Expectations growing for ocean-thermal energy conversion in harmonious relationship with agriculture and fishery

Kumejima's 100-kW plant in continuous operation for decade, drawing global attention

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International observation parties from 68 countries

Kumejima, Okinawa Prefecture is an isolated island on the East China Sea, 100 kilometers off to the west from Naha City. The area of 63.65 km^2 is home to approximately 8,000 people. Highly cultivated with sugarcane, taro and other crops, and blessed with rich fishing grounds provided by the Kuroshio Current as well, the island has also experienced recent development in culture of prawns and others.

The world's first ocean-thermal energy conversion (OTEC) system was put into operation in the island in June, 2012. It is said that Okinawa Prefecture, with the cooperation of Saga University, built a demonstration facility with a capacity of 100 kW, which became the world's first facility to successfully generate electric power by using direct seawater. The facility is on its ninth year since the commencement of operation, and still operating smoothly (**Figure 1**).

Figure 1 ● Ocean-thermal energy conversion demonstration facility operating in Kumejima, Okinawa Prefecture

(Source: Nikkei BP)

OTEC is a system that utilizes the temperature differential between the surface and deep seawater to generate electric power. A deep diving into the sea finds that almost no sunlight reaches at depths of 200 meters or so in water, and in the depths of the sea, approximately at a depth of 1,000 meters, the seawater temperature stays as low as 4 to 5°C throughout the year. On the other hand, with the sun blazing down, seawater surfaces are warm; their approximate temperatures are 26°C in waters off Okinawa, and their annual average temperatures are approximately 30°C in areas near the equator such as Hawaii.

The OTEC demonstration facility in Kumejima utilizes the temperature differential between the deep water of 8 to 9°C pumped from the ocean floor at a depth of 612 meters, 2.3 kilometers off shore, and the surface water of approximately 26°C. The facility operates in such a cycle that the surface water vaporizes a low-boiling-point working fluid, with the force of its expansion spinning the turbine to generate electric power, and that then deep water of 5°C cools the vapor, turning it back into liquid that is to be vaporized by the surface water again (**Figure 2**).

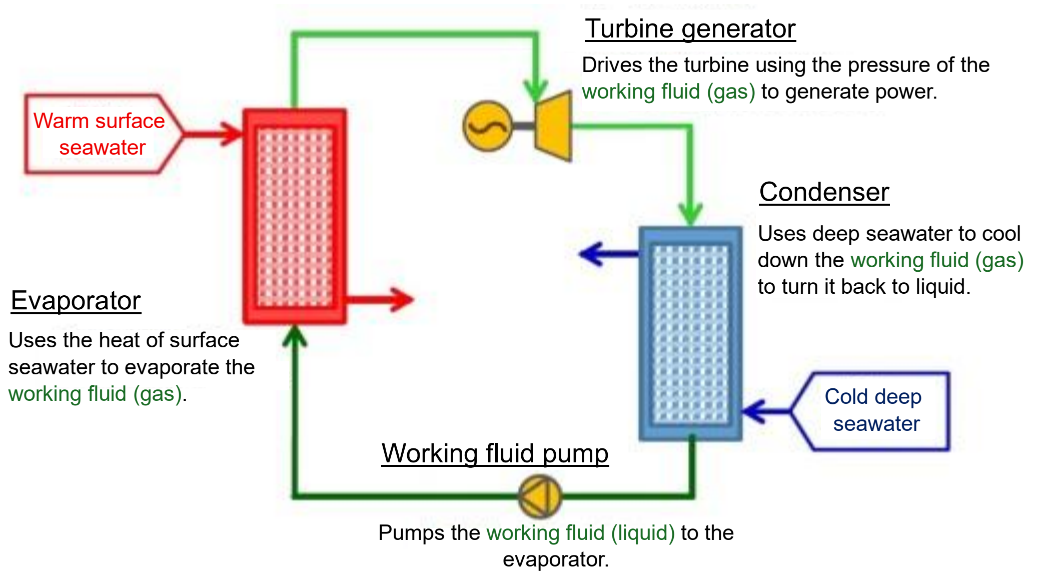

Figure 2 ● Principle of ocean-thermal energy conversion (OTEC)

(Source: Okinawa Prefecture's brochure on ocean-thermal energy conversion demonstration facility)

With rising expectations for OTEC, which is regarded as a next-generation renewable energy source, the demonstration facility in Kumejima has been visited by not less than 12,000 observers from 68 countries worldwide since the operation commencement as it has been attracting attention as a facility that has showcased the practical utility of the system with the direct use of seawater.

