Moonshot R&D MILLENNIA* Program

*Multifaceted investigation challenge for new normal initiatives program

"Research on the realization of the personal grid (PG) that can be integrated whose core technology is electrolysis" Initiative Report

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1. MS target proposal

1.1 Names of the MS target proposal

"Realization of the society that offers home with personal circulation systems for energy, materials and water by 2050."

1.2 The vision of the society we would like to realize by 2050

Realize a society where everyone, regardless of where they are living, will be circulating the energy, materials and water that are enough for survival within the unit of their living space by 2050. Until now, energy/materials/water have been provided to individual living space via large-scale infrastructures. By reducing this infrastructure network to the level of individual living space, it will be possible for everyone to locate the base of their life in the location/land they want. Concretely, this will involve: ① Radical reduction of the CO_2 emission from living spaces by perfectly integrating the renewable energies to the energy circulation. ② In addition to the elimination of plastic wastes through decomposition, polymerization and molding of polymeric materials, production of fake meat using the amino acid synthesis technology will be enabled as material circulation. And ③ securing of safe drinking water everywhere through water circulation and appropriate wastewater treatment is enabled for individual living space. If every living space retains these three circulations, it would dramatically reduce the dependence on the existing infrastructures, and the effect on critical infrastructure caused by natural and manmade disasters can be minimized. Moreover, as it would enable construction of closed system at each living space unit, it would allow building of a society that is resilient against pandemics such as the one caused by COVID-19.

Meanwhile, as it is predicted that by 2050, the diverse lifestyles using the digital space and AI/robots as envisaged in other Moonshot targets will be realized, enabling one to live in diverse environments not only in the digital space but also in the real world, new cultures based on unprecedented values will be created.

The system that can realize circulation of energy, materials and water that are enough for survival is called the personal grid (PG). In the society of 2050, where the PG is widespread, people can live in any place they want, not only in the digital space but also in the real world, and they will be sharing a new culture based on more diverse values with the whole world, without being limited by their locations.

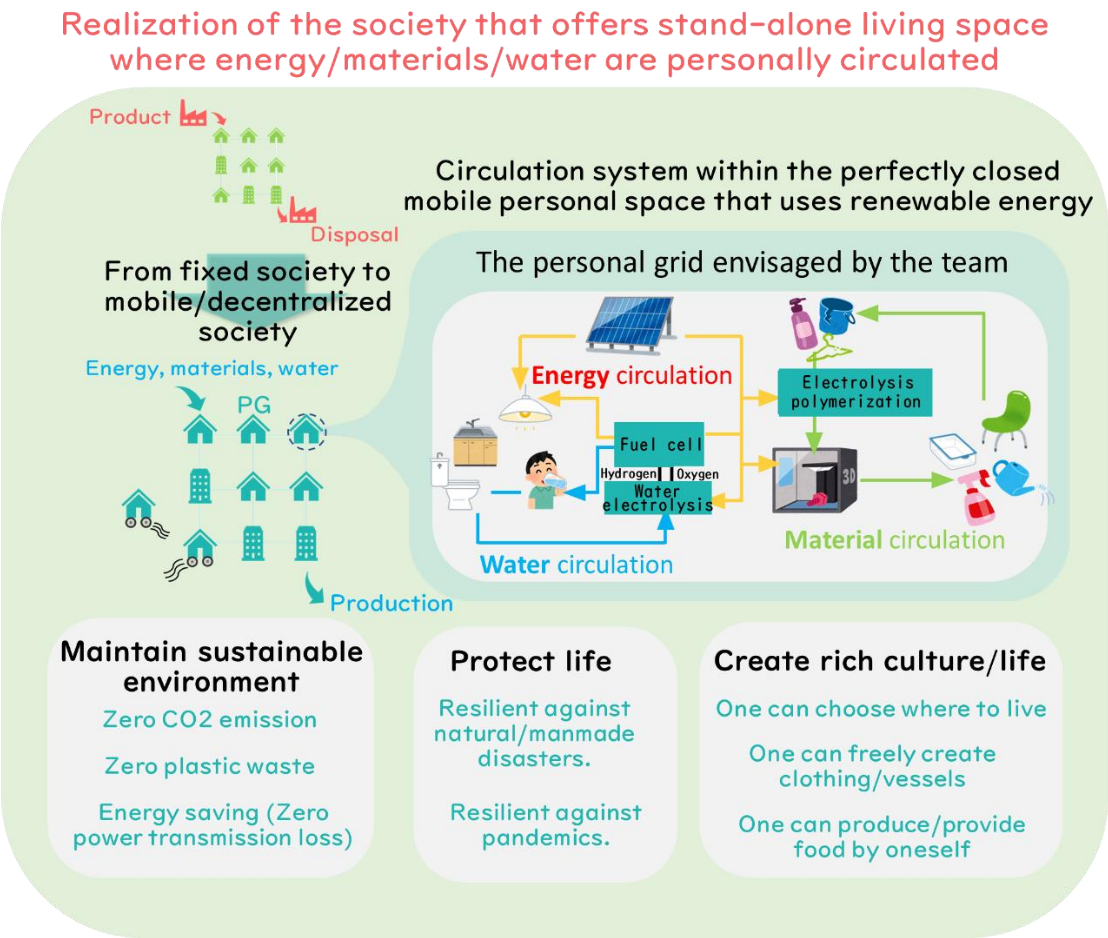


Figure 1 Vision of 2050 society

2. Targets(The scenes where this MS target are achieved. What will be achieved by 2050 (and 2030))

By 2050, three circulations that are the foundation of the PG, namely those of energy, materials and water, will be built for each living space. The concrete examples and targets to be achieved for each circulation are as follow.

① Energy circulation

We will work toward building a system that can generate the energy necessary for basic living at each living unit by using renewable energies and fuel cells capable of flexibly responding to the changes in energy demand when combined with domestic storage batteries. This is a target for 2050. As this system will cause major changes to existing electricity distribution, it may lead to the disappearance of "purchasing externally supplied electricity" as conducted today.

The system to aggregate and optimize the energy demand of each living space is already established as the Home Energy Management System (HEMS). Following the "Green Policy Principles" (National Policy Unit, Secretariat of the Cabinet Office) from 2012, the target is to install a HEMS in every living space inside Japan by 2030. Thus, the HEMS that balances energies within a living space unit is already constructed, and it is assumed that it will have have experienced further updates through the expansion of the ICT technology in society. Power generation by HEMS is conducted by the renewable energies, especially solar power, as well as fuel cells. Both of these power generation methods are part of the national project toward 2050 by the New Energy and Industrial Technology Development Organization, which examines how to increase power generation, reduce cost, prolong lifespan, etc. Moreover, discussions for instance on hydrogen storage technology, which is the fuel of the fuel cells, are ongoing. In addition, development of innovative batteries that are low cost, with high energy density and high output density is also similarly ongoing as a national project on power storage technology. Furthermore, there is an ongoing national project on the electrolysis technology which supports power generation by fuel cells. Therefore, it is inferred that the elemental technologies for circulating energy within individual living spaces by 2050 can be realized thanks to the benefits of the achievements of other national projects.

As interim goals, targets are set to bring the power generation cost of solar power to 7 yen/kWh, conversion efficiency of its practical module to 25%, the power generation performance of fuel cells to 6 kW/L, and its system cost to less than 4000 yen/KW by 2030. At the same time, performance of 500 Wh/kg and long lifespan of more than 15 years are required of the secondary batteries. In addition, system reforms are required, such as enactment of the feed-in tariff law for purchase of renewable energy at more favorable price. It is predicted that installation of a HEMS at individual living space will be realized by achieving these interim goals.

② Material circulation

By 2050, it will be possible to recycle clothing and plastic material that are necessary at minimum for living, to produce fake meat through amino acid synthesis and cultivation of agricultural products at individual living spaces. This will eliminate generation of domestic plastic wastes, enable production of the basic clothing and everyday goods necessary for survival with a 3D printer, and allow cultivation of fake meat and agricultural products on one's own.

Today, recycling of plastic wastes is already conducted. For instance with PET resin, the technology to return polymer products to the monomer material and reuse them is already established. Thus, it is expected that by 2050, new materials and their circulation technologies that can decompose polymers other than PET resin to monomer will be established. Moreover, examination of amino acid synthesis technology that utilizes electrolysis technology has already started, suggesting synthesis of artificial fake meat is not impossible. Furthermore, examination of production of clothing and food using 3D printers is already ongoing, and technological innovations to bring it to the scale that can be used in individual living spaces are expected to occur by 2050. In addition, the technologies to cultivate agricultural products are already established. However, synthesis of ammonia or utilization of organic wastes (kitchen refuse and excrement) as biomass as fertilizer is necessary, considering that a living space is a closed system. Thus, in order to realize material circulation by 2050, examinations of dramatic energy and size reductions of existing ammonia synthesis technology and biomass utilization technology are necessary.

As the interim goals, establishment of technology to decompose polymers other than PET resin to monomer as well as amino acid synthesis technology that utilizes electrolysis technology by 2030 are set as the target.. Furthermore, establishment of small-scale ammonia synthesis technology will be aimed.

③ Water circulation

By 2050, it will be possible for everyone to secure safe drinking water anywhere and conduct appropriate wastewater treatment and water access at individual living space unit. By circulating water within the living space unit for this purpose, it will be possible to secure drinking water regardless of the environment of the dwelling and eliminate domestic wastewater, including sewage.

Today, an integrated system of sea/fresh/sewage water recycling has been developed by the Global Water Recycling and Reuse System Association, and its demonstration has started abroad. However, this system anticipates a large-scale facility, and its scale has to be reduced down to the individual living space unit. Moreover, an example of small-scale water circulation system includes the water recycling system installed on the International Space Station. This system can recycle approx. 18 L/day, while the next generation small water recycling system can recycle approx. 1 L/day. Furthermore, the water generated by the fuel cell used in the energy circulation field can be used as drinking water, in addition to the recycling of wastewater obtained from the surrounding environment. Therefore, it is expected that by 2050, a small water circulation system at the scale appropriate for individual living space will be in place.

As an intermediate goal, we aim to establish a water circulation system that can produce 100 L/day of drinking water from domestic wastewater, including seawater and manure, by 2030. We also aim to establish hydrogen production technology by direct electrolysis from seawater and organic wastes as a collaborative field with other circulation systems.

In order to install the PG in society by 2050, development of a next generation HEMS that enables close coordination and mutual information transmission of the abovementioned three circulations is essential.

3. Purpose for setting this MS target, social significance of achieving the target, etc.

3.1 The reason why the setting of this MS target and the measures to achieve this target is necessary now

In the society of 2050 where 1 to 7 moonshot targets currently under the examination are realized, lifestyles, including employment types, will change due to the development of the digital space, AI and robot technology; healthy lifespan will be further prolonged due to the realization of super-early medicine and remote medicine, and sustainable resource circulation and new food supplies in harmony with the environment will be realized. The universal quantum computer that sustains these changes will have been developed. Therefore, it is inferred that the sense of values in 2050 will be significantly different from the existing ones. However, even if the existing moonshot targets are reached, the main place of residence for people is predicted to be the urban area. Thus, the current situation, which is weak against natural and manmade disasters, vulnerable against pandemics such as the one caused by COVID-19 and regional gaps in various areas are easily created, will not radically change.

Interestingly, the main areas of residence have not changed significantly from the first formation of cities to today. In fact, people are still living in the areas where the Sumerian city states, which are the earliest known civilization, were located, and people are also still living in the area around the three great pyramids of Egypt. One reason for this is the fact that various infrastructures were constructed in cities in each era, making them convenient to live in. Especially the infrastructures that supply materials and water, including the distribution that we take for granted today but is essential for living, are potentially the factor that holds people to one place. In general, new cultures are created in the places where many people gather. Thus, it is predicted that in the future, which is the continuation of today, the center of culture will be the metropolitan areas, as is the case today. Naturally, cities that are the center of culture attract people. Therefore, it is easy to imagine that by 2050, the regional gap that is widening today will be further exacerbated. Indeed, the 2050 grand design of the country by the Ministry of Land, Infrastructure, Transport and Tourism, estimates that 60% of regions will have less than half of the population compared to today, and 20% of the total will be uninhabited. Such regional gaps will push up the usage fee of various infrastructures, preventing distribution of population to the depopulating areas. In order to correct the regional gaps and construct a dispersed society that is resilient against disasters and pandemics, it is necessary to enable everyone to have an equally healthy and cultural life regardless of where they are living. As it consists of energy/materials/water circulation systems for individual living spaces, the PG can be considered as a means to promote this dispersed society.

Examples of the technologies that build energy circulation within the PG include renewable energy-related technology, fuel cell technology and hydrogen storage technology. These are important technologies for realizing a sustainable low-carbon society. Similarly, the technologies for building material circulation is also the technologies to process plastic waste, which is a problem widely debated today, and the technology to synthesize fake meat through amino acid synthesis will increase the food self-sufficiency rate of Japan. The purification technology that will build water circulation is the technology for obtaining drinking water where it is needed both inside and outside of the Earth. This purification is essential in places such as space colony and underwater city. The technologies that support each circulation the PG consist of are in high technological demand also for other purposes.

Thus, the PG is a system that integrates science and technologies from other fields, and the performance required of its component technologies is at the same level as other national projects, which is extremely high. Therefore, it is impossible to engage with the PG in a short term, and it is necessary to promote it as a national research and development program of our country.

3.2 Social significance of achieving the target

First, the social significance expected of each circulation is outlined because the PG consists of three circulation technologies, namely of energy, materials and water.

In the energy circulation, the goal is to build a system where the energy necessary for basic living is generated through renewable energy and fuel cell at each living space that is capable of flexibly responding to changes in energy demand through combination with storage batteries. Self-sufficiency in energy implies free choice of living space and access to the digital space without being constrained by the social infrastructure for power and energy supply. It will enable minimization of damage caused by natural and manmade disasters as well as speedy recovery from them.

Moreover with the PG, it is possible to generate more energy than required for personal consumption. Thus, it is possible to turn the household sector consumption, which is approx. 14% of the primary energy consumption in Japan (Fiscal Year 2019 Comprehensive Energy Statistics), into a production sector from a energy consumption section, bringing forth the era where individuals receive payment for electricity instead of paying for it. Generation and supply of electricity from renewable energy and fuel cell not only do not generate CO_2 from the household sector, but they also contribute to the CO_2 reduction in the industrial sector, to which the electricity is going to be supplied. Thus, the PG will be an effective social system for realizing a carbon-neutral society.

In the material circulation, the goal is to create a system that enables recycling of clothing and plastic products, production of faux meat consisting of amino acid synthesis, and production of crops using organic waste. By decomposing plastic wastes and chemical fibers into monomers, which are their material, and then re-polymerizing them, it will be possible to eliminate generation of plastic wastes. After re-polymerization, the materials can be remade into clothing and plastic products using a 3D printer. Through this, all old clothing and plastic products generated by each living space will become materials for new products. The inhabitants of the PG will be able to purchase design data and produce plastic products using this data. For food, in addition to the fake meat production through electrolysis synthesis of amino acids, they will be able to cultivate agricultural products inside the PG using the modular plant factory according to their needs. The inhabitants will purchase recipe data, and produce the necessary amount of food from the agricultural products whenever required using the 3D printer.

