{service}$ with wind power alone without power consumption.

$$P_{add} = 0.01 \times P_{output} \times \left(\frac{V}{V_{service}}\right)^3 \tag{2}$$

$$P_e = P_{hull} + P_{add} - P_{wind} \tag{3}$$

TPG ship operational rule model

The TPG ship operational rule model is a model that describes how a TPG ship makes decisions and acts according to the situation. The amount of power a TPG ship generates may vary depending on the operational rules for judging the situation. This case study implements the TPG ship operational rule model as an agent model. Figure 6 shows the overview of the adopted TPG ship operational rule model. We have implemented this TPG ship operational rule model to prevent the TPG ship's inefficient actions, such as tracking typhoons that the TPG ship cannot catch. In addition, we adopted a rule that the TPG ship's power generation output is frequently handed over to the base. This rule eliminates the need for massive power storage capacities and, thus, the need to adopt a huge TPG ship design proposal. As for the specific decision-making process in Figure 6, first, the system selects typhoons that can arrive and decides to call at the base when it is possible to do so via the base. Next, the destination is determined based on whether the TPG ship has stored at least 25 % of its storage capacity; if the TPG ship has arrived, it waits; otherwise, it takes action to move toward the destination. The developed simulator applies this operational rule at every time step in the simulation run.

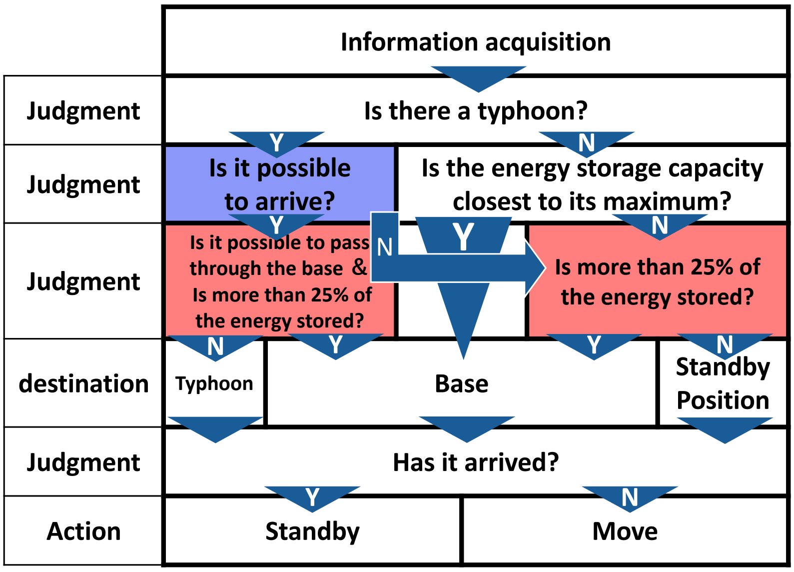

Figure 4: Overview of the TPG ship operational rule model

Typhoon forecast model

The developed typhoon forecast model focused only on the track and consisted of forecast period and accuracy. In this case study, the forecast period of the target typhoon track was set to five days from the time of the forecast, and the forecast accuracy of the track was set to 100 %. Although 100 % accuracy in typhoon track forecasting is unrealistic, the accuracy of typhoon track forecasting has been dramatically improved in recent years compared to typhoon intensity forecasting, and there is no significant difference in the judgment of TPG ship operations unless a typhoon makes landfall. Since the purpose of this case study is the primary design of a TPG ship, the above settings were adopted because they are expected to generate a considerable amount of power. In addition, the TPG ship can freely generate power outside the exclusive economic zone.

Operation environment model

The TPG ship is to be operated in Japan, and its base position is 24 degrees north latitude and 153 degrees east longitude, assuming MINAMITORISHIMA island. The standby position is where a TPG ship anchors at sea to capture typhoons efficiently. The TPG ship is assumed to be completely stationary in the standby position and does not generate power. Land and sea locations were roughly set up on the simulator from map data so that the TPG ship could only operate at sea locations. In addition, track information for each typhoon in the developed simulation was produced using the track history data of typhoons that passed near Japan from 2017 to 2022.

Results

By using the above settings, the annual power generation was calculated by varying the power storage capacity specification of the TPG ship performance model from 5 GWh to 150 GWh in 5 GWh increments. Figure 5 shows the annual power generation of the TPG ship for each power storage capacity specification. The horizontal axis represents the power storage capacity setting in the TPG ship performance model. The vertical axis represents the annual power generation resulting from the simulation. Each line shows the simulation results for each year. This figure shows that improving the power storage capacity in any year becomes ineffective against annual power generation above a certain level. Table 1 shows the number of typhoons has occurred and past near Japan each year. From Table 1 and Figure 5, we can see that the amount of electricity generated tends to saturate and become constant earlier when the number of typhoons is small, in contrast to the improvement in storage capacity. It can also be read that the amount of electricity generated by the TPG ship is positively correlated with the number of typhoons and that the amount of electricity generated by the TPG ship is not simply proportional to the number of typhoons. A more detailed analysis of the simulation results shows that the amount of electricity generated is correlated with the number of typhoons. The time of occurrence or landfall also significantly affects the amount of electricity the TPG ship generates. Based on these results, it can be concluded that an power storage capacity of 50 GWh to 60 GWh is appropriate for the TPG ship in this problem setting.