It is not an innovative underlying technology that made OTEC feasible. The cycle, which is composed of the evaporator, the vapor of a medium, (turbine spins), and then the condenser, is the same as the cycle of typical thermal power generation with steam turbines. This is called a Rankine cycle. In Rankine cycles, the use of high-temperature, high-pressure steam of several hundred degrees centigrade generated by burning fossil fuels causes a large difference from the ambient temperature, leading to relative efficiency in power generation. However, a temperature differential of 20°C or so results in low efficiency and does not make the system practical.

In fact, running a typical Rankine-cycle plant with the use of temperature differentials created by seawater ends up with no net power obtained because the power generated is used to power the pump for drawing deep water. Against this backdrop, OTEC had not been put into practical use although its principle had already been proposed in the 1880s by a French physicist.

Uehara Cycle by researcher at Saga Univ.

Under these circumstances, in the 1980s, Dr. Kalina in Russia devised a cycle that used a mixed medium of ammonia and water as a working fluid and involved an additional regenerative cycle to preheat the working fluid with the use of the vapor that had spun the turbine. This was called the Kalina cycle, and made it feasible to generate power with a small temperature differential.

In the 1990s, the late Haruo Uehara, a former President of Saga University, developed an improved version of the Kalina cycle. This Uehara cycle, with two turbines and an increase in the regenerative cycle, successfully further increased efficiency. He was also engaged in the development of a heat exchanger with higher performance, and successfully increased efficiency in the exchange of heat with seawater by adopting an applied titanium plate-type heat exchanger in the generating facility.

In 2003, Saga University established the Imari Satellite of the Institute of Ocean Energy in Imari City, Saga Prefecture, and developed an OTEC system with a capacity of 30 kW as a demonstration of the feasibility of obtainment of the net power. Furthermore, the institute developed the multi-stage Rankine cycle, which facilitated reductions in power generation costs, and obtained an international patent. The multi-stage Rankine cycle was a combination of two or more cycles of a single medium, without the use of mixed media in the working fluid. The demonstration facility in Kumejima was put into operation in 2012 as an application of these findings obtained by Saga Univ. on the actual seawater, with a CFC substitute adopted as the working fluid (**Figure 3**).

Figure 3 ● OTEC demonstration facility located in Imari Satellite of Institute of Ocean Energy, Saga University

(Source: Nikkei BP)

Having had their eyes on these results achieved by Saga University in the early phase, Xenesys in Koto Ward, Tokyo has collaborated with the university to put OTEC to practical use. They have also jointly worked on the demonstration projects in the Imari Satellite and Kumejima. Since April, 2022, Mitsui O.S.K. Lines has also joined the running of the OTEC business in Kumejima. Mitsui O.S.K. became the first private enterprise to participate in a power generation business itself, not in the manufacturing or construction of the facility.

The demonstration facility in Kumejima has been capable of taking approximately 60 percent of the electric power generated by the turbine generator as the net output, with the remaining approximately 40 percent consumed for circulating the working fluid and as power for pumping seawater.

Situated beside the coast, the demonstration facility in Kumejima is a three-story OTEC plant with white and black pipes installed. The deep seawater of 8 to 9°C that has been pumped from the ocean floor approximately 600 meters below the surface is running through the white pipe, while through the black pipe, the surface seawater of 26°C is flowing. For the installation of the temperature sensor, a part of the white pipe remains without a heat insulator. The part is chilly to the touch with bare hands, with its surface covered with a thin film of condensation (**Figure 4**).

Figure 4 ● White pipe through which deep seawater of 8 to 9°C is running, and black pipe through which surface seawater of 26°C is flowing

(Source: Nikkei BP)

The second floor of the generation plant accommodates titanium plate-type heat exchangers, and a turbine generator is located on the third floor. As a demonstration facility, not entirely covered by the building roof and walls, the plant has operated for nearly a decade, with some noticeable scattered corrosion caused by sea breeze, which is said to have no impact on the operation (**Figure 5**) (**Figure 6**).