The material circulation in PG will enable everyone to obtain the clothing, plastic products, food, etc. that they want at any time regardless of where they are. At the same time it will be a social infrastructure that can respond to situations where obtaining food is difficult due for instance to disasters or poverty. All waste generated by each living space will become materials for new products or fertilizer for the agricultural products, which will eliminate wasted food. Thus, it will reduce discharge of common wastes, plastic wastes and food wastes into society, allowing significant reduction in the scale and cost of the existing waste treatment and recycling system. Moreover, as cooking ingredients will be produced through amino acid synthesis or at the plant factory, which will be then directly processed into food by the 3D printer, it will be possible to increase the food self-sufficiency rate of Japan while eliminating the environmental burden generated by agricultural cultivation, food production and their transportation.

The goal of water circulation is to build a total circulation system of water that allows everyone to secure safe drinking water and eliminate wastewater discharge regardless of where they are. The water circulation system, composed of the technology to turn seawater, river water and rainwater into drinking water and the wastewater purification technology, will enable every living space to secure drinking water and treat sewage. Thus, it will provide a social infrastructure even to the areas without waterworks and sewers. Meanwhile, it can also reduce the risk of cutoff of water supply and reverse flow during disasters, as well as the repair cost of these, in the urban areas.

In Japanese society, where the population is decreasing, the increasing maintenance cost and water intake cost from the social infrastructures related to waterworks and sewers, as well as the size of inequality in their usage cost between regions and generations, are becoming serious problems. In the stand-alone and decentralized PG, as well as in the integrated grid (IG) that integrates the PGs, such inequality does not exist. Moreover, society at large will have only small maintenance costs. Thus, it is highly likely that these grids will become the new social infrastructure. Furthermore, the byproducts of the water circulation system, such as the ammonia and various organic wastes obtained during the wastewater treatment, will be separated and refined, and supplied as the fertilizer or compost for agricultural product cultivation to the aforementioned material circulation system. Thus, the water circulation system also functions as a part of the material circulation system. In addition, hydrogen production by direct electrolysis from seawater and organic wastes is closely related not only to the water cycle but also to the energy cycle and material cycle system.

The PG provides energy, materials and water circulation system to everyone. Its function is beneficial not only in the depopulated areas and countryside where the social infrastructure is insufficient, but also in the urban areas as it provides a new type of social infrastructure. By 2050, more diverse senses of values will be accepted in society due to the development of digital technology, AI and robot technology. Thus, it is predicted that the residential areas will be distributed between countryside and urban areas according to the individual sense of values.

In the urban areas, a new social infrastructure will be realized through the IG that integrates the PGs as shown in Figure 2. While development of similar systems such as Peer to Peer (P2P) and Internet of Energy (IoE) are already ongoing today, the integrated system will enable circulation of the three resources of energy, materials and water in coordination within specific areas. In cities where IGs are built within areas such as city block, apartment building or neighborhood, production and consumption of energy, materials and water are optimized within each area, building a new, stand-alone and decentralized social infrastructure that can maintain/manage systems such as power grid, waterworks and sewer network, garbage collection, recycling and food production in a batch.

Moreover, as the amount of production and consumption of the electricity, water, amino acids, monomer, agricultural products, fertilizer, etc., produced at each living space within an integrated system will be different, it will be possible to optimize the supply and demand balance within the grid by for instance setting a local currency for the grid. At the same time, it will be possible to build a business system between IGs or with external companies. Here, the IGs are connected through the network-type system, building a regional social infrastructure that can optimize the circulations of energy, materials and water within the whole region.

Both in the countryside and the urban areas, the PG and the IG will unify the energy/materials/water circulation system and provide a stand-alone and decentralized social system where the production of materials and products as well as their consumption, usage and recycling will be conducted within the grid. Moreover, as everyone will be provided with the life base of food, clothing and shelter necessary for living inside the PG, it is highly likely to become the new foundation of a society for the people to live comfortably regardless of where they are living, their occupation, age, family structure or income.

Thus far, the social significance of the PG is discussed from the perspective of each circulation. However, when the overview of its social impacts is considered, the following three “key concepts” become apparent.

The first key concept is “Maintenance of sustainable environment”. In the PG, CO_2 emissions from each living space will be zero thanks to the utilization of total renewable energy, achieving carbon neutrality in the household sector. Moreover, in the material circulation, plastic wastes and food wastes from each living space will be eliminated, and therefore, environmental burden caused by the landfill, burning, chemical treatment or transportation of these will also be eliminated. Furthermore, as food production will be conducted within the grid, the impacts on water and soil or CO2 emissions from the production and transportation of agricultural goods and food can also be eliminated. In addition, as the water circulation will eliminate usage of surface water and ground water, as well as discharge of wastewater, environmental burden on water resources from the household sector or on the natural resources from mega water supply facilities such as dams will also disappear.

The second key concept is “Protection of life”. The PG is a mobile system where each individual can enjoy an independent living space without being constrained by the existing large-scale grid. It will enable residential space to move from the areas where many natural/manmade disasters, such as earthquake, typhoon, flood, heat wave, cold wave and fire, are predicted. Moreover, even when an entire area experiences a natural disaster or a pandemic, forcing the residents to live in a harsh natural environment, it will be possible to live within the PG or the IG. Especially in the urban areas, which are considered to be vulnerable to disasters, formation of the IG will protect the social infrastructures that support the lives of people and will enable fast recovery from the disaster.

The third key concept is "Creation of rich culture and life". In the PG, each residence is a closed system, which allows more choices in where one can live. Not only can each individual live in diverse types of spaces, but it will also enable formation of cities by integrating multiple units. As the IG, which integrates PGs, allows bottom-up city formation, construction of cities will be possible in diverse living environments such as desert, mountainous area, remote island, on the ocean, bottom of the ocean or in space. The realization of diversification of residential areas will encourage creation of new cultures and senses of values based on diverse perspectives. Moreover, the environment where anyone can select the place they want to live, grow their necessary food using the food factory, and create freely designed clothing and household items or food they want to eat using the 3D printer will lead to the creation of rich culture and lives.

The objective of the PG is to build a society where everyone, regardless of their nationality, race, location, occupation, age, family structure or income, can live a comfortable life protected from natural and manmade disasters without impacting the environment, and where new culture/life based on diverse senses of values is created. Thus, its realization has a large social significance.

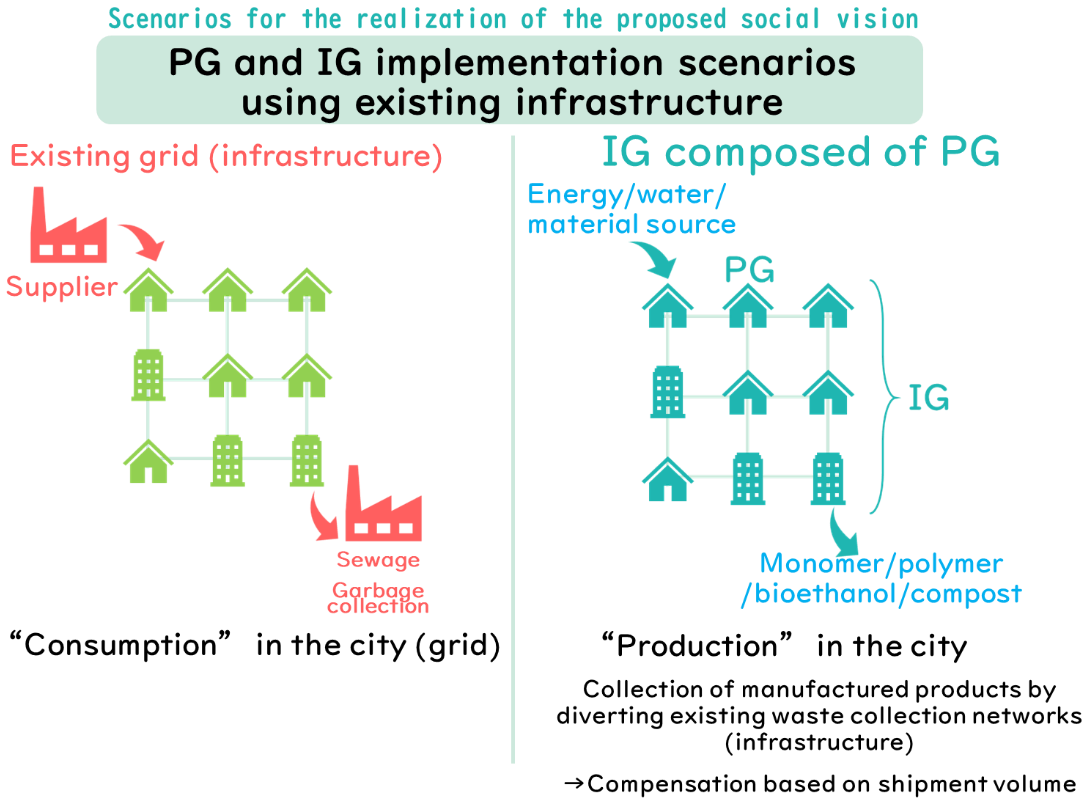


Figure 2 Scenario for the introduction of Integrated Grid (IG), which consists of Personal Grid (PG).

3.3 Outline of the efforts by society at large for achieving this MS target

The following is a list of items to be concretely examined for the realization of the PG organized by each circulation.

① Energy circulation

1. Increasing the efficiency of renewable energy use, mainly solar power.
2. Hydrogen production and storage technology
3. Increase of fuel cell output/durability
4. Size reduction and capacity increase of storage battery and prolongation of its lifespan
5. Feed-in-tariff (FIT) and separation of power generation and distribution

While technological development by researchers/technicians from both industry and academia is essential, it is also necessary to design the post FIT system together with the consulting businesses and economic analysts in response to electricity distribution that is shifting toward market liberalization.

② Material circulation

1. Establishment of material conversion technology that can convert freely between polymers and monomers (manufacturing and recycling of plastic products)

2. Establishment of small-scale highly efficient amino acid synthesis technology
3. Establishment of small-scale, high-efficiency ammonia synthesis
4. Manufacture of clothing and food products by 3D printing

Technological development by researchers/technicians from both industry and academia conducted across disciplines including chemistry, agriculture and biology is essential.

③ Water circulation

1. Technology to turn seawater, river water and rain water into drinking water
2. Purification technology of wastewater that contains excrement
3. Technology to produce hydrogen directly from wastewater that contains excrement, seawater, river water and rain water

Technological development by researchers/technicians from both industry and academia conducted across disciplines including chemistry, agriculture, biology and hygiene is essential.

④ Electrolysis technology and PG-related technology required for the three cycles

1. Miniaturization of reactors for PG scale (microreactors)
2. High-efficiency electrolysis technology with high generation rate to satisfy demand
3. Modularization of reactors and reaction systems for portability
4. System technology to control energy, mass balance, and efficiency between each circulation

It is necessary to collaborate in research and development in a wide range of fields, including system technology, mechanical design, and catalyst synthesis, as well as electrolysis engineers.

4. Changes in the social/industrial structures brought about by achieving this target

In the PG, a circulation process where all waste generated from energy, materials and water will become materials for other processes is formed. The massive and concentrated social infrastructures of today that provide energy/materials/water and treat wastes and wastewater will shift to the decentralized network-type social infrastructures that will calibrate the excess and shortage of energy/materials/water among the PGs and will provide monomers, ammonia and amino acids generated by the PGs to industry. Large-scale power plants, power transmission facilities, dams, waterworks, sewer and waste treatment plants whose construction, maintenance and updating cause social problems will become unnecessary and the cost paid by society at large for social infrastructure will decrease. In such a society, a sustainable life base that incurs little economic burden will be provided to every resident living in the PGs, and at the same time, the international competitiveness of the companies and industrial facilities based in Japan will be strengthened.

It is highly likely that Japan will also experience global-scale environmental/social risks such as climate change, water shortage, destruction of nature and pandemic. The PG will be able to adapt to such situations, and will enable living and economic activities of people in regions with inadequate social infrastructure or areas with harsh living environment. Thus, by expanding the PG into diverse areas including the countryside and urban areas or internationally, it will be possible to promote a new infrastructure industry of Japan that can simultaneously solve social problems and achieve good economic performance.

In addition to the social infrastructures, provision of clothing, food and household items made of plastic are essential for people to live. In the PG, these are produced/consumed within the grid. From the outside, design for clothing, design drawings for plastic products, food recipes, plant seeds and knowhow for their cultivation are what will be purchased mainly. This will lead to the clothing/food/household item industries experiencing a significant shift to the so-called intellectual property industry that provides information instead of objects. Similarly, a sharing system for the PGs themselves where the service is provided to the inhabitants by the regional energy companies and regional resource companies who perform installation, management and moving is expected. It is predicted that by 2050, changes in the structure of the industries that support the lives of people shifting from manufacturing to intellectual property services will accelerate due to the integration of AI, robot, 3D printer, plant factory, etc., into the PG.

The PG is the means to enable everyone to have a comfortable and rich life regardless of where they are living, whether it is on land, in the ocean or in outer space. In addition to generating no environmental burden, it is possible with the PGs to form stand-alone and decentralized residential spaces or cities that are not affected by the damage caused by natural disasters. Such personalization of social infrastructures by the PG will enable Japanese society to shift to a sustainable society, characterized by regional decentralization, proximity between residential areas and workplaces, regional circular and ecological sphere, coexistence with nature and prevention of disasters, and drive the social structure reform in Japan toward 2050.

II. Statistical/Comprehensive Analysis

1. Challenges (scientific, technological and social) and necessary measures in achieving this MS target

1.1 Energycirculation

In order to realize the material cycle in PG, the following issues must be considered.

1. Use of renewable energy, mainly solar power
2. Hydrogen production and storage technology
3. High power and high durability of fuel cells
4. Increasing the size, capacity, and longevity of storage batteries
5. Feed-in tariff (FIT) and separation of power supply and distribution

1.1.1 Renewable energy as represented by solar power

Photovoltaic power generation and wind power generation, which are attracting attention as renewable energy sources, are expected to be used as large-scale power sources in the future. In fact, in the Ministry of Economy, Trade and Industry's "Green Growth Strategy for Carbon Neutrality in 2050," solar power and wind power are listed as areas that will grow through 2050. However, these technologies have strong location constraints because of the importance of sunshine hours and wind conditions. As an example, Figure 3 shows the amount of electricity generated annually by prefecture for residential PV power generation[1)]. As shown in Figure 3, the average annual electricity generation is about 1000 kWh/kW, but there is a variation of 10-30% depending on the region and year. The installation potential for residential buildings in Japan is 65 GW for roof and rooftop installations, and 91 GW if sidewalls are added.