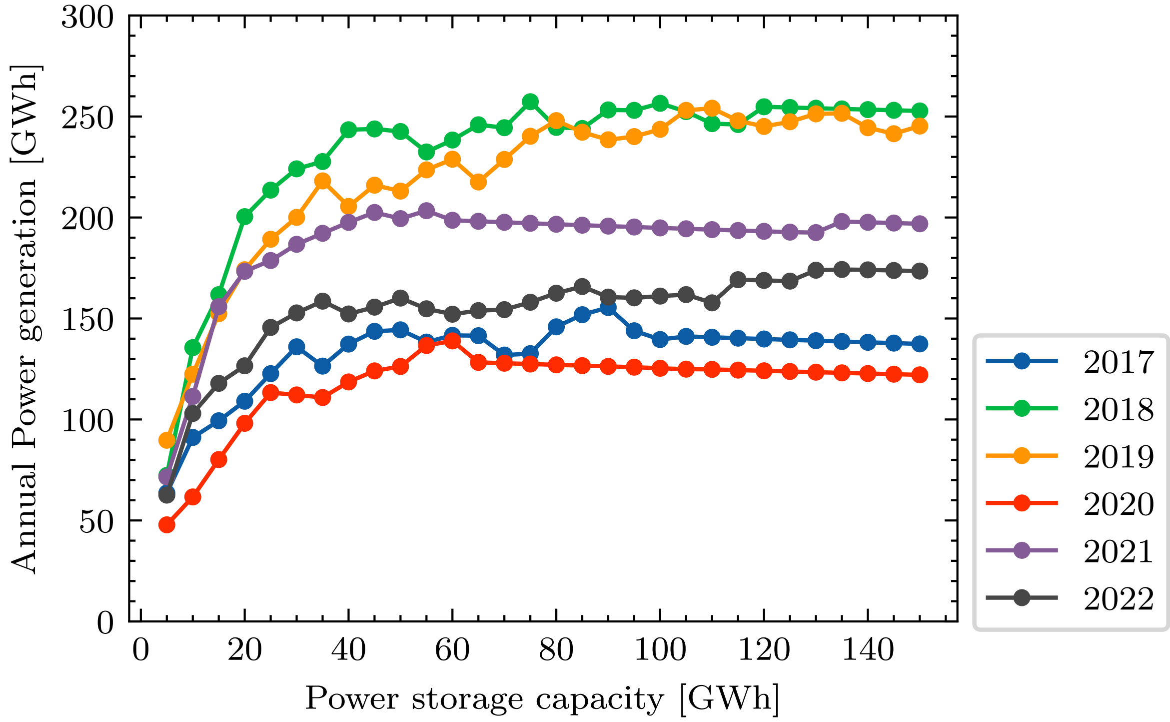

Figure 5: Annual power generation of TPG ship

Table 1: Number of typhoons has occurred and past near Japan each year

YEAR	NUMBER OF TYPHOONS
2017	27
2018	29
2019	29
2020	23
2021	22
2022	25

Sensitivity analysis

A sensitivity analysis was performed to see how the annual power generation would change if the standby position were moved slightly from this problem setting. Simulations were conducted by changing the standby location using the TPG ship performance model setting of this case study when the power storage capacity specification was set to 60 GWh. In the case study, the standby position was set to MIMAMITORISHIMA island. However, this sensitivity analysis conducted four additional simulations with the center of MIMAMITORISHIMA island shifted ten degrees in latitude or longitude (about 1000 km) to the east, west, south, or north. Figure 6 shows the simulation results for each case from 2017 to 2022. From Figure 6, we can see that the annual power generation difference between each standby position setting is at most 5 % or less under the current conditions. The above results indicate that the effect of changing the standby location is small under this problem setting and simulation assumptions used in this study.

