Next-generation Energy-utilization and CO_2-conversion Technologies Contributing to Zero Environmental Impact

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Abstract

This article outlines next-generation energy technologies to enable the use of overwhelmingly clean and inexhaustible energy sources, which are expected to be put to practical use, and carbon dioxide (CO_2)-conversion technologies to effectively fix CO_2 and reduce the total CO_2 emissions of business activities to zero or less.

Keywords: fusion energy, space solar power, CO_2 conversion

1. Initiatives to use next-generation energy

To achieve a sustainable society, the Next-Generation Energy Technology Group in NTT Space Environment and Energy Laboratories is working on two themes: technology related to *fusion energy*, which is an overwhelmingly clean and inexhaustible energy source, and space solar-power-generation technology.

1.1 Optimal operation technology for fusion reactors

The fusion energy technology will be used to optimize fusion reactor operations by using the Innovative Optical and Wireless Network (IOWN). In May 2020, we concluded a comprehensive cooperation agreement with the ITER International Fusion Energy Organization (ITER Organization, where "ITER" means "the way" in Latin) [1]. In November 2012, we also entered into a partnership agreement with the National Institutes for Quantum and Radiological Science and Technology to develop innovative environmental energy technologies ahead of the rest of the world [2]. Fusion energy is produced by the sun and other stars in the universe. It is a nuclear reaction in which light nuclei fuse to form heavier nuclei. For example, in DT nuclear fusion reaction*1 in which the nuclei of deuterium (D), which is an isotope of hydrogen, and tritium (T) are fused, helium and neutrons are produced, and the energy generated from the nuclear fusion reaction of only one gram of deuterium and tritium is equivalent to the heat generated from burning about 8 tons of petroleum (a full lorry). The ITER project is a very large international project (**Fig. 1**) with the goal of using fusion energy for power generation. The seven regions of Japan, Europe, the United States, Russia, South Korea, China, and India are promoting the project, and preparations are underway at Saint-Paul-les-Durance in southern France to commence operation in 2025. Fusion energy, combined with more distributed renewable energy sources such as solar and wind, is expected to provide a safe and reliable energy for the world for millions of years.

In the ITER experimental nuclear fusion reactor, deuterium and tritium, which are forms of hydrogen

*1 DT nuclear fusion reaction: D + T = He (3.52 MeV) + n (14.06 MeV). To overcome the repulsive force of electric charge and to collide D and T, a speed of 1000 km/s or more and heating temperature equivalent to 100 million degrees or more are required.

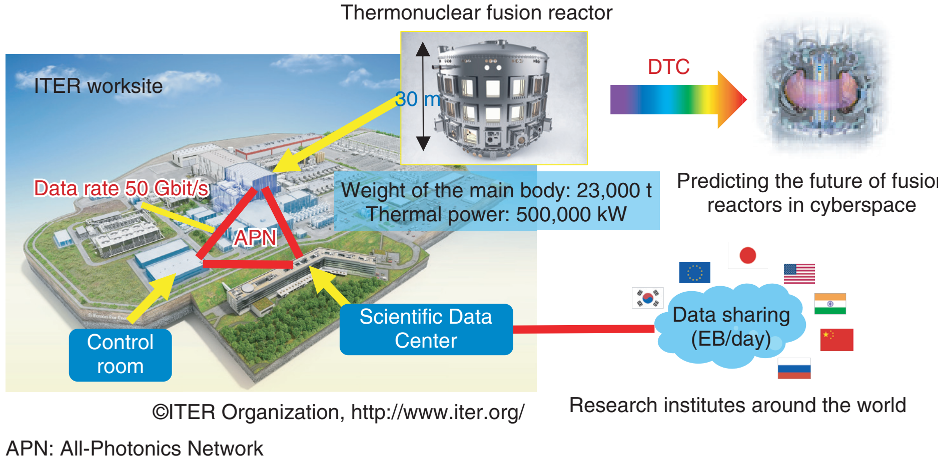

Fig. 1. Overview of ITER worksite and optimal operation technology for fusion reactors.