Figure 5 ● Two blue installations that are plate-like in shape contain plate-type heat exchangers

(Source: Nikkei BP)

Figure 6 ● Plate components for heat exchange displayed in Imari Satellite

(Source: Nikkei BP)

Demonstration facility in operation also in Hawaii

Professor Yasuyuki Ikegami, Director of the Institute of Ocean Energy, Saga University says "As OTEC research and development have now become active worldwide, it is also appreciated that the situation is a secondary boom. The Kumejima site's success was one of the factors that sparked off the recent OTEC boom."

Following the oil shocks in the 1970s, researches on OTEC had been actively pursued both in Western countries and Japan, but the fall in oil prices in the 1990s slowed down the researches in countries other than Japan because OTEC was regarded as technically feasible but not cost-effective. But the researches began to be active again in the late 2000s. The background "includes that the commencement of the large-scale introduction of renewable energy due to the global warming issue, which had become even more serious, raised the value of renewable energy sources that provide stable power generation as well as variable renewable energy sources like solar and wind power," says Professor Ikegami.

In addition, the growth of the binary-cycle power generation using a low-boiling-point medium, such as effective utilization of exhaust heat from plants and hot springs' heat, to a stage of proliferation and the progress in the underlying technology for enabling power generation with a small temperature differential are also major factors. He says that the success in Kumejima, a demonstration of the capability of continuous power generation by direct seawater as a result of a compilation of such cutting-edge technologies, encouraged many researchers in the OTEC field.

After the facility in Kumejima had started operating, in August, 2015, the world's second demonstration facility was put into operation with a capacity of 105 kW in the Island of Hawaii, the state of Hawaii in the

United States. The facility was installed by Makai Ocean Engineering, an ocean-related construction company based in the state of Hawaii. The state is aiming to use 100 percent renewable energy for electric power by 2045, with high expectations for OTEC (**Figure 7**).

Figure 7 ● OTEC demonstration facility completed in Island of Hawaii

(Source: Makai Ocean Engineering's website)

In 2020, with OTEC emerging again, the Ocean Thermal Energy Association was established. With participation by researchers, enterprises, governmental organizations, and others from not less than 38 countries and regions, the association is committed to sharing and disseminating information on OTEC, and chaired by Japan. The association holds an annual international symposium where a researcher who has made achievements in OTEC research and development is awarded the Uehara Prize. The prize is awarded in memory of the late Haruo Uehara, who worked to promote development of OTEC.

In the field of renewable energy, Japan and Japanese enterprises are reducing their presence year after year in terms of advanced researches, technological development, manufacturing of equipment and facilities, and others. However, OTEC can be viewed as one of a small number of renewable energy technologies in which Japan leads the globe.

To be enlarged to 10-to-100-MW scale in future

While expectations for OTEC are growing, it is also a fact that the high cost of generating power remains a high hurdle preventing practical use.

Professor Ikegami stresses that it costs so much to manufacture and install the intake pipe for pumping deep ocean water, which makes pursuing economies of scale essential to increase economic efficiency in OTEC. According to him, commercialization requires a capacity of at least 1 MW, and current estimates are that 10-MW-level power generation costs 20 to 25 yen per kWh, and that in order to aim to reduce the generation cost to 10 yen per kWh or lower for the base-load power source, an investment of five billion yen or more in 100-MW-level power generation will be required.

Japan is behind other countries in moving towards larger scales. In April, 2013, Lockheed Martin in the U.S. announced its joint OTEC project with an investment company in China to construct a 10-MW floating offshore system off the coast of China. Its roadmap presents the design concept of increasing the scale to 100 MW in the future, including ships transporting hydrogen or ammonia produced on the floating system to places in need.

On the other hand, Makai Ocean Engineering working on OTEC demonstration in Hawaii, having developed its design concept of a 100-MW-scale floating plant for commercial use, has revealed its estimates that advanced heat exchangers will make it possible even for a 10-MW-scale facility to achieve profitability (**Figure 8**).

Figure 8 ● Floating OTEC system being planned in Hawaii

(Source: Makai Ocean Engineering's website)

Deep ocean water leading to development of culture industry

Attempts are also being made to increase economic efficiency by combining efforts to reduce generation costs through economies of scale with another approach. "Since the uses of deep ocean water are not limited to power generation, sharing the costs of laying the intake pipe with multiple uses assumed allows a significant reduction in power generation costs," says Professor Ikegami.

Actually, the OTEC project in Kumejima also began with such an idea. In Kumejima, before the OTEC facility started operating, thirteen thousand tons of deep ocean water a day had been pumped and utilized for the culture of sea grapes and prawns for over a decade.