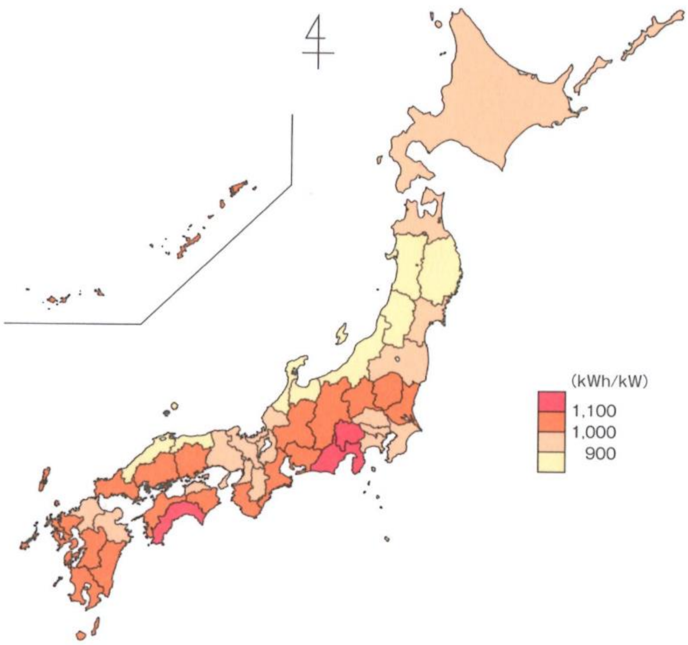


Figure 3 Annual electricity generated by residential solar power generation by prefecture[1)]

Currently, photovoltaic (PV) power generation is widely recognized and used by the general public due to the FIT system and increasing environmental awareness. In order to improve the utilization rate of renewable energy and to make it the main power source for PG, it is important to consider the cost reduction, improvement of power generation efficiency, and long-term reliability of the power generation system.

1.1.2 Hydrogen production and storage technology

As electrolysis of water does not emit carbon dioxide during its production process of hydrogen, it will be possible to build an ultimate environmentally harmonious energy system by using the hydrogen produced through electrolysis of water as the energy source for fuel cells. The main methods of water electrolysis include the alkaline water electrolysis, the solid polymer type water electrolysis and the high temperature water vapor electrolysis, and the storage/transportation methods of hydrogen include compressed hydrogen, liquefied hydrogen, organic hydride and ammonia[2)].

1.1.3 Increasing the power and durability of fuel cells

In the polymer electrolyte fuel cell (PEFC) used in fuel cell vehicles and ENE-FARM, the oxidation of hydrogen occurs at the anode and the reduction of oxygen to water occurs at the cathode. The catalyst is platinum, a noble metal. In order to achieve high output and high durability, it is important to develop a catalyst that can efficiently promote the oxygen reduction reaction, which has a high energy loss. Since platinum, a precious metal, is used as a catalyst, development of a catalyst that shows high durability even under high temperature (~80°C) and acidic conditions while reducing the amount of rare platinum is being promoted worldwide.

1.1.4 Increasing the size, capacity, and longevity of storage batteries

Storage batteries are not limited to use in portable devices, but can be used for storage of renewable energy and emergency use, and are therefore essential for the realization of PG. The major issues are to increase the capacity and the lifetime of the batteries, and at the same time, to reduce the size of the batteries. In addition, organic electrolytes have been used in conventional storage batteries, but their reliability has been questioned due to the occurrence of fires caused by errors in the system. In recent years, the development of reliable all-solid-state batteries has been actively pursued both in Japan and overseas, but their low storage efficiency is an issue.

1.1.5 Feed-in tariffs (FIT) and the separation of transmission and distribution

The electricity system continued to grow massively through coordination using synchronous generators. But as its consequence, it is vulnerable against major chain blackout at the time of disasters[3)]. As the existing electricity system has limited system capacity, the situation where the renewable energies reach their growth limit due to the limit in the system capacity no matter how much their introduction is promoted via the feed-in tariff (FIT).

As the renewable energies have regional unevenness, they are highly compatible with dispersed power source. Microgrid is being developed toward proactive introduction of renewable energies. A microgrid is “a group consisting of a dispersed power source and demand that is independent from the electricity system and can be controlled from one location. There are cases where they are coordinated with the electricity system, and the cases where they are not.” While diesel generators are used to supply electricity in for instance remote islands, they have high fuel cost compared to coal or gas fired power generation. Thus, it is inferred that the microgrid that combines renewable energy with storage batteries will be economically acceptable. Visualization of energy decentralization using the microgrid is shown in Figure 4[4)].

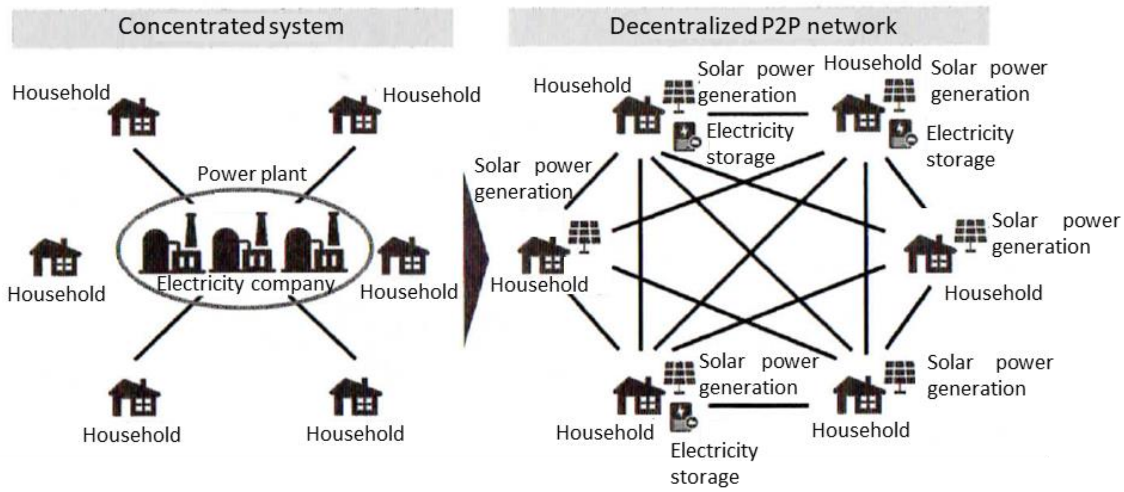


Figure 4 Visualization of energy decentralization using the microgrid[4)]

As smart grids and microgrids are dependent on the voltage/frequency of the system and require constant backup, the fact that no technology that can ensure that they will switch to uninterruptible power source during a blackout is a challenge they are facing. Digital grid is proposed as the solution to this problem. It is important that cell grids are possessed by bodies other than the power companies and enable direct integration of renewable energies into them in order to trigger innovations in the electricity system[5)].

Moreover, asynchronous tie will be important for avoiding the vulnerability during disasters. Asynchronous tie is a mechanism that is expected to be used for maintaining the stability of the electricity system during the mass introduction of the renewable energies. The fact that it allows exchange of electricity even when there is a phase shift is the benefit of this asynchronous tie. By expanding its area of usage to lower level voltage system such as high or low voltage distribution system, it will be possible to freely control active power and reactive power and solve the problem of voltage. For instance, if the inverters, etc., of the solar power can freely inject reactive power, it will be possible to control and stabilize its voltage by utilizing the reactor component of pole-mounted transformers, leading to stable supply of the electricity from renewable energy. By using the asynchronous tie technology called BTB (Back to Back) that uses two inverters to turn alternating current into direct current and then produce alternating current again from this direct current, Japan will be released from the constrain in frequency it is facing[3)].

1.2 Material circulation

In order to realize the material cycle in PG, the following issues must be considered.

1. Establishment of material conversion technology that can move freely between polymers and monomers (manufacturing and recycling of plastic products)

2. Establishment of small-scale and highly efficient amino acid synthesis technology
3. Establishment of small-scale, highly efficient ammonia synthesis
4. 3D printing for clothing and food production

While some of these component technologies are already industrialized, they are not yet at the level that can be used within the PG. In other words, their cost reduction, size reduction, energy reduction and sustainability must be achieved. Each component technology is still in the research stage. Moreover, a strong platform that can connect and control them must also be developed.

1.2.1 Production/recycling of plastic products

Plastic is mainly made from petroleum or natural gas. In Japan, most of them are made from naphtha (crude gasoline) obtained by refining crude oil. Most of the crude oil used in Japan in a year (slightly less than 200,000,000 kL) can be converted to gasoline, kerosene, light oil or heavy oil, and naphtha, which accounts for only <10%. The percentage of naphtha used for plastic production in the yearly used crude oil and imported naptha in Japan is only approximately 3% (weight %). Thus, the crude oil used for plastic is only a few percent of the total, and most of crude oil is consumed as thermal energy (Figure 5). In other words, the reduction of the amount of plastic will have almost no impact on the reduction of amounts of crude oil or the climate change on the basis of the use of crude oil. Therefore, we should forcus on reducing the consumption of plastic as thermal energy sources rather than the reduction of amounts of plastic used to discuss saving crude oil or reducing the CO_2 emission from crude oil.

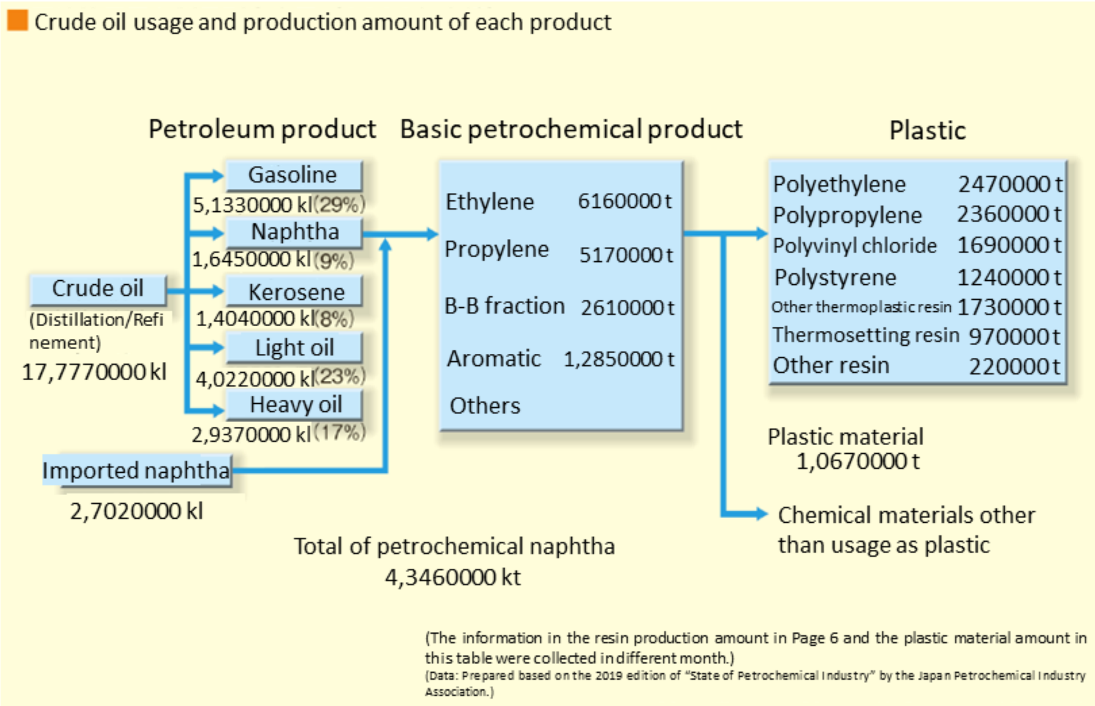
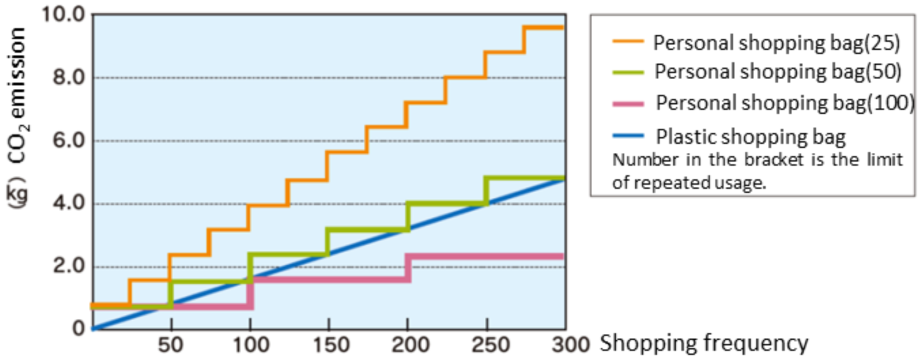


Figure 5 Flow from crude oil to plastic[6)]

Since July in 2020, plastic shopping bags (supermarket bags) are no longer freely available in Japan. However, the debate about the relationship between less usage of plastic shopping bags and less emvionmental impacts is not straightforward: when the relationship between the frequency of shopping (a plastic bag/a reusable shopping bag) and CO_2 emission is examined, there is almost no contribution to CO_2 reduction unless the reusable bag is repeatedly used for at least 50 times because the CO_2 emission from the reusable bag production (presumed to be made of 100% polyester) is higher than that of plastic bag production (presumed to be made of 100% high density polyethylene) (Figure 6). Moreover, if the weight of a reusable bag (32 g/bag) is postulated to be approximately 10 times that of a plastic bag (3.0 g/bag), there is almost no contribution to the reduction of plastic wastes unless the reusable bag is repeatedly used for at least 10 times[7]. In reality, the amount of CO_2 emission can fluctuate when we consider the maintenance of reusable bags (cleaning with hot water or soap) and their usage frequency. Although the debate is not straightforward, it is true that repeating usage of plastic products many times definitely reduces environmental impacts.