that serve as fuel, are confined in a doughnut-shaped magnetic field, heated to a plasma state, and further heated to 150 million degrees Centigrade to generate a nuclear fusion reaction. The ability to stably produce such plasma for extended periods is essential if we are to extract energy from a hydrogen fusion reactor. This requires an enormous volume of sensor data, up to 50 Gbit/s, obtained from the fusion reactor to be transferred to the control center, where optimal values for controlling the plasma shape must be instantaneously calculated and sent back to the reactor. To facilitate this, it is vital to further increase the speed and reduce the latency of the control network. In addition to the high-quality, large-capacity, and low-latency All-Photonics Network, which is one of the elemental technologies of IOWN, our goal is to achieve this by using disaggregated computing, which is a new computing architecture that enables high-speed and high-efficiency data processing. When a fusion reactor is put into full operation, experimental data at the exabyte (EB) level are generated per day. We believe that IOWN can contribute to the storage of such data in datacenters around the world and the high-speed replication between datacenters. We plan to further improve control technology by using Digital Twin Computing (DTC) to realistically reproduce a hydrogen fusion reactor in cyberspace, conducting highly advanced simulations, and predicting the future performance of a hydrogen fusion reactor.

1.2 Space solar-power-generation technology

Space solar-power-generation technology generates solar power on a satellite in geostationary orbit 36,000 km above the ground, transmits the energy to the ground by lasers or microwaves, and converts it back to electric power or other energy on the ground (**Fig. 2**). A satellite in geostationary orbit can receive

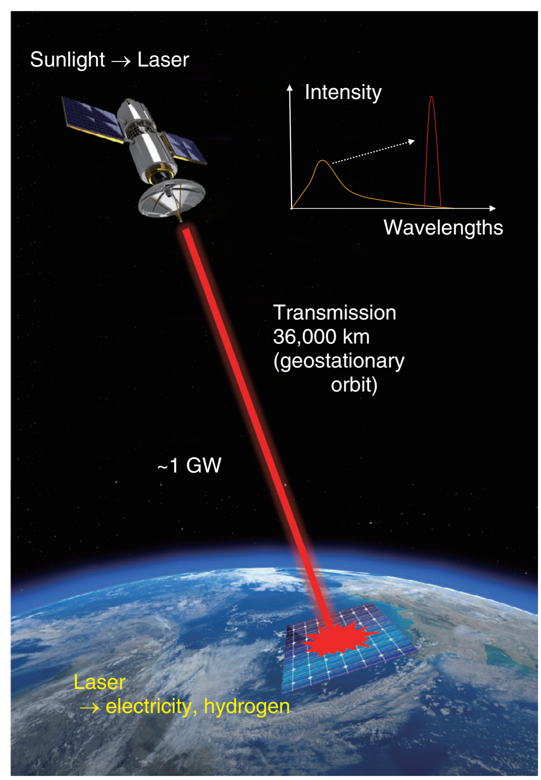

Fig. 2. Space solar-power-generation technology.

energy from the sun almost 24 hours a day, 365 days a year, and because the satellite is not affected by the absorption or scattering of energy by Earth's atmosphere, it can stably receive about 10 times more energy per unit area than on the ground. The Japan Aerospace Exploration Agency and other organizations are conducting research and development (R&D) with the aim of putting this technology into practical use after 2030, and if it is achieved, clean and inexhaustible energy can be used. Since the wavelength of lasers is about 3–4 orders of magnitude shorter than that of microwaves, we are investigating an approach using lasers because the beam divergence angle is small and it is easy to transmit over long distance.

There are three major technologies for generating space solar power. The first is effeciently converting sunlight into a laser on a satellite in geostationary orbit. Unlike the conventional method of laser oscillation using power generated from solar cells, we are conducting research on a system that executes laser oscillation with high efficiency by directly irradiating a special crystal with sunlight to excite a laser. The second technology accurately irradiates a target on the ground with a laser beam. Although the laser can be easily transmitted over long distance, a direction control accuracy of 0.3 µrad (2×10^{-6} degrees) is required to irradiate a laser beam with an accuracy of ± 10 m from a satellite in geostationary orbit. The effects of atmospheric turbulence must also be removed. Therefore, we are conducting research on optical systems with deep focal depths such as the Bessel beam[*2] and beam transmission systems that use adaptive optics[*3] used in astronomy to eliminate fluctuations in light propagating through the atmosphere. The third technology converts lasers into energy with high efficiency. Since laser light is a single wavelength, unlike sunlight in which light of various wavelengths is mixed, we are researching solar cells with high conversion efficiency at specific wavelengths. When a laser is converted into electric power using a solar cell, about half the energy becomes heat. Therefore, we are studying methods of storing energy in different forms such as hydrogen and ammonia using thermochemical reactions instead of converting lasers directly into electricity. We believe that this technology can be key to achieving a hydrogen-based society.