The OTEC facility is adjacent to the Deep Sea Water Research Center under the management of Okinawa Prefecture, and the pipe leading seawater to the power generation facility is connected from the water storage tank located in the research center for storing deep ocean water. Having been pumped from the ocean floor 600 meters down, the deep water is stored in this tank before being supplied to culture farms and the OTEC facility.

At depths of 200 meters and beyond, the temperature of deep ocean water is low throughout the year. In addition, phytoplankton cannot inhabit these deep ocean waters, which makes the water rich in nutrients such as inorganic salts (nitrogen, phosphorus, and silicon) and high in purity and cleanliness, e.g., with almost no bacteria. These characteristics make the water suited for inland aquaculture and production of foods and cosmetics.

With a concentration of prawn and sea grape culture farms around the Deep Sea Water Research Center, such deep water industries in Kumejima have grown to reach a production scale of approximately 2.5 billion yen (**Figure 9**).

Figure 9 ● In Kumejima, sea grape culture is active with deep ocean water utilized

(Source: photoAC)

Also for algae cultivation and inland oyster aquaculture

For these deep water industries and OTEC, with temperature zones, multi-stage utilization of deep water can be achieved without conflict. For culture and food production, post-OTEC process deep water of approximately 11°C can also be used. Indeed, in Kumejima, the deep water that has been used for power generation in the demonstration facility is sent to culture farms, etc. to be reused.

Aiming to increase the range of uses for deep water, enterprises have their research facilities around the Deep Sea Water Research Center in Kumejima. Rohto Pharmaceutical has developed the vegetable factory where the cooling effect of deep water is utilized for cultivation, and is working on the cultivation of algae, making effective use of the high purity and cleanliness and rich nutrients of deep water. Leafy vegetables are sensitive to high temperatures, making it difficult to grow many of them in tropical regions like Okinawa, but reducing the temperature with deep ocean water enables cultivation of these vegetables. In addition, microalgae are said to have a wide range of applications that are not limited to food materials but include coloring matters, functional materials, feed materials for production of fish fry for culture, and livestock feed. (**Figure 10**) (**Figure 11**).

Figure 10 ● Algae cultivation facility operated by Rohto Pharmaceutical in Kumejima

(Source: Nikkei BP)

Figure 11 ● Vegetable factory operated by Rohto Pharmaceutical in Kumejima, using cooling effect of deep water

(Source: Nikkei BP)

Also, General Oyster based in Chuo Ward, Tokyo, a firm rolling out a chain of oyster restaurants, oyster bars, across Japan, is tackling the challenge of becoming the world's first company to successfully culture oysters in an inland aquaculture facility. It may be feasible to achieve stable inland production of safer oysters by utilizing deep water of high purity and cleanliness (**Figure 12**).

Figure 12 ● Inland oyster aquaculture being carried out by General Oyster in Kumejima

(Source: Nikkei BP)

Further, the Imari Satellite, Saga Univ. is working on a system to desalinate seawater by reusing the deep water of approximately 11°C that has already been used for OTEC. Through the Hybrid OTEC Cycle, which combines the seawater desalination system that evaporates seawater in an enclosed space under reduced pressure and OTEC, although compared to a cycle where all the temperature differentials are converted into electricity, there is a reduction in power generated, fresh water can be obtained instead.

Shin Okamura, the manager of the OTEC Engineering Department, responsible for the administration and management of the OTEC facility in Kumejima says that whereas there is little need for fresh water in Kumejima, which is rich in underground water, there are remote islands where water is more valuable than electricity, and that deep water is utilized differently according to the region. "Enterprises eager to take advantage of deep ocean water to launch a new business have their research centers in Kumejima. They are accumulating expertise, stimulating each other. An approach to the future of the OTEC system has come into view; deep water will continue to be utilized as an energy source with an integration of an ever-wider range of industries," he says.

OTEC facility to be increased to megawatt scale

In January, 2021, Kumejima Town in Kumejima announced its Zero Carbon City Declaration, a commitment to eliminate emissions of greenhouse gases by 2050. The town's energy vision includes its plan to replace all of the energy consumed in the island with renewable energy by 2040. The primary means to achieve this goal are OTEC and solar photovoltaic power generation.

The town is aiming to increase the OTEC facility in scale, to the 1-MW scale in 2025 and to the 6-MW scale in 2035. This is the idea that the base-load power source will rely on OTEC, while daytime increase in demand will be covered by solar photovoltaic power generation (**Figure 13**) (**Figure 14**).

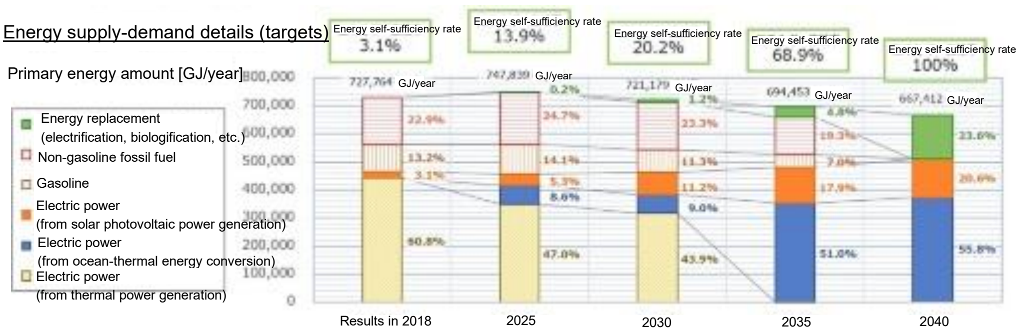

Figure 13 ● Energy mix scenario leading up to 100% renewable energy in Kumejima Town

(Source: Kumejima Town Energy Vision 2020)

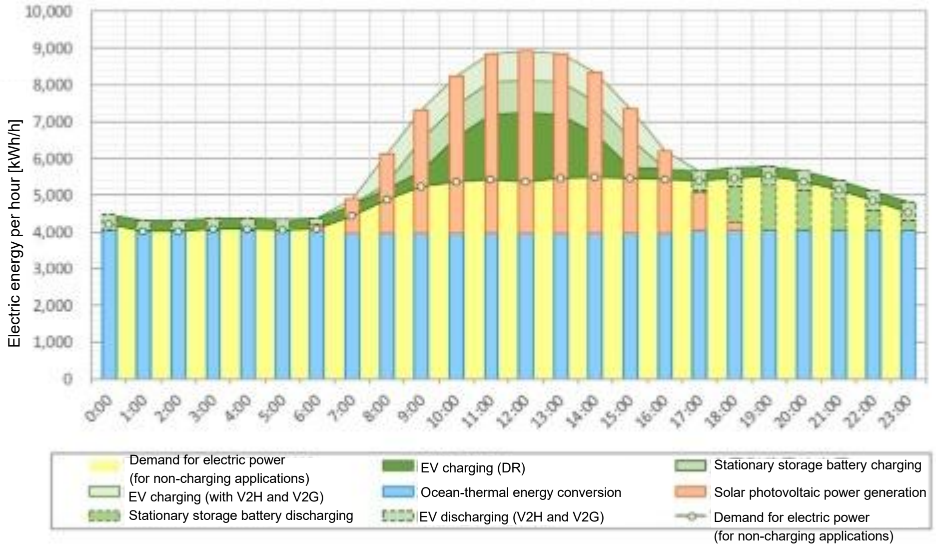

Figure 14 ● Simulation of supply-demand balances of electric power over day in 2035

(Source: Kumejima Town Energy Vision 2020)

In 2016, the town built a 389-kW solar photovoltaic power generation facility fronting the reservoir in the island. Furthermore, in February of last year, Kumejima Mirai Energy (based in Kumejima Town) was founded through regional funds, and began providing service that allows users to introduce the solar photovoltaic power system and storage batteries in their homes on an on-site power purchase agreement (PPA) basis without initial investment (**Figure 15**).

Figure 15 ● Mega-solar power plant operating in Kumejima

(Source: Nikkei BP)

In the case of OTEC, expansion of the current 100-kW facility to the 6-MW scale requires an even larger amount of deep water to be taken. Currently, the daily amount of water taken is 13,000 t, one of the largest amounts in Japan, all of which has already been consumed for the expansion of industries including the culture industry.

Therefore, the town is aiming to increase the amount of deep water taken ten-fold. Achieving this will allow the OTEC facility to be increased to 1 MW in scale and even to 6 MW.

Deputy Mayor Yukio Nakamura of Kumejima Town expects that they will be able to reduce greenhouse gases through multi-stage utilization of deep ocean water for OTEC, the culture businesses and others, leading to industrial development of the town, and create a win-win situation for the town and enterprises, which will energize the entire island.