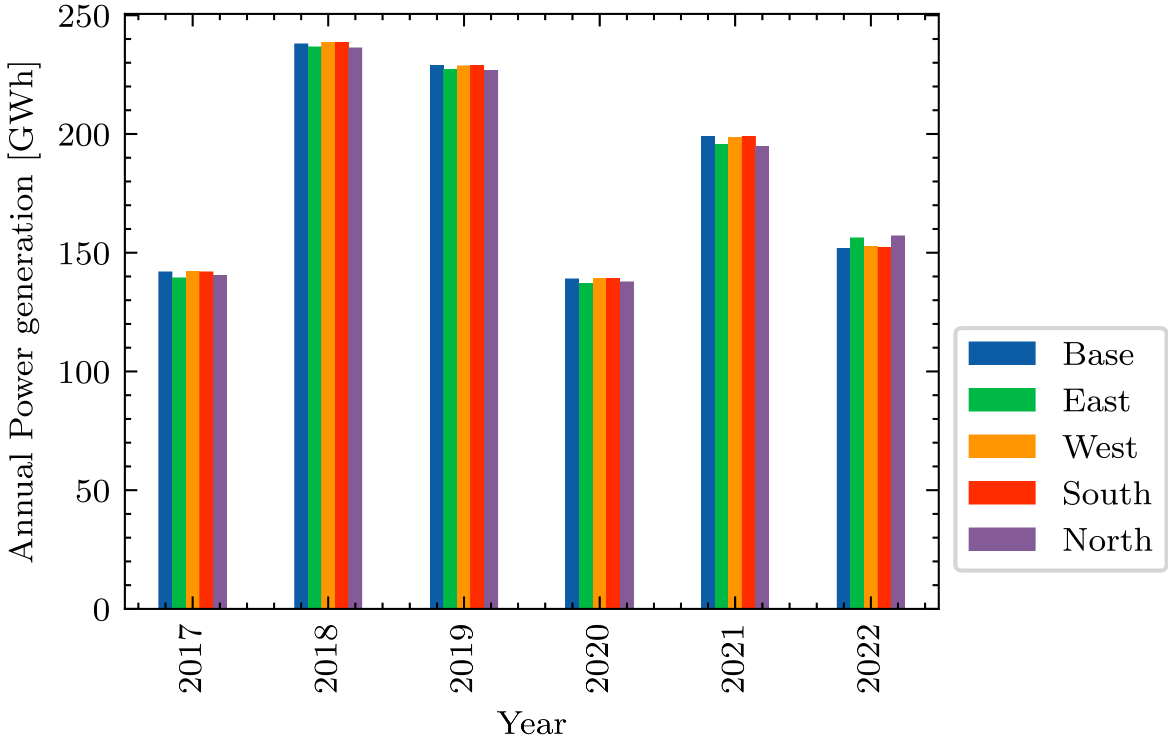

Figure 6: Annual power generation for standby position of TPG ship

DISCUSSION

This paper estimates the appropriate specifications of a TPG ship using a developed TPG ship operation simulator and simplified models. However, to provide a stable power supply, a TPG ship will be necessary to generate power not only from typhoons but also from ordinary ocean winds. This is because typhoons tend to occur more frequently in the summer, and typhoon power generation cannot occur during winter. On the other hand, the optimal decision on the extent to which typhoon power generation should be conducted and the extent to which power generation should be conducted using ordinary ocean winds is expected to vary depending on the specifications of a TPG ship. In this paper, simulations were conducted under the assumption that a TPG ship can operate as required, even in a typhoon environment. However, it is necessary to quantitatively estimate the extent to which operation is possible under a typhoon environment, reflect the results in the TPG ship operation simulator, and then develop the agent rule settings.

CONCLUSIONS

This paper proposes a typhoon power generation ship concept. The TPG ship concept model consists of the operational concept, operation method, and necessary specifications of a target TPG ship. For designing a preliminary concept of typhoon power generation ship, this paper developed a system simulator for evaluating the operation concept of a typhoon power generation ship using typhoon track history. Developed simulator was applied to the case study for designing a TPG ship which is operated near Japan. The case study showed that the annual power generation of the TPG ship tends to saturate and become constant earlier when the number of typhoons is small, in contrast to the improvement of power storage capacity. It can also be read that the amount of electricity generated by the TPG ship is positively correlated with the number of typhoons and that the amount of electricity generated by the TPG ship is not simply proportional to the number of typhoons. A more detailed analysis of the simulation results shows that the amount of electricity generated is correlated with the number of typhoons. The time of occurrence or landfall also significantly affects the amount of electricity the TPG ship generates. Based on these results, it can be concluded that an power storage capacity of 50 GWh to 60 GWh is appropriate for the TPG ship in this problem setting. This result indicates that appropriate size of TPG ship has existed in the current technology level. However, to provide a stable power supply, a TPG ship will be necessary to generate power not only from typhoons but also from ordinary ocean winds. In addition, it is necessary to quantitatively estimate the extent to which operation is possible under a typhoon environment, reflect the results in the TPG ship operation simulator, and then develop the agent rule settings.

CONTRIBUTION STATEMENT

Taiga Mitsuyuki: Conceptualization; methodology; writing – original draft. **Haruki Ebihara:** Data curation, methodology. **Shunsuke Kado:** conceptualization; writing – review and editing.

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