2. Efforts to reduce carbon dioxide (CO_2) emissions to zero or less

To contribute to the restoration of the global environment and achieve a sustainable society, the Sustainable Systems Group is engaged in the R&D of sustainable systems that reduce all environmental loads to zero or less and their implementation in society. Below zero means not only reducing emissions but also reducing what already exists. There are various factors in terms of environmental impact, and one is CO_2. Under the Paris Agreement, reduction of CO_2 emissions is required. Therefore, the Sustainable Systems Group has been conducting R&D on two approaches to reduce CO_2 (**Fig. 3**).

2.1 CO_2-conversion technology (electrochemical approach)

One approach is an electrochemical approach that applies the semiconductor technology used in communication devices and the catalyst technology used in fuel cells. This involves the R&D of CO_2-conversion technology for generating hydrocarbon fuels such as methane and formic acid, which is a storable hydrogen carrier, from water (H_2O) and CO_2 using light and electromagnetic energy such as solar light, as well as reducing the amount of atmospheric CO_2. This is also called *artificial photosynthesis*[*4] because it mimics the photosynthesis of plants that use sunlight and other light energy to synthesize carbohydrates from H_2O and CO_2. An advantage of the electrochemical approach is that it enables the production of storable fuel (source of energy) from natural energy sources such as solar light, which can be used in a variety of applications, and is expected to be a carbon neutral energy source.

There are still problems regarding practical application. For example, a semiconductor device (material) that generates hydrogen ions and electrons using the energy of sunlight is installed in water as an electrode, which ionizes (corrodes) the surface of the device and degrades its performance. Since the wavelengths of light that can be used as energy are limited

*2 Bessel beam: A type of non-diffracted beam in which the beam does not expand because of diffraction phenomena.

*3 Adaptive optics: A technique to improve image quality by measuring the fluctuation of an image caused by the atmosphere with a wavefront sensor and correcting it dynamically.

*4 Artificial photosynthesis: This technology imitates the action of plants to produce starch and oxygen from carbon dioxide and water using solar energy and generates organic substances from carbon dioxide and water by chemical reaction using solar energy and water used as raw materials.

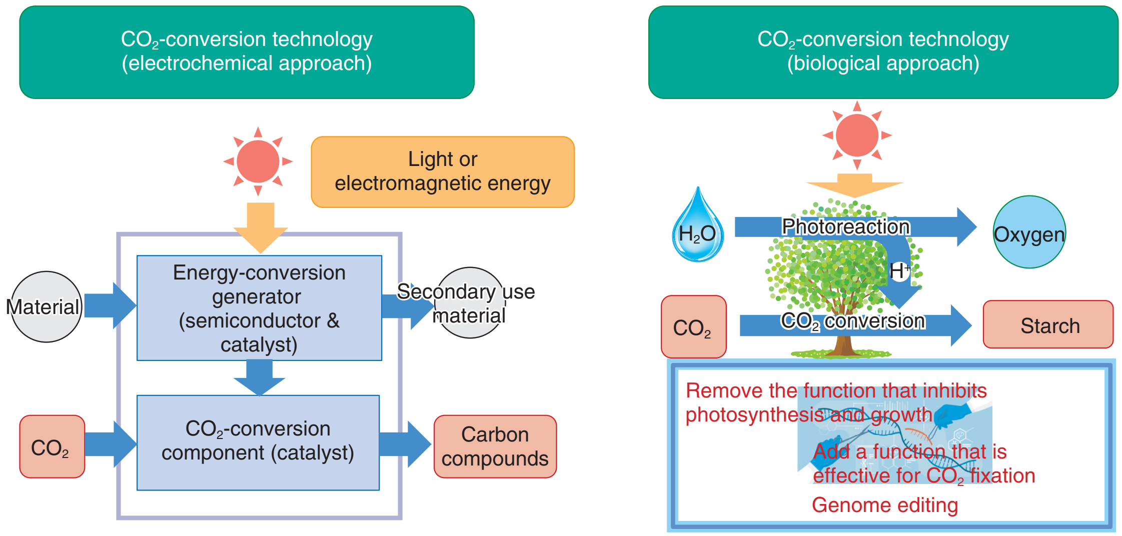

Fig. 3. Two approaches of CO_2-conversion technology.

depending on the physical properties of semiconductor devices, a wide bandwidth that can absorb energy of various wavelengths is required. It is also necessary to establish a technology to extend the life of catalysts for reducing CO_2 by reducing performance degradation due to repeated chemical reactions. Therefore, the group is collaborating with NTT Device Technology Laboratories, which has experience and skills in semiconductor devices and catalysts.