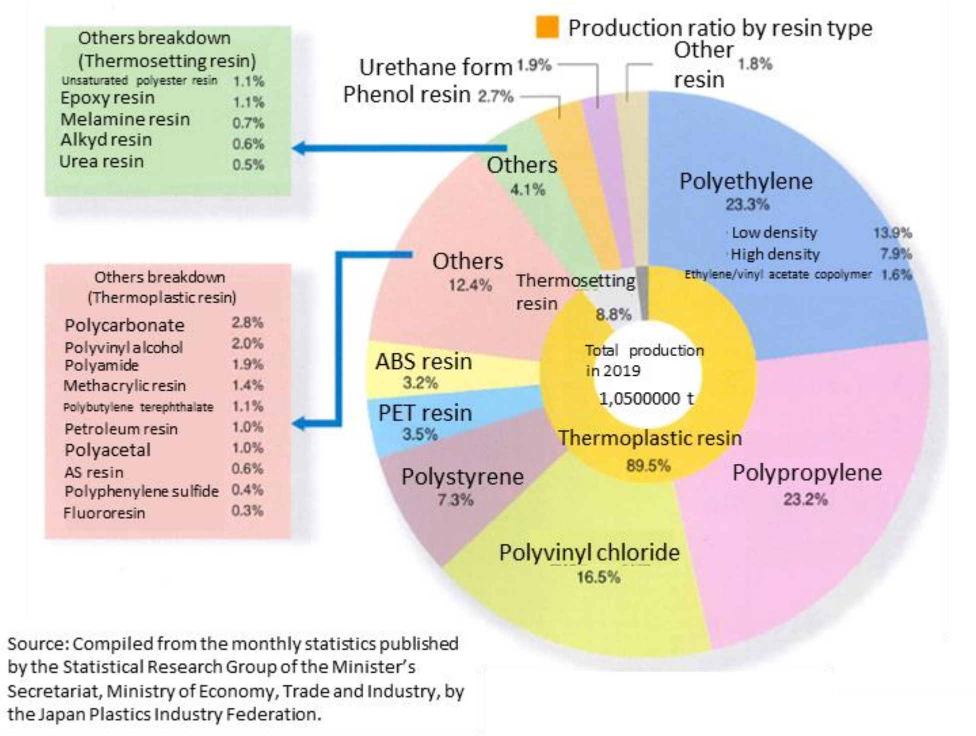
		Plastic shopping bag	Personal shopping bag
Premise	Weight (g/bag, per bag)	3.0	32.2
	Material	HDPE (High density polyethylene) 100%	Polyester 100%
	Produce in	China (Fujian Province)	
	Production method	Inflation processing	10 minutes sewing using sewing machine with 250W rated power
	Distributed/used in	Japan	
	System boundary	Material mining - Production - Transportation (ocean) - Usage - Simple burning	
Evaluation result CO_2 emission (g/bag)	Material stage	4.1	675.0
	Production stage	1.5	30.7
	Transportation stage	0.2	1.8
	disposal stage	9.6	74.3
	Total	15.4	781.7

[Inventory data]
LCA Japan Forum "JLCA-LCA database" (3rd edition, 2008)
PWMI "Inventory data study report on resin processing" (2000)
Manufacturing Industries Bureau, Ministry of Economy, Trade and Industry "LCA study report on textile products (clothing)" (2003)
National Bureau of Statistics of China "China Energy and Engineering Statistical Yearbook 2006" (2007)

Figure 6 Relationship between the frequency of shopping and CO_2 emission and premise for its calculation[8)]

From the debate on the relationship between the percentage of plastic in the total crude oil usage, shopping frequencies and CO_2 emission, the situation is clearly not as simple as “the reduction of plastic and shopping bags = the reduction of environmental impacts and the conservation of natural resources”. Thus, it is important to clarify which we should discuss, the environmental burden caused by CO_2 emission, generation of wastes or environmental pollution such as microplastics in the ocean.

While the percentage of plastics among crude oil usage is small, still approximately 10.5 million t of plastic is produced in Japan in 2019. 46.5% of plastic products are made of polyethylene and polypropylene. This is due to the fact the approx. 40% of plastic usage is for packing materials and wrapping sheets such as plastic bags and cling film. Consequently, the production volume of polyethylene and polypropylene is large (Figure 7).



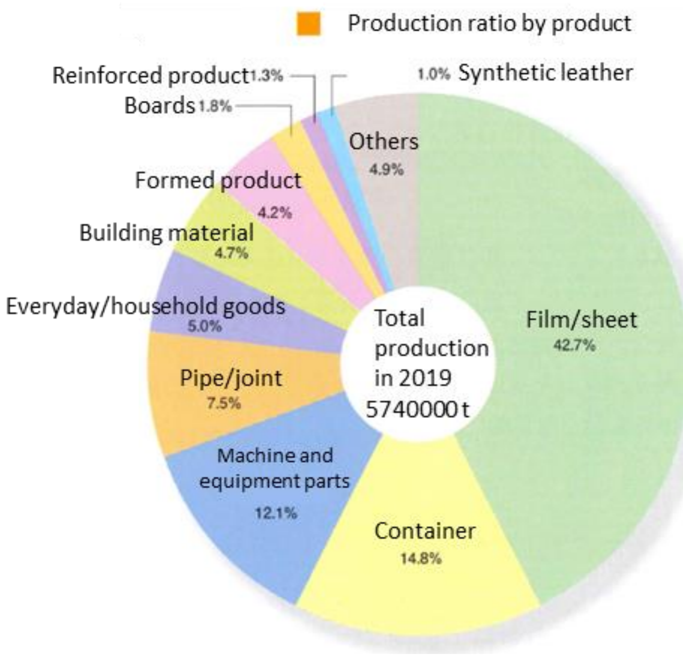


Figure 7 Ratio of plastic production according to their resin and purpose (2019) [6].

Plastic recycling in Japan is classified into the following three categories: the material recycling, chemical recycling and thermal recycling (energy recovery), as shown in Table 1. In the material recycling, plastic wastes were melt and reused as materials. The process of collection, treatment and re-commercialization of PET bottles is an example of this process. In the chemical recycling process, plastic wastes were converted into materials, monomers, gases or oil through chemical treatments to use them again. From the perspective of materials circulation of plastic in the PG, the chemical recycling process is particularly important. Lastly, in the thermal recycling process, plastic wastes are burnt for the heat or power generation. Note that in the world standard the thermal recycling is a part of energy recovery, not classified into recycling. Therefore, the material and chemical recycling processes are discussed in this section.

Table 1 Three recycling categories. *1: Refuse paper & plastic fuel. High-calories solid fuel made from old papers and plastics that are difficult to material-recycle. *2: Refuse derived fuel. Solid fuel made from organic wastes, combustible wastes or plastic wastes. [6)]

<table>
<tr><th>Category (Japan)</th><th colspan="2">Recycling method</th><th>ISO 15270</th></tr>
<tr><td>Material Recycling</td><td colspan="2">Reusing
Returning to plastic materials
Recycling into plastic products</td><td>Mechanical Recycle</td></tr>
<tr><td rowspan="4">Chemical recycling</td><td colspan="2">Returning to materials/monomers</td><td rowspan="4">Feedstock Recycle</td></tr>
<tr><td colspan="2">Blast furnace reducing agent</td></tr>
<tr><td colspan="2">Returning to chemical materials in coke oven</td></tr>
<tr><td rowspan="2">Turning into gas</td><td>Returning to chemical materials</td></tr>
<tr><td rowspan="2">Thermal recycling (Energy recovery)</td><td>Fuel</td><td rowspan="2">Energy Recovery</td></tr>
<tr><td colspan="2">Turning into cement material /fuel, Waste power generation
RPF*1 RDF*2</td></tr>
</table>

Among the 8.3 billion tons of the global output of plastic, 4.9 billion tons are disposed for instance as landfill, 0.8 billion tons are burnt, and approx. 0.6 tons are recycled (Figure 8). These numbers show that only 9% of plastic wastes are recycled. In European countries, the percentage for the plastic recycling is between 26% and 52% (Figure 9).

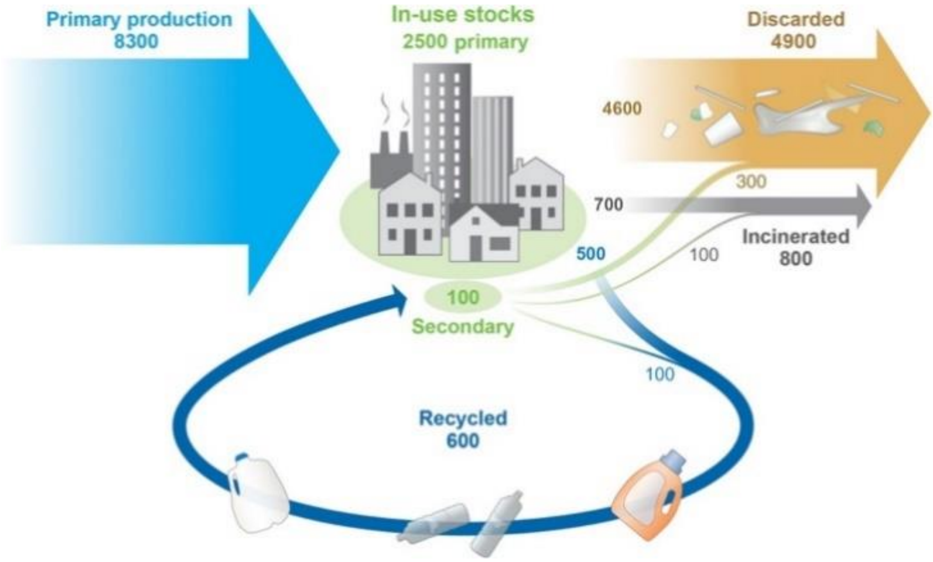


Figure 8 Amount of plastics produced, used and disposed of globally between 1950 and 2015 (Unit: Million ton) [9].

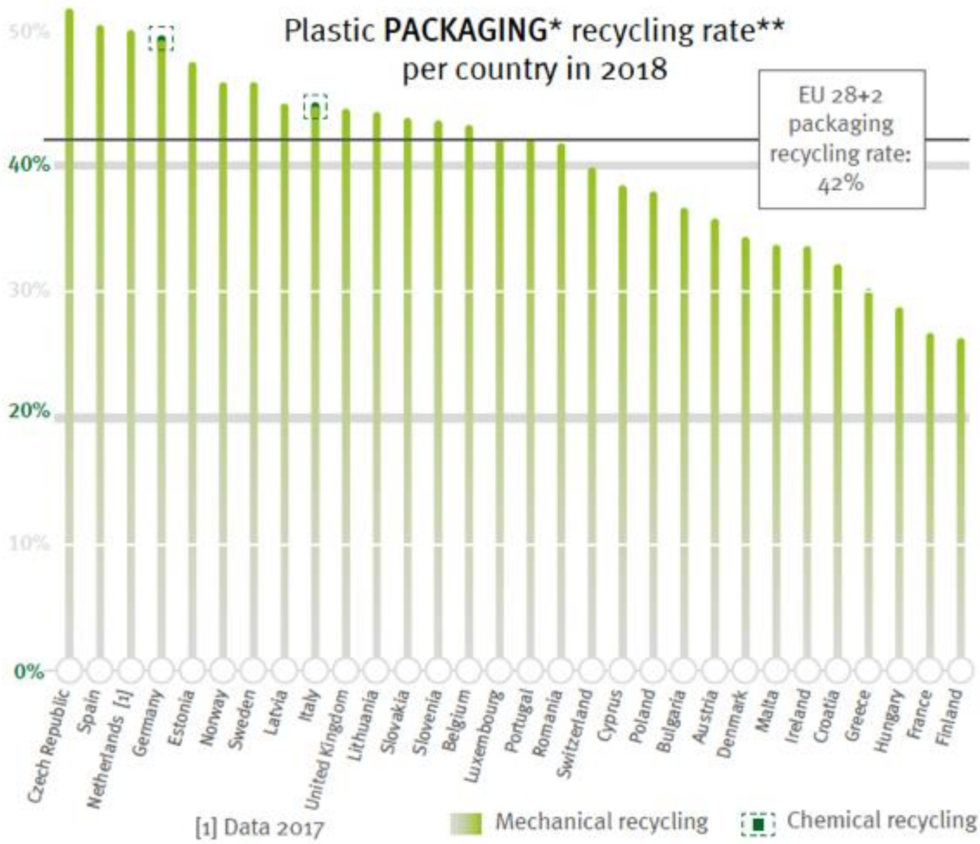


Figure 9 Recycling rates among European countries in 2018[10]

1.2.2 Production of amino acids

Amino acids are essential compounds for human activities as food, medicine, and macromolecules, and the independence of PGs would be greatly enhanced if it were possible to manufacture them within PGs. Chemical, biochemical, and extraction methods can be used to produce amino acids, and research is being conducted on chemical methods that are not limited to naturally occurring amino acids but have a wide range of applicability. For example, fluorine-containing amino acids and their derivatives produced by chemical methods are widely used in the fields of medicine and pharmacy. However, the commonly used chemical method is still a production method with a large environmental impact.

1.2.3 Ammonia production

Ammonia (NH3) has been widely used as the material for nitrogen fertilizer, nylon fibers used in clothing and medicine. Until today, its production has been mainly through the Haber-Bosch process. However, as this production process requires high temperature/high pressure environment (400 to 600 °C, 100 to 200 atmospheric pressure), large amount of energy is used for it. Thus, new ammonia production methods that can overcome this problem are being examined. For instance, JST CREST (achievement of Tokyo University) developed the method that enables easy and high-speed synthesis of large amount of ammonia from nitrogen gas and water in normal temperature and pressure, the first of its kind in the world[11)]. It is regarded to be an important possibility for developing the next generation ammonia synthesis reaction that will replace the current Haber-Bosch process, and its practical application is eagerly anticipated.

1.2.4 Current Status of 3D Printers

In the PG, matters are returned to the amino acids or the monomer level through the electrolysis technology, and then recomposed into necessary items by the 3D printer within the PG.

Precisely speaking, 3D printers (Official name: AM (Additive Manufacturing) are categorized into the following seven methods.

1. Vat photopolymerization: VPP
2. Material jetting: MJT
3. Binder jetting: BJT
4. Powder bed fusion: PBF
5. Material extrusion: MEX
6. Directed energy deposition: DED
7. Sheet lamination: SL

In each of these methods, the shape is obtained by molding the material to be shaped into the product while it is in a fluid state, such as powder or liquid.

The methods to mold polymer include:

I. The monomer is discharged by the inkjet and then polymerized with UV immediately. (MJT,VPP)

II. Thermoplastic polymer is melted and extruded, and they immediately cooled to solidify it. (MEX)

III. Pulverized polymer is selectively melted and solidified for instance by laser. (PBF)

When considered for the usage within the PG, I or II is inferred to be the base.

However, as I involves polymerization, the safety of photoinitiator or the residual monomer after the polymerization can become challenges, especially when used for clothing.

And with II, the supplied material and discharged material are the same, and there is no example where reaction or synthesis is performed within the device.

1.3 Water circulation

In order to realize water circulation within the PG, the following factors must be realized.

4. Technology to turn seawater, river water and rain water into drinking water
5. Purification technology of wastewater that contains excrement
6. Technology to produce hydrogen directly from wastewater that contains excrement, seawater, river water and rain water

The technologies to turn river water and rainwater into drinking water are widely used both in large scale, as purification plants, and in small scale, as for instance plastic bottle-shaped purifiers. Moreover, the purification technologies of Wastewater that contains excrement, and used water are already used for instance in sewage-treatment plants. In addition, the direct hydrogen production method from seawater is a research theme that will gather significant attentions. Following is the outline of the current state of water circulation-related technologies and the challenges facing their application to the PG[12, 13]. Regarding the mechanism of purification plants, including the purification technology employed, each municipality makes it available in their websites and other channels.

1.3.1 Technology to turn seawater, river water and rain water into drinking water

At purification plants, the process of providing drinking water is roughly as follows, which is the same in every municipality.

① Take in river water, lake water, etc., from the inlet.
② Precipitate large trashes and gravel in the water.
③ Condense cloudiness and dirt in the water using chemical, etc., and precipitate larger lumps.
④ Filter and the water and disinfect it with chemicals.
⑤ Place the water in service reservoir and distribute it using the conveying pump.

In principle, small mobile purifier also obtains drinking water by filtering the raw water such as river water and rainwater. Moreover, desalination of seawater also obtains drinking water through multiple filtrations. As the purpose of desalination facilities of seawater is to secure large amount of drinking water, they are large-scale facilities similar to purification plants. While there are some developments in small desalination device of seawater to be used in ships and during disasters, it is currently not the mainstream of desalination facility.

There are two types of filtration used at purification at purification plants, namely the rapid filtration that uses chemicals and the slow filtration that uses biofilm made of microbe, and both of them obtain purified water by letting the water go through the sand layer and gravel layer. Meanwhile for the desalination of seawater, reverse osmosis (RO) membrane is often used. That is because the research and development of RO membrane developed around its application to seawater desalination. Most of existing technology to obtain drinking water is based on filtration technology. Thus, replacement of filter is crucial. In addition, large-scale water treatment plants such as purification plants are very common. In order to realize the large-scale dissemination of the PG, making filter maintenance-free, extending its lifespan and reducing its cost are essential. And considering that it is to be installed in individual living spaces, size reduction is also necessary. Therefore, development of technologies to obtain drinking water that considers purification methods other than filtration is desirable.

1.3.2 Purification technology of wastewater that contains excrement

Current sewage treatment combines physical/chemical method that uses precipitation and filtration and biological method that uses on wastewater including excrement/used water. Though this is not frequently thought about by the general public, Sewerage Act was enacted in 1900, and the development of sewer as a social infrastructure has been ongoing for a long time. For this reason, current sewage treatment is mainly conducted at large-scale facilities. On the other hand, examples of small-scale treatment include the portable toilets used during disasters or camping. Most of them are the type that uses bactericidal coagulant to solidify the water content which is sealed after the usage and disposed of as a combustible waste. Moreover, treatment of at mountain cottages, etc., in natural environment is also a major issue to be examined in order to create harmony with the natural environment. As a part of the Environmental Technology Verification program of the Ministry of the Environment, the PR materials related to the human waste treatment technology in natural areas from 2004 to 2016 are available in their website[14)]. Many of these human waste treatment technologies in natural areas use biological treatment with bacteria, which requires pretreatment, unlike the aforementioned portable toilet. The only other method aside from the biological treatment is the treatment with drying and burning. Currently, both toilet that uses biological treatment with sawdust and oyster shells and toilet that uses burning are installed in Mount Fuji[15)]. In recent years, Mr. Bill Gates was discussing the necessity of hygienic toilets from the perspective of public health in front of the newly developed self-contained toilet in the GatesNotes from 2018[16)]. Following this, three types of toilet developed through the support from Bill & Melinda Gates Foundation were presented at the Toilet expo. The overview these three types of toilet was succinctly summarized in an article from The Wall Street Journal at the time[17)]. The developed technology employs the method that separates excrement into liquid and solid, and removes the contained organic substance using either decomposition with bacteria or burning. In addition, the water recycling system used at the International Space Station also employs the method that distills urine, mixes it with humidity in the air or used water and filters/purifies it[18)]. However, only approx. 18 L/day of recycled water can be obtained.

Considering the water circulation to be built by the PG, while the technology to obtain drinking water from excrement will be useful, it will not be possible to obtain all the water necessary for living from it. Therefore, a circulation that includes domestic wastewater will be necessary. When considering the treatment of domestic wastewater, the existing self-contained toilet will be insufficient. Moreover, the sewage/wastewater treatment built around the biological treatment is not able to perfectly remove chemicals from medicine and everyday goods. Especially, some of antibacterial agents, antibiotics and antipyretic analgesics cannot be decomposed of through biological treatment using bacteria, and the danger of drug-resistant bacteria emerging from sewer or purification tank has been pointed out. Therefore, physical and chemical treatments, such as those using burning, ozone, ultraviolet light irradiation, hydrogen peroxide and electrolysis, must also be examined actively. In addition, it is necessary to simultaneously guarantee the treatment speed and reduce size is necessary for the water circulation technology to be installed on the PG.

1.3.3 Technology to produce hydrogen directly from Wastewater that contains excrement, seawater, river water and rain water

Toward the hydrogen society to come, Japan also determined its Basic Hydrogen Strategy, and it lists the fuel cell system as a replacement of existing energy system used at households, etc., after 2030. The PG proposed in this report also recognizes the fuel cell technology as an important component technology that links the energy circulation and the fuel circulation. For fuel cells, obtaining hydrogen, which is its fuel, is the urgent issue, and its examination is ongoing, for instance in "Advancement of Hydrogen Technologies and Utilization Project" of NEDO. For the methods to obtain hydrogen, reports researches on directly obtaining hydrogen from seawater or wastewater is rapidly increasing in recent years.

As Figure 10 is the result of searching with limited keywords, it does not cover every relevant report. However, it still shows that the number of reports is clearly increasing in recent years. Especially the result from 2021 shows the number of reports that is more than half of the previous fiscal year even though it is only the number until May. It shows that the technology to directly produce hydrogen from seawater or wastewater can potentially become a global hot topic.

Hydrogen production from seawater and that from wastewater require different approaches. When using seawater, electrolysis technology is the main method, and photoelectrochemical method using photocatalyst is the main method using wastewater. This is inferred to be due to the difference in where the problem arises from during electrolysis of water. Concretely, the problem when using seawater is the anion species contained in various types of seawater, and the problem when using wastewater is the organic substances it contains. Note that the optimal electrode catalyst for either method has not been discovered. Thus, in order to realize the PG, development of a highly active electrode catalyst that also has long lifespan and is low cost is essential.

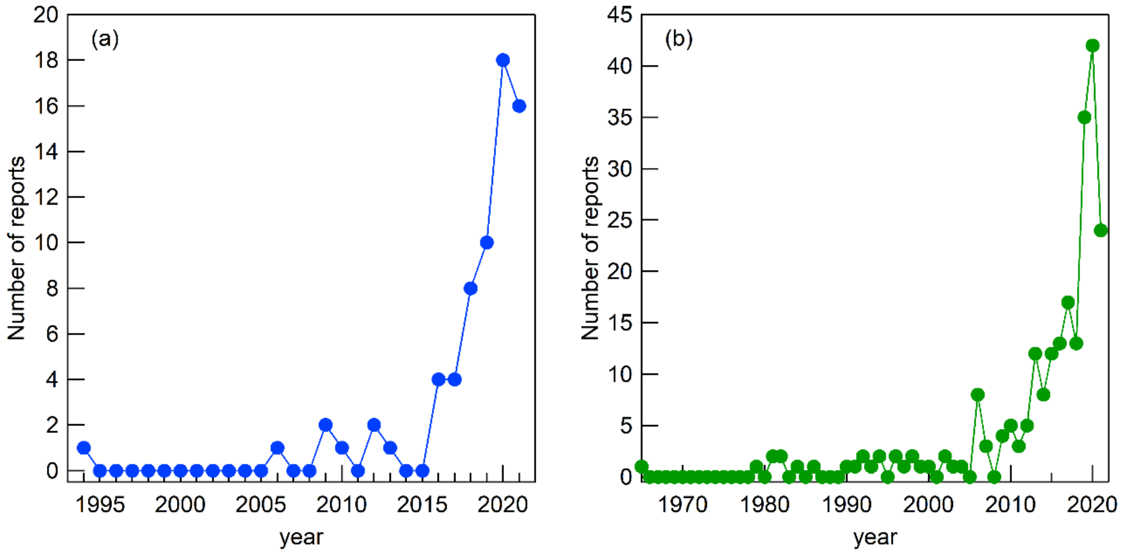


Figure 10 Results of searching for academic papers using the following keywords: (a) “electrolysis”, “seawater” “water splitting”, (b)“electrolysis”, “wastewater” “splitting”.

2. The comprehensive vison in research and development required for achieving this MS target

2.1 Energy circulation

2.1.1 Use of renewable energy, mainly solar power

Photovoltaic (PV) power generation is considered to be a potential energy suitable for PG, and is therefore discussed below. For a detailed overview of the field, we refer to the "R&D Overview Report" of the Center for Research and Development Strategies (CRDS) of the Japan Science and Technology Agency (JST).

According to 2019 data, the global weighted average cost of electricity generation is 0.068 USD/kWh, while the weighted average cost of electricity generation in Japan is 0.163 USD/kWh, which is about 2.4 times higher than the global cost. According to NEDO's PV roadmap (PV2030+), the cost of PV power generation will be 7 yen/Wh or less after 2030. According to NEDO's PV roadmap (PV2030+), the goal is to reduce the cost to less than 7 yen/Wh after 2030. In order to reduce the cost by increasing the lifetime of the system, research on the degradation mechanism of crystalline

Si solar cells is being conducted. In addition, research is being conducted to develop solar cells with high efficiency and high reliability. However, the current trend of research and development is to focus on efficiency improvement rather than material development with the aim of reducing the overall system cost.

2.1.2 Hydrogen production and storage technology

PG is required to produce hydrogen by electrolysis of water using electricity derived from renewable energy sources, and to store the hydrogen. Among water electrolysis, alkaline water electrolysis is the most established technology, and it has the advantage of low equipment cost and large scale production because it does not require precious metal materials. Polymer electrolyte water electrolysis can provide high current density, but the cost is high due to the use of noble metal materials. Therefore, the development of depreciated precious metal electrocatalysts and corrosion resistant and inexpensive coating materials for the electrolyzer vessel are required, but the characteristics are suitable for the introduction to PG. High temperature steam electrolysis is expected to have higher efficiency than various water electrolysis systems with low temperature operation, but high durability is required for the materials because of the high temperature operation.

Various forms of hydrogen storage have been studied, but the most practical hydrogen storage methods are compressed hydrogen and liquefied hydrogen. Liquefied hydrogen is about 10 times more prone to evaporation than LNG, so it requires about 10 times higher insulation performance. Organic hydrides, which are expected to be a form of transportation that is easy to handle, are a method of fixing and storing hydrogen by converting aromatic compounds such as toluene into naphthenic compounds such as methylcyclohexane through hydrogenation reactions, and extracting hydrogen through dehydrogenation reactions when it is used. Aromatic compounds such as toluene, which are produced in the dehydrogenation reaction, can be recovered and reused. Figure 11 shows a diagram of the gravimetric and volumetric hydrogen densities of hydrogen storage materials. In terms of gravimetric and volumetric hydrogen densities, ammonia is an excellent hydrogen carrier. However, its high toxicity to the human body is an issue[2)].

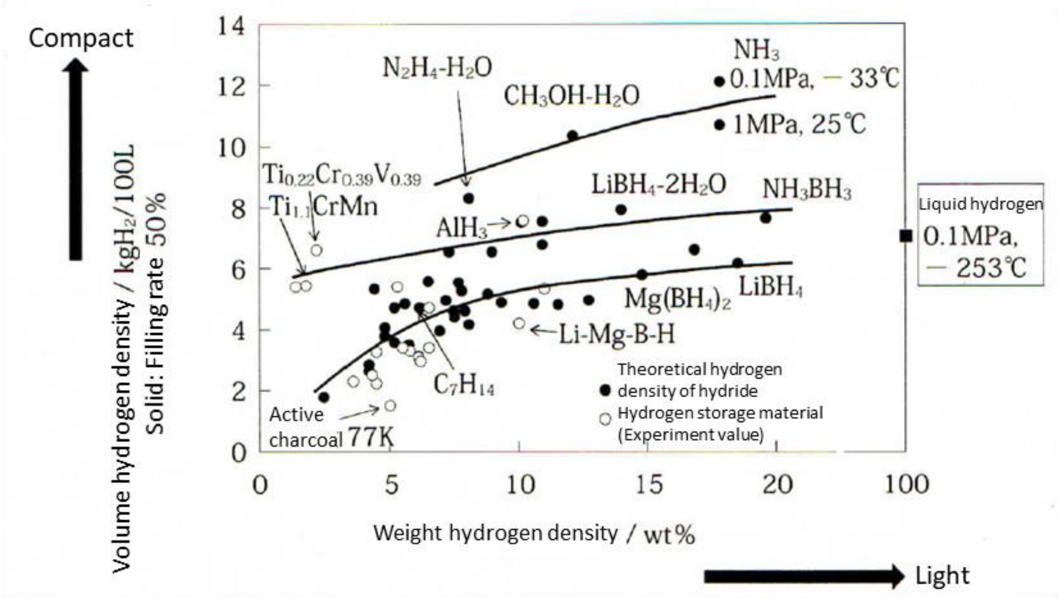


Figure 11 Weight hydrogen density and volume hydrogen density of hydrogen storage material[2)]

2.1.3 Increasing the power and durability of fuel cells

Since the Great East Japan earthquake, decentralized energy systems tolerant to natural disasters are highly demanded. Fuel cells are suitable for such decentralized power sources. The most common fuel cell is a polymer electrolyte fuel cell with a proton exchange membrane as a polymer electrolyte film. In order to improve its chemical stability, addition of a substance that excels in decomposition of hydrogen peroxide is necessary, and for the improvement of mechanical durability, swelling toward the interior of the cell must be prevented. Moreover, acceleration of back diffusion is effective for low-humidifying operation, and thinning of porous films is being attempted[2)].

2.1.4 Increasing the size, capacity, and longevity of storage batteries

In organic electrolyte storage batteries, the degradation behavior of the electrodes is being clarified and technology is being developed to suppress it. Since the active material swells and shrinks repeatedly during charging and discharging, technology is also being developed to suppress the battery degradation caused by this process. On the other hand, in all-solid-state batteries, both the electrode active material and the solid electrolyte are being intensively investigated from both experimental and theoretical aspects.

2.1.5 Feed-in Tariffs and the Separation of Power and Electricity

The high cost has been the disadvantage of solar power. However, since the introduction of Feed-in Tariff (FIT), the accumulated introduction of solar power in Japan has seen increase trend. Following Figure 12 shows the transition in accumulated introduction since 2007[19)].

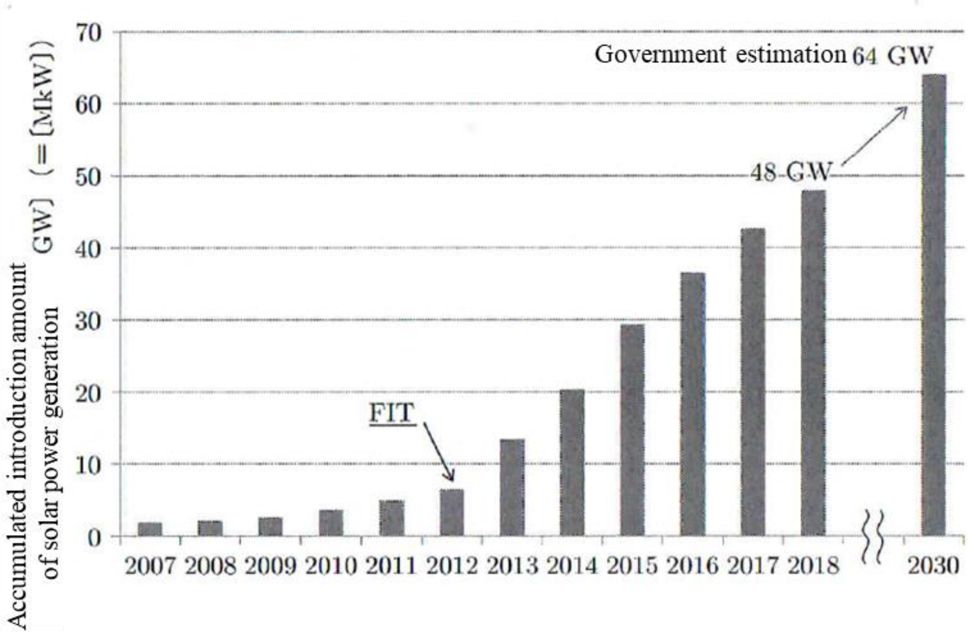


Figure 12 Accumulated introduction of solar power in Japan[19)]

If solar panels, etc., are installed on private houses in order to prepare for the introduction of the PG, it will generate surplus power, which will require self-consumption. Self-consumption involves storage of surplus power generated for instance from solar power generation and its discharge when necessary, allowing inclusion of surplus power to one's own power consumption. EMS is expected to become the technology to promote self-consumption. EMS is an energy control system that uses information communication technology to visualize electricity consumption, control devices toward energy reduction and control solar power generation and storage battery[20)].

2.2 Material circulation

2.2.1 Manufacture and recycling of plastic products

The recycling rate in Japan is 22% with material recycling, and 3% with chemical recycling, in total 25%. Compared to the recycling rates of European countries, it is not particularly higher and therefore can be regarded as average. While chemical recycling that uses plastic by converting it into monomer or other compounds is important for material circulation, it is clear that conducting material recycling based on chemical recycling is difficult at this point from the fact that its ratio is only 3%.

When recycling of plastics is difficult, they are either burnt or sent to landfill. In Japan, 8% of them are simply burnt and 6% go to landfill. The problem facing the recycling of plastic is "impurities contamination". For instance in material recycling, sorting of plastic types and removal of impurities through cleaning are crucial. More functional plastic becomes, more difficult mechanical plastic sorting becomes due for instance to difference in specific weight caused by usage of several monomers or addition of compounds such as plasticizer, leading to further reduction in recycling rate. In order to improve the recycling rate, integrated thinking on design, production, usage and collection of plastic premised on recycling will be more important in future.

2.2.2 State of chemical recycling of plastic

One of the chemical recycling methods is the technology to return plastic wastes into oil, which is in their original state. This method was used in industry in the past (Figure 13). Unfortunately however, they were forced to withdraw from large-scale facilities by the mid-2000s. For instance, Sapporo Plastics Recycling Co., Ltd. (established in 1998) was engaging with a plastic liquefaction project, but it was withdrew in 2010. Problems with the liquefaction technology include requiring thermal energy, securing of commercial scales (ensuring that large quantity of plastic wastes is always available), reducing running costs, controlling the molecular weight distribution of products, and purifying the purification of products. As Asian countries have been banning import of plastics for recycling in recent years, stable supplies of plastic wastes would be available in Japan. However, the use of the liquefaction technology again in the industry in the future will be highly unlikely.

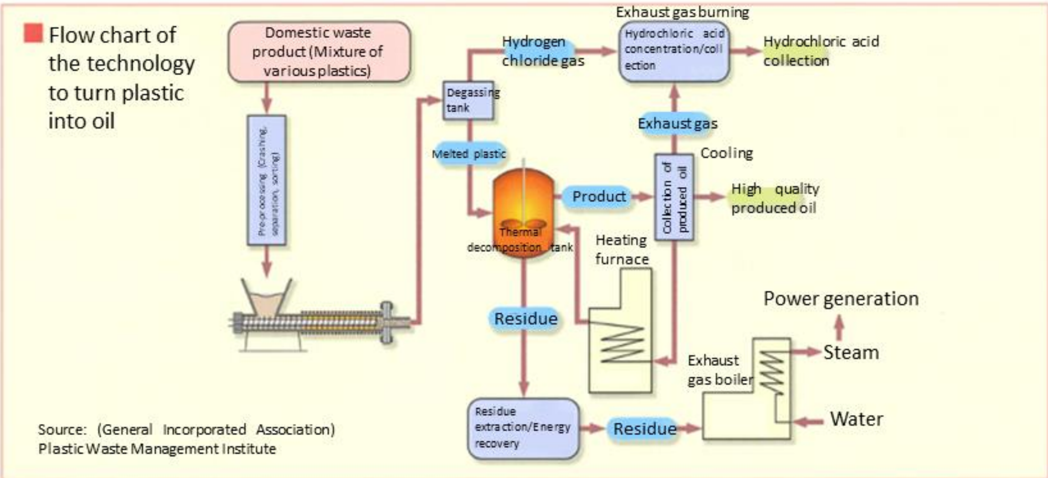


Figure 13 Liquefaction technology flow chart[6)]

Recycling through depolymerization and re-polymerization of polymers is also being examined in the chemical recycling. For example, polyester and PET are collected from threads and fabrics of clothing, depolymerized using ethylene glycol to obtain bis(2-Hydroxyethyl) terephthalate (BHET), which can be purified and then re-polymerized back to PET (Figure 14). While securing stable quantities of materials (PET bottles and clothing) in order to maintain such a cycle remains challenging, it may become one of the options for the chemical recycling in Japan in the future because of the increase in ESG investments and the import restriction and ban of plastic wastes to Asian countries.

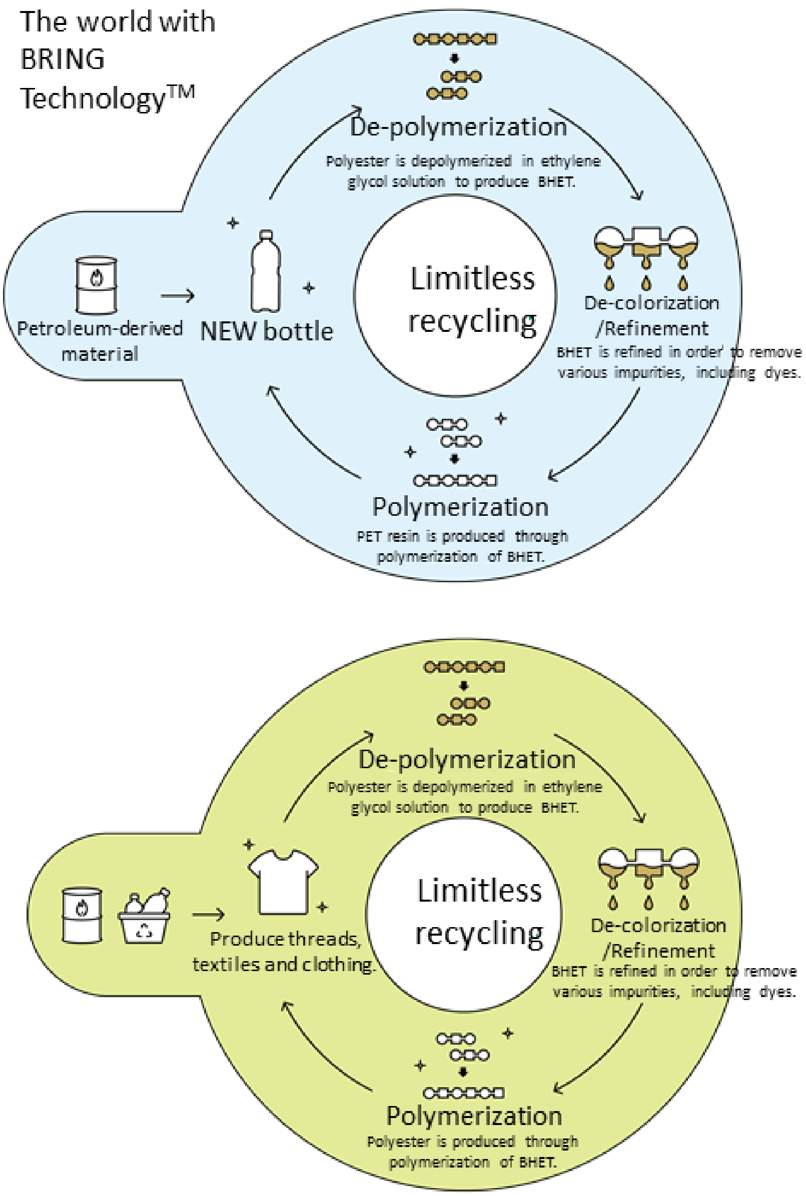


Figure 14 Flow of chemical recycling[22].

2.2.3 Production of amino acids

Amino acid is a general term for compounds that have a carboxyl group and an amino group. α-Amino acid refers to compounds in which the carboxyl group and the amino group are bonded to the same carbon atom. Alpha-amino acids are useful compounds that are widely used in foods and pharmaceuticals. In particular, there are 20 kinds of essential α-amino acids in the body, and continuous intake is necessary. Therefore, methods to artificially synthesize them, including α-amino acids, have been studied for a long time. The Strecker method and Zelinsky-Stadnikoff modification, which are conventional methods, use highly toxic hydrogen cyanide and cyanide ions for carboxylation. A clean synthetic process without the use of toxic substances is required. As a synthetic process that does not require highly toxic cyanide or stoichiometric amounts of organometallic reagents, α-amino acid synthesis by organic electrosynthesis has been reported.

2.2.4 Ammonia synthesis

Ammonia plays important role as a material for fertilizers, chemicals and polymers. It will also be an important building block for the PG as the material for fertilizers of agricultural products and organic compounds. For ammonia synthesis, technologies to produce ammonia from nitrogen in the air, such as the Haber-Bosch process, are established. However, they require high temperature and high pressure (370 to 510°C, 14~30 MPa)[23]. Since the hydrogen gas obtained through electrolysis of water predicted to be used in the PG is in normal pressure. Thus, as these methods require energy consumption through pressurization, they are not ideal for the PG. While catalyst that can be active under low pressure is also being developed, hope is on the electrochemical process that can offer strong reaction field and induce reaction under the temperate conditions of normal temperature and pressure.

2.2.5 State of recycled materials on 3D printer

P&G announced that they donated face shields made by 3D printers using the recycled plastic (PP) from used plastic containers from their own products partly as materials together with affiliated companies (four companies)[24]. Canon Ecology Industry Co., meanwhile announced that it has developed “PC+ABS” and “HI-PS”, two types of original filament for 3D printers made 100% from plastic recycled from the exterior/cassette pedestal of multi-function printers collected from the market[25]. Both cases are examples of utilization of their own products retrieved from the market, and they are materials whose origin and cleanliness are controlled. They were only crashed/re-melted, and no re-polymerization were conducted.

2.3 Water circulation

2.3.1 Technology to turn seawater, river water and rain water into drinking water

For the PG, water purification technology using a small-scale purification facility will be essential. In order to obtain drinking water through the membrane separation process, desalination of seawater using the reverse osmosis membrane (RO membrane) and purification technology using microfiltration membrane (MF membrane) and ultrafiltration membrane (UF membrane) are necessary. This report describes the new problems that have emerged due to the recent desalination of seawater.

2.3.1.1 New problems caused by desalination of seawater [26, 27]

The method to use the RO membrane is widely used in the desalination of seawater. Due to the nature of this RO membrane, highly saline water (brine) is drained together with the fresh water. As this brine has higher salinity than normal seawater, it can potentially form brine undercurrent that consumes dissolved oxygen (OD) at its drainage area. Dr. Edward Jones, who studied the impact of brine in Wageningen University, warned Carolyn Fortuna from CleanTechnica that “the brine undercurrent can deplete dissolved oxygen of the receiving waters. If the salinity increases and dissolved oxygen decreases, it can greatly impact benthos, and can potentially impact the whole food chain.” Moreover, the wastewater from the desalination treatment contains harmful chemicals such as scale inhibitor and antifoulant in addition to the brine, and the possibility of their negative impacts on marine organism or marine ecosystem has been pointed out.

Separation and refinement using the RO membrane inevitably produces unnecessary treated water to be disposed of. When considering its application to the PG, safe and low cost circulation of the unnecessary treated water must be devised.

2.3.2 Purification technology of wastewater that contains excrement

Since RO, UF, and MF membranes are used in sewage and wastewater treatment as well as in the above-mentioned water purification technologies, we will focus on the treatment methods.

2.3.2.1 Biological treatment

Biological treatment is one of the treatment methods of wastewater that contains excrement. This biological treatment can be categorized into the following seven processes; ①activated sludge process, ②biofilm process, ③carrier process, ④anaerobic treatment process, ⑤nitrification and denitrification process, ⑥biological phosphorus removal process, and ⑦anammox process. Each of these processes uses biome of bacteria, fungus or protozoan to treat organic wastewater that contains excrement. Among them, the biome are supported in the membrane or the carrier in ②biofilm process and ③carrier process, and they do not float freely inside the treatment tank (reaction tank).

In biological treatment, organic contaminant is decomposed by the chosen biome. Thus, it is necessary to prepare an environment where it is easier for the biome to perform the decomposition. Moreover, the vast majority of the microbe existing in the treatment environment are deemed to be impossible to culture in the common agar medium, and even in the activated sludge where the ratio of microbe that can be cultured is high, their percentage remains between 1 and 15%[28)]. This means that unknown microbial communities exist in the activated sludge and they are decomposing the organic contaminant. In order to ensure more efficient biological treatment, it is necessary to deepen more detailed understanding of these microbial communities and feed that knowledge back into the wastewater treatment process. Moreover, it is necessary to examine how to remove substances that cannot be biologically treated, such as antibacterial agents, antibiotics and antipyretic analgesics.

2.3.2.2 Physicochemical treatment

There are following eight physical treatment, which are; ① sedimentation, ② coagulative separation, ③floatation, ④filtration, ⑤membrane separation, ⑥activated charcoal absorption, ⑦ oxidative decomposition, and ⑧sterilization. Most of them perform separation by utilizing the surface charge or specific weight of the solid contained in the liquid. Activated charcoal absorption is highly effective for removal of small amount of organic substances, and it is employed in many purification plants.

Oxidative decomposition uses the strong oxidizability of substances such as ozone and OH radicals to oxidize and decompose contaminants. With its strong oxidizability, OH radicals particularly can decompose substances that are difficult to decompose through biological treatment, and it is expected to be highly effective against dioxins and pesticides. Formation of OH radicals is conducted through irradiation with ultraviolet rays or ultrasound[29)], utilization of Fenton reaction using reagent[30)], irradiation of ultraviolet rays on peroxydisulfuric ion[31)], irradiation with plasma[32)], etc. However, for it to be utilized in the water circulation of the PG, it is necessary to solve the amount it can treat, treatment efficiency, equipment cost, running cost and frequency of its maintenance in order to meaningfully deploy the plasma treatment and other methods.

The methods to treat wastewater/used water through electrolysis treatment are already established. Following Table 2 shows example of its application on real wastewater.

Table 2 Example of electrolysis treatment of real wastewater. [33)]

Anode material	Cathode material	Processing target	Initial COD [g/L]	Current efficiency [%]	Energy efficiency	Removal rate [%]	Cl concentration in discharged water [g/L]
Ti/Pt	SUS304	Wastewater from olive oil factory	178.22		1.27 ~ 4.73 kWh/kg ~ COD_{Cr}	41 ~ 76 (COD_{Cr})	24.3
Ti/Pt	SUS304	Common sewage	1.047		12.4 kWh/kg ~ COD_{Cr}	89 (COD_{Cr})	8
Ti/Pt	Pt	Wastewater from chemical factory	1.361	18		40 (COD_{Cr})	
Ti/Pt	Ti/Pt	Wastewater from tannery (After final processing)	0.093	12		65 (COD_{Cr})	1.84
Ti/Pt	Ti/Pt	(After secondary processing)	0.235 ~ 0.458	18.2 ~ 25.8		62 ~ 64 (COD_{Cr})	2.47 ~ 2.56
Ti/Pt	Ti/Pt	(Original waste water)	1.774	6.1 ~ 7.4		46 ~ 70 (COD_{Cr})	2.562
Ti/Pt-Ir	Ti/Pt-Ir	(After final processing)	0.146	25		57 (COD_{Cr})	1.846
Ti/Pt-Ir	Ti/Pt-Ir	(After secondary processing)	0.176	6.9 ~ 9.4		19 ~ 43 (COD_{Cr})	1.935
Ti/Pt-Ir	Ti/Pt-Ir	(Original waste water)	1.774	21		11 (COD_{Cr})	2.562
Ti/Ta-Pt-Ir	SUS316L	Wastewater from olive oil factory	1.475		32.2 ~ 82.1 kWh/kg-COD_{Cr}		1 ~ 4 %
Cast iron	Cast iron	Wastewater from tobacco factory	1.120 ~ 1.245		55.6 ~ 116 kWh/kg-COD_{Cr}	42 ~ 60 (COD_{Cr})	0.460
Ti/$Ru_{0.3}Ti_{0.7}O_2$	SUS304	Wastewater from textile factory	~ 0.225		154.0 ~ 822.3 kWh/kg-TOC		3.55
Ti/RuO_2	SUS304	Wastewater from olive oil		7 ~ 48		17 ~ 93 (COD_{Cr})	0.800
Ti/RuO_2	Ti	Wastewater from distillery	9.54	7	2.82 kWh/kg-COD_{Cr}	89.62 (COD_{Cr})	35.5
Ti/RuO_2	Ti	Concentrated water from RO membrane processing of sewage/wastewater from textile factory	0.151 ~	15			0.595 ~
BDD	Ti		0.171	35			0.804
BDD		Wastewater that contains oil from car factory	2.57	61 ~ 95		99 % (COD_{Cr})	

Electrolysis can said to be one of effective methods not only of treating domestic sewage but also of purifying industrial wastewater. However, as it uses Pt as its electrode, its electrode cost is preventing its wide application. Purification and recycling of wastewater/used water is highly compatible with the PG. For its application on the PG, selection of an electrode catalyst is essential.

2.3.3 Technology to produce hydrogen directly from wastewater that contains excrement, seawater, river water and rain water

As discussed in Section 1.3.3, different approaches are required for direct hydrogen production technology from wastewater/used water and from seawater. There have already been many research and development on the hydrogen production technology using photocatalyst originating from photolysis of water in photo-electrochemistry. Among them, the highly efficient method to obtain hydrogen by adding organic substances such as pigment or sacrificial reagent to the reaction system is already commonly used. For this process, evaluation is conducted by mixing[34] triethanolamine[35], which is the ph regulator of shampoo and other products, methanol, formic acid or ethylene glycol to the existing photocatalyst. At this stage, mostly simulated wastewater, where organic compounds are mixed into electrolytic solutions, are used, and experiment using real wastewater is inferred to be extremely rare. Therefore, there are still many issues to be addressed, such as cost, durability and treatment speed, before its practical application. Especially with real wastewater that contains many substances, there is a reasonable chance that adsorbed state or competing reactions that are impossible to occur in simple systems would occur. Thus at this stage, examination of type of electrode catalyst and electrode structure that are capable of directly producing hydrogen from wastewater containing excrement and used water is necessary.

Unlike the generation oxygen, no competing reactions that are thermodynamically close in direct hydrogen production from seawater, and therefore it appears to have fewer problems. However, it is difficult to obtain desired catalytic activity from the seawater that is interference ion and neutral region. Some of the electrode catalysts that have been examined after 2016 are discussed in the review[36] that collected the research trend in direct decomposition of seawater in recent years. While a new catalyst is proposed almost every year, much better stability and hydrogen generation activity are necessary in order to enable real commercial hydrogen production. In addition, components such as the electrolyte film used in electrolysis cell must be examined.

Meanwhile, a method to produce hydrogen using electrolysis technology after desalinating seawater with the RO membrane has been proposed. While this can be regarded as the most realistic option at this point, it is inferred that examining how to obtain hydrogen directly through electrolysis of seawater as much as possible is still more desirable considering the durability, maintenance and device size of the RO membrane.

2.4 Electrolysis technology and PG-related technology required for the three cycles

2.4.1 Reactors suitable for PG

As the usable space will be limited in the PG, it will be difficult to install large devices. Moreover, a flow system that can be easily connected to other processes is desirable in order to conduct various processes continuously. It is inferred that the reaction using heat is unsuitable for the PG that is to be used in small scale indoor from the point of view of energy efficiency and safety. On the other, the electrolysis has superior start/stop trackability, and, and it is unlikely to become out of control due to the heat, and therefore its usage in the PG is being examined. However, as the electrolytic reaction is a heterogeneous reaction that occurs on the surface of the electrodes, only their surfaces are the reaction fields. In addition, movement of the electrolyte between the electrodes is necessary for the reaction to progress. Various types of electrolytic reactors have been devised in order to minimize the limitations due to the principle of the reaction and conduct free and highly efficient electrolytic reaction. It is inferred that especially by connecting several extremely small reactors such as micro reactors, smooth energy circulation/carbon circulation within the PG can be realized.

3. The (overall) trend in research and development, international trend and the strength of Japan related to this target

3.1 Energy circulation

3.1.1 Use of renewable energy, mainly solar power

Large overseas projects include Horizon 2020 (Europe) and the Sunshot Initiative (U.S.), where a wide range of research and development is being conducted from basic to applied research. On the other hand, in Japan, it is estimated that the trend is to focus on the improvement of deterioration diagnosis and the optimization of the system assuming a large-scale grid. In the CRDS R&D overview report, R&D in Japan, the U.S., China, and Korea is described as maintaining the current status, while Europe is described as having an upward trend in both basic and applied research.

3.1.2 Hydrogen production and storage technology

As described in Section II 2.1.2, solid polymer water electrolysis is one of the hydrogen production technologies suitable for PG, but the high cost due to precious metal materials is an issue. As an R&D effort to reduce the amount of precious metals used, in 2018, Toshiba Corporation succeeded in developing a precious metal-saving electrode using nanostructure control technology with the sputtering method. In the past, several g/cm^2 of precious metals were used as powder catalysts and coating materials for anodes, but this technology succeeded in reducing the amount of precious metals to 0.1 mg/cm^2.[37)]

In 2009, Chiyoda Corporation succeeded in developing a dehydrogenation catalyst that can stably generate hydrogen for more than one year in a laboratory scale lifetime test. In 2011, the company established a system to manufacture and procure the catalyst on an industrial scale. In 2011, we established a system to manufacture and procure this catalyst industrially, and built a pilot plant, which was operated for a total of about 10,000 hours from 2013 to 2014, and confirmed that the catalyst worked stably[2)].

3.1.3 Increasing power densities and durability of fuel cells

For the development of cathode catalysts, which are the key to polymer electrolyte fuel cells (PEFCs) with high power densities and durability, researches and developments of platinum alloy nanostructures that maximize the activity, minimize the amount of platinum used are conducted all over the world. Non-platinum-based catalysts are also being actively researched and developed both in Japan and overseas, aiming at the widespread use of PEFCs after 2040. Although a domestic automobile company is the first in the world to launch fuel cell vehicles, the percentage of Chinese researchers in the population of researchers at the basic research level is quite high, considering the number of papers reported. In order for domestic researchers to maintain their leadership in the development of catalysts and fuel cell vehicles, innovative catalyst development will be necessary.

3.1.4 Increasing the size and capacity of storage batteries

In the current situation, especially, the development of all-solid-state batteries is very active. Specifically, the development of technology to build a good conduction path for lithium ions between the active material and solid electrolyte is attracting attention. Sulfide-based solid electrolytes have been mainly studied, but in recent years, oxide-based solid electrolytes have been attracting attention. Oxide electrolytes have lower ionic conductivity than sulfide electrolytes, and require higher technology for the construction of the electrolyte-active material interface. Currently, NEDO and JST projects are promoting research and development in collaboration with industry, government and academia.

3.1.5 Feed-in tariffs (FIT), and the separation of transmission and distribution

As discussed in Chapter II 2.1.5, while the introduction amount of renewable energy in Japan is increasing following the implementation of FIT, it is still small compared to Europe. An important factor causing this situation is the cost. Following Figure 15 shows the transition of renewable energy costs in Japan and in Europe. In order to further increase the scale of renewable energy, measures to reduce cost are urgent[23)].

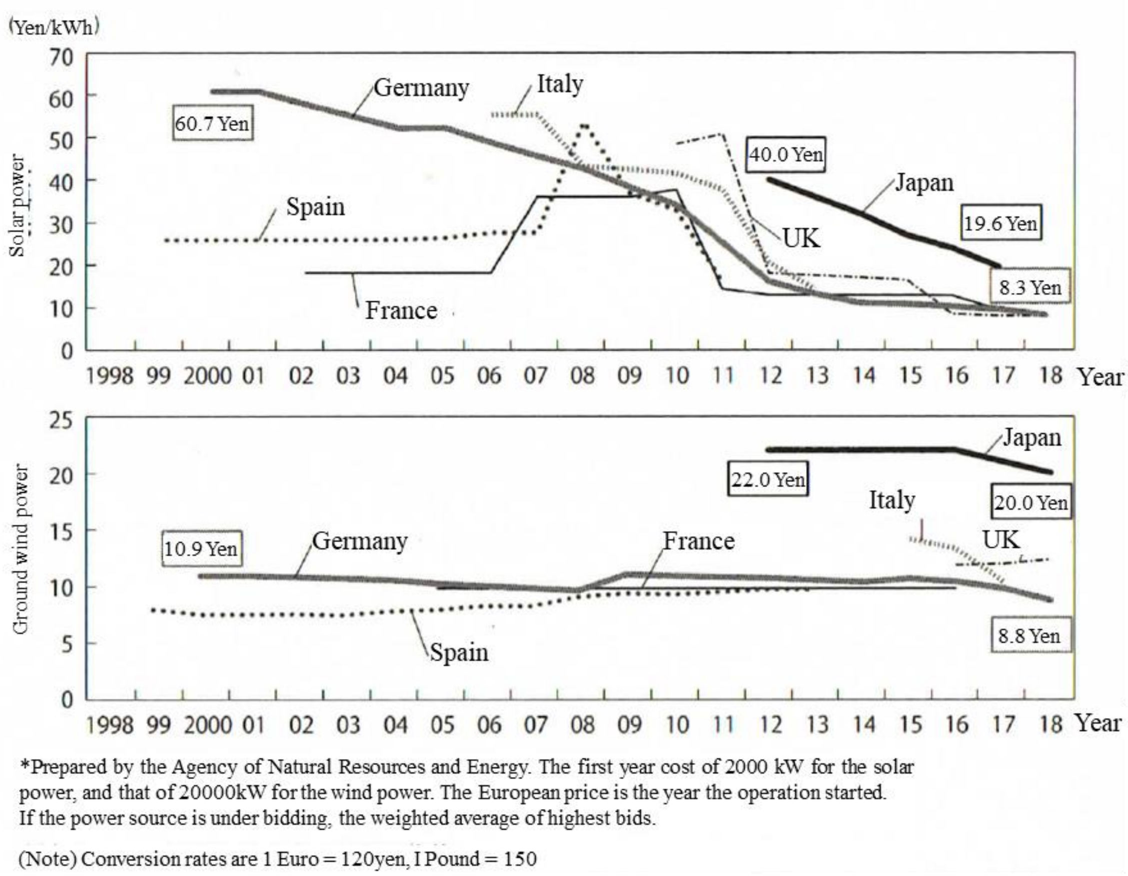


Figure 15 Transition of renewable energy costs in Japan and in Europe[23)]

As self-consumption is being demanded in order to solve the site constraint, some countries/region outside Japan are introducing the net metering system. This system calculates the retail rate of electricity trading, including deduction and carry over, in order to promote the introduction of small and decentralized power sources for the purpose of self-consumption. In the United States for instance, introduction of this system played a major role in dissemination of small and decentralized power sources such as domestic solar power[20)]. Moreover in the United States, the federal government supports building of safe power supply system following the experience of blackout caused by hurricanes especially around its northeastern states, leading to the increase in the introduction of microgrid. In addition to the northeastern regions, introduction of mircogrid is progressing in the West Coast where decentralized power, especially the renewable energy, sources are increasing[4)].

The asynchronous tie mentioned in Section 1.1 of Chapter II is effective in cases such as regional difference in power frequency as in Japan, and it is already used in frequency converter stations. Internationally, continental Europe and the Scandinavian peninsula, the United States and Mexico, the United States and Canada, and Brazil and the countries around it for instance are connected through asynchronous tie, and within China, more than twenty direct current power transmission projects are planned. It is planned that tie using the BTB is planned for the connecting points between Russian and China[3)].

Europe has built a power system suitable for renewable energy by organizing it as shown in Figure 16. However, Japan is an isolated island nation, and its electric system is a longitudinal transmission system as shown in Figure 17. Thus, it cannot directly apply European system. Therefore, it will be important to use the digital grid utilizing the BTB[4)].

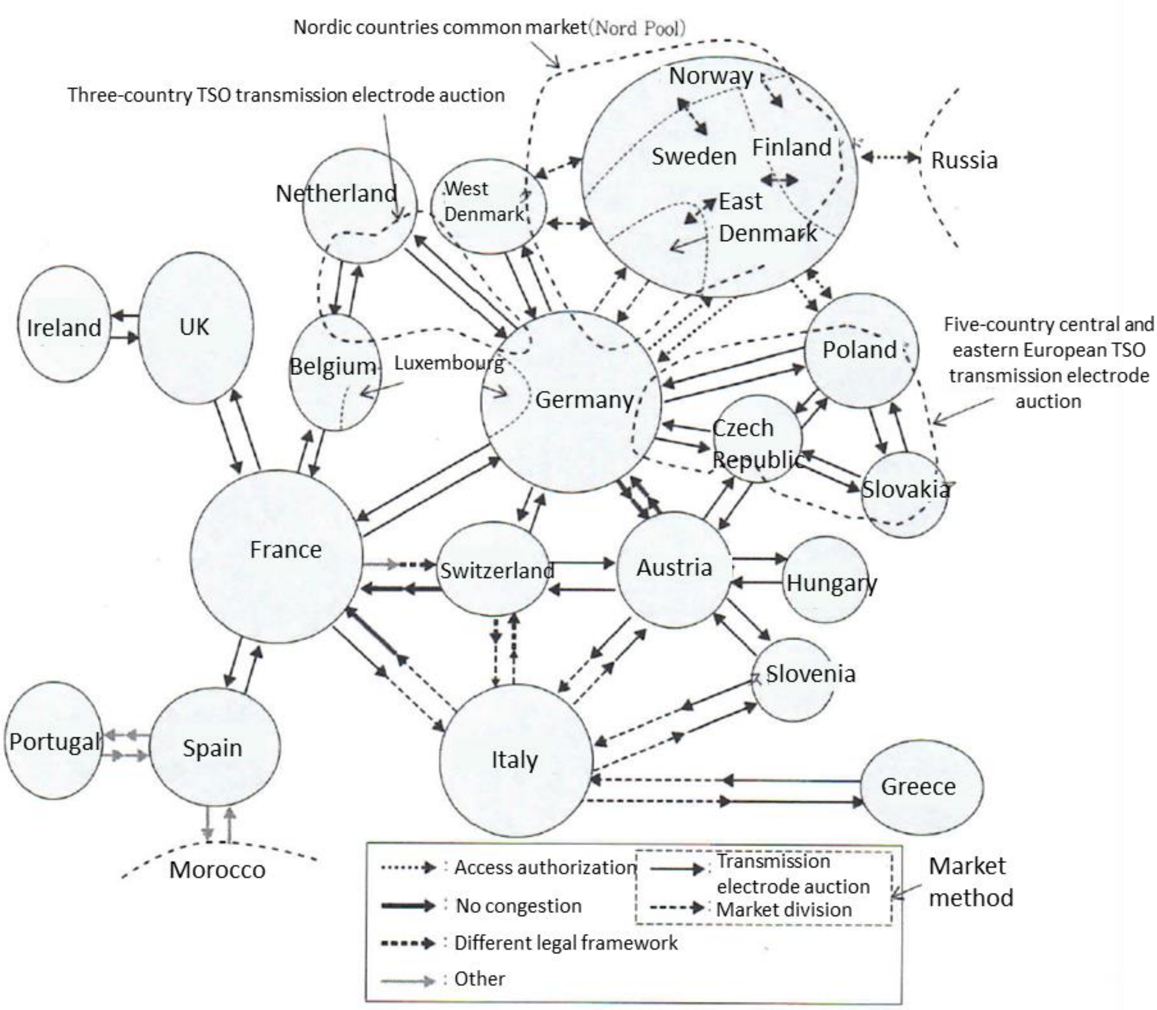


Figure 16 Power system of Europe[3)]

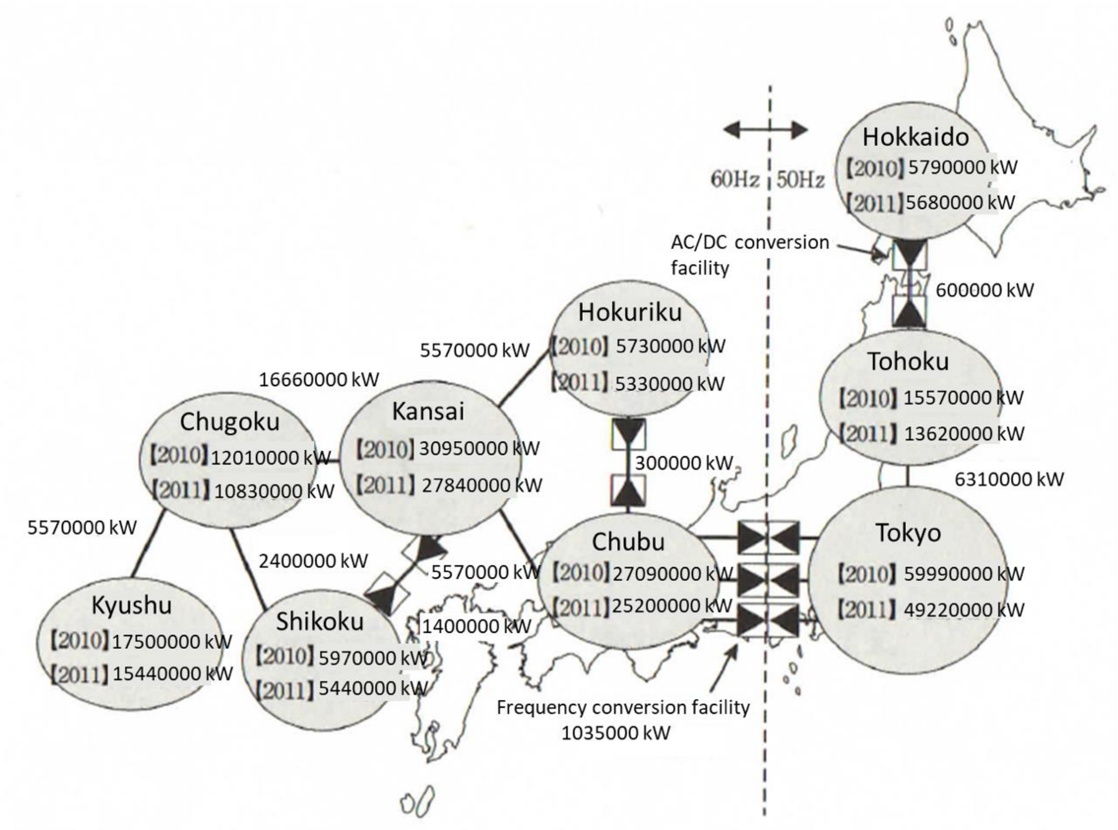


Figure 17 Power system of Japan[3)]

3.2 Material circulation

3.2.1Recycling of plastic products[38)]

The recycling of plastic products has been recognized as an important issue both domestically and internationally due to the recent tightening of waste plastic import regulations in Asian countries including China and the ocean plastic problem. Specifically, in Japan, the "Action Plan for Marine Plastic Litter Problem" and the "Strategy for Recycling Plastic Resources" were formulated in May 2019, and the "Development of Innovative Plastic Resources Recycling Process Technology" will start in 2020 under the leadership of NEDO. In this project, (1) development of an advanced sorting system, (2) development of a material recycling process (material recycling), (3) development of a petrochemical raw material conversion process (chemical recycling), and (4) development of a highly efficient energy recovery and utilization system are being carried out. However, it can be read from the basic plan for the development of innovative plastic resource recycling process technologies that these are intended for the treatment of large scale and large amount of waste plastic.

In the EU, the European Plastics Strategy was released in 2018, and in the US, the Reducing Embodied-energy And Decreasing Emissions (REMADE) initiative was launched in 2017 by the US Department of Energy's Office of Energy Efficiency and Renewable Energy. In the United States, the

Reducing Embodied-energy And Decreasing Emissions; REMADE, led by the Office of Energy Efficiency and Renewable Energy of the U.S. Department of Energy, was launched in 2017 to provide funding for recycling and reuse in general. Therefore, it can be said that research and development on the use of waste plastics is becoming more and more active in many countries.

3.2.2 Production of amino acids

3.2.2.1 α-amino acid synthesis through direct carboxylation using photoredox catalysis

It is known that when photoredox catalysis is used, one electron reduction of CO2 occurs, causing reaction with alkyne, alkene, halogenated organic and amine, which are radical acceptors. Fan et al. achieved α-amino acid synthesis through carboxylation of benzophenone ketimine derivative. (Figure 18)[39]. It is a synthesis process that simplified its procedure and used the sunlight as its driving power. However, it has a problem that it requires heightening of nucleophilicity of the reactant, necessitating the usage of stoichiometric amount of organometallic reagent or expensive transition metal catalyst.

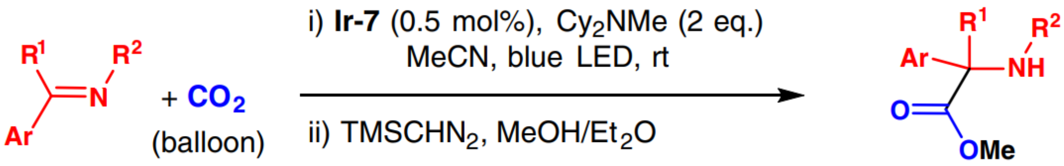


Figure 18 α-amino acid synthesis through direct carboxylation

3.2.2.2 α-amino acids synthesis through electroorganic synthesis using electrocarboxylation

As a synthesis process that does not require highly toxic cyanide or stoichiometric amount of organometallic reagent, the α-amino acid synthesis method through electroorganic synthesis has been reported[40]. It is a synthesis process that utilizes the electrocarboxylation reaction of benzylideneaniline at the electrode through two-electron reduction. However, it requires stabilization of benzylideneaniline reductant, and it is limited to the synthesis methods using sacrificial anode.

3.2.3 Synthesis of ammonia

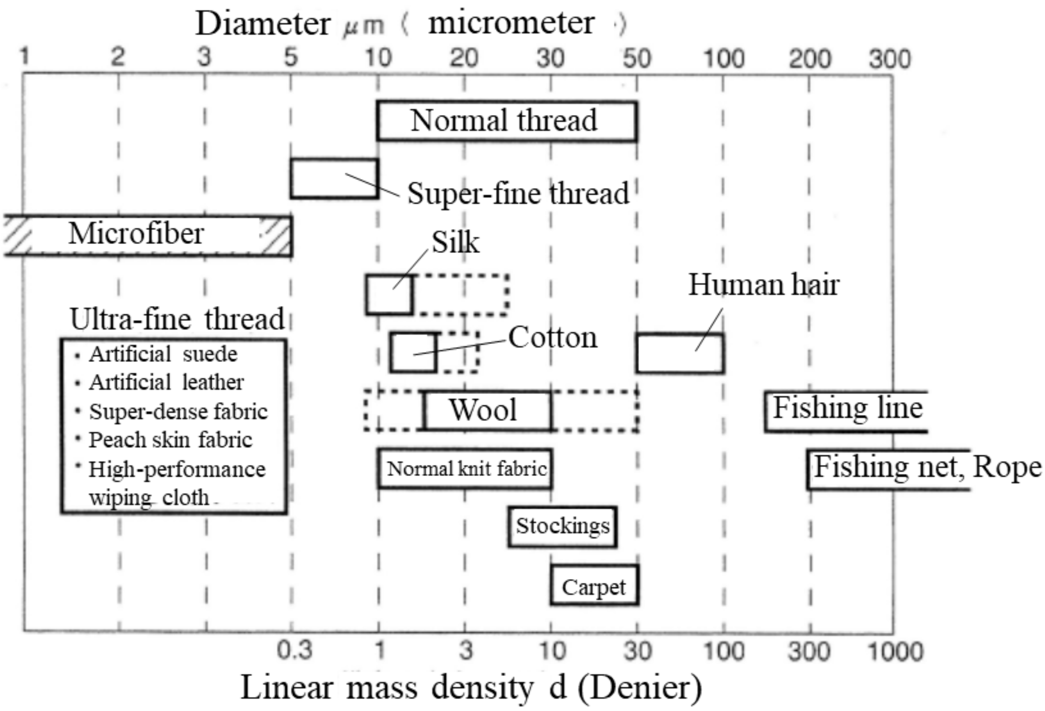
Ammonia synthesis Fe base catalysts are used for the existing ammonia synthesis methods such as the Haber-Bosch process. However, as Fe base catalysts require high pressure, researches on Ru base catalysts are ongoing. At the National Institute of Advanced Industrial Science and Technology, development of Ru/CeO_2(Cs-Ru/MPC) catalyst and its demonstration experiment (20Kg/day) are already being conducted. During the demonstration experiment, 25.4% hydrogen conversion rate was achieved at 400°C, reaction pressure .0 MPaG and H2/N2 ratio 1.0 mol/mol.

Ito et al. achieved electrosynthesis of ammonia in nitrogen under normal pressure and at 300°C using a LiCl-KCl-CsCl eutectic mixture containing Li_3N (0.5 mol%) as the electrolyte and Ni cathode and carbon anode (glass carbon or boron-doped diamond) as the electrode catalysts. In this electrolysis process, the cathode reduces the nitrogen into nitride ion (N^{3-}), which reacts with water to generate ammonia. Its research and development toward industrial usage is ongoing [18)].

3.2.4 3D printer

There are many ongoing initiatives to apply 3D printers to clothing, for instance by Materialise in Belgium[41)]. However, all of them, even those for fashion, are not fibers and instead have chain mail-like structure, and not practical for clothing. Examples of initiatives to produce fabric by piling fibers through 3D printer include Nike Zoom VaporFly Elite Flyprint, which Nike presented in 2019[42)]. It uses the fabric produced by 3D printers for the upper part of sneakers. As 3D printers allow free setting of position density of mesh, they have the benefit of setting optimal contractibility for each position. However, common 3D printers are used for its production, and the thickness of the fiber is 400μm.

Figure 19 shows summary of the thickness of fibers used in clothing. The thicknesses of fibers used for clothing that touches skin directly are between 10 and 30μm. Synthetic fiber is processed into the desired thinness by stretching the resin extruded from the nozzle. Due to the issue of viscoelasticity, it is difficult to extrude common polymers out from nozzles between 10 and 30μ, and there has been no example of using such small nozzles being used with the MEX type 3D printers.



Source: Hideo Matsui, March 25, 1992 (Senkei Shimbun)

Figure 19 Classification of clothing fibers and their thickness

Initiatives to produce food using 3D printers, especially to produce fake meat, include those announced by Novameat in Spain and RedefineMeat in Israel[43)]. Both examples use the MEX type 3D printers. They recreate muscle fiber by extruding protein out of nozzle in order to obtain texture close to meat. And both company announced that they will start providing their products to restaurants within 2021.

3.3 Water circulation

The latest national and international trends related to water circulation are discussed in pp. 471 - pp. 484 of the research and development overview report compiled by the JST Center for Research and Development Strategy (CRDS). Please refer to it for details.

The key water circulation technologies the PG will be composed of include the RO membrane. Researches and developments on the RO membrane have been conducted in Japan since the early 1970s, and following the Japanese production of the RO membrane for seawater desalination, which was conducted as a national project, and thanks to the technologies developed by that project, Japanese technology on this field is leading the world. However, partly due to the fact that Japan is not facing a sever problem with its drinking water, it is not in absolutely superior position against Europe, the US and China. According to the analysis by the CRDS, wide-ranging researches and developments from basic research to applied research are being conducted in China, which is facing the problem of water pollution. Meanwhile, the water purification technologies, including the desalination technology, are currently stagnating. Thus, it is necessary to promote from basic to social implementation, for instance through collaboration of the industry and the academia.

While it is partially due to the difference in the number of researchers, presence of Japan cannot be deemed as strong in the technology to directly produce hydrogen from seawater or wastewater as the number of Japanese reports is low. As this is a field where the number of reports is rapidly increasing in recent years, it can be hoped that Japan will become the country that leads the world if Japanese researchers turn their attentions now.

3.4 Reactors suitable for PG

3.4.1 Thin layer type electrolytic cell (capillary gap cell)

The thin layer type electrolytic cell is a reactor designed for significant reduction supporting electrolyte through the closeness of its electrodes. Indeed, BASF from Germany reduced the usage of supporting electrolyte through industrial production of bipolar electrosynthesis of phthalide and t-butylbenzaldehyde using a thin layer type electrolytic cell[44].

3.4.2 Electrolytic flow microreactor

Microdevices that perform chemical reaction are called microreactors. They are designed with passage width between few dozen to few hundred μm. They are normally a flow system, and they are capable of continuous production. For electrosynthesis, efficient reaction can be achieved by using the passage walls as the electrodes. Such reactors are called the electrolytic flow microreactors. Following is its uniqueness compared to the chemical reaction using the conventional batch type reactors such as beakers or flasks[45, 46].

(a) Extremely large specific surface

By reducing the size of reactor to micro scale, the specific surface per volume of the electrode becomes extremely large. This is expected to greatly accelerate electrolytic reaction. Moreover, as thermal transfer occurs rapidly from the