There are also operational and safety issues for the practical application of CO_2-conversion technology using the electrochemical approach. For example, many artificial photosynthesis systems currently under development are evaluated for their performance in laboratories and other environments that are relatively easy to control. For example, although highly pure and highly concentrated CO_2 is often added from gas cylinders in the laboratory, it is necessary to act on approximately 0.04% of the atmospheric concentration of CO_2 with high efficiency.Therefore, R&D on a technology called direct air capture (DAC) for directly recovering low concentrations of CO_2 from the atmosphere is being promoted. However, if the combination of an artificial photosynthesis system with DAC becomes essential, the cost becomes even higher, and an optimal design is required so that either one does not become a bottleneck. In addition, hydrogen and carbon monoxide are included in the gases used as raw materials for electrochemical reactions, and strong safety designs are required to prevent these gases from being released into the atmosphere in the event of an emergency. For practical application of CO_2-conversion technology using this electrochemical approach, it is not enough to simply pursue efficiency, it is also essential to search for optimal solutions that simultaneously solve operational and safety issues.

2.2 CO_2-conversion technology (biological approach)

The other approach to CO_2-conversion technology is the biological approach that maximizes the photosynthetic function of plants and algae through genome editing[*5] and optimal control of breeding and growth environments. Over the past 30 years, the area of forests around the world has been increasing, but it has been reported that the diversity and soundness of forests have been decreasing due to global warming and logging. This may indicate that the natural division of roles necessary for the symbiosis and coexistence of the vegetation forming the forest and the organisms and microorganisms living there are not optimum. Therefore, we are carrying out R&D for maximizing the photosynthetic capacity per plant by making full use of genome-editing technology and growing-environment control technology by accelerating the time when plants activate photosynthesis

*5 Genome editing: The technology to change the characteristics of an organism by editing a specific base sequence (DNA sequence) in the genome of the organism.

(early growth) and maintaining that time for a long period (long-term soundness). If we can increase the forest area where photosynthesis is enhanced per tree, we can achieve long-term carbon fixation through plants. If we focus on vegetables and trees, which are food and industrial resources, we can absorb more CO_2 during the growing season by promoting early growth while maintaining high quality, and after harvesting and felling, we can use vegetable and tree wastes for other carbon cycles. Regarding algae, we believe it is possible to efficiently absorb CO_2 dissolved in water and improve the environment of wetlands and seagrass beds by using genome-editing technology and environmental-control technology to proliferate algae within a short period.

The issues with CO_2-conversion technology using the biological approach are as follows. Trees, which can fix carbon over a long period and have a high photosynthetic capacity, have a large number of genes, and it takes a great deal of time to analyze genome and identify the genes that determine early growth and long-term health. Even if genome editing is carried out, it is not easy to confirm the effects of such editing because it takes many years for trees to grow.

Although genome analysis and editing are relatively easy regarding algae due to the small number of genes, a large amount of energy is required for resource recovery (machining) to increase added value after growth and for disposal of the parts of algae that cannot be used effectively.

Therefore, we are studying using DTC, one of the elemental technologies of IOWN, as a time-saving means to verify the effect of genome editing on trees. If an analytical model of plants and growing environments can be constructed in a virtual space and virtual growth simulations can be conducted, the effects of genome editing should be predicted in a short period without real verification such as cultivation. If it is possible to select genetic characteristics with low disease risk at the seed and seedling stages, selective breeding can be achieved. Regarding the issue of algal waste, we believe that it is important to efficiently link a number of carbon cycles such as providing algal waste as food and resources to other organisms.

3. Future developments

The challenges we are taking on concerning next-generation energy-utilization and CO_2-conversion technologies were outlined in this article. Technologies developed through optimization of fusion-reactor operation will be applied to other industries as a use case of cooperation among cyber-physical systems through real-time control. We plan to commercialize the space solar-power-generation technology by introducing it on the ground for supplying power to devices such as drones for long-term operation and supplying emergency power to evacuation centers and isolated islands.

To address these issues with the CO_2-conversion technology at an early stage, we will promote R&D focusing on where the effects of information and communication technology can be expected, such as physical properties of electrochemical materials, useful genomes of plants and algae, and virtual growth simulation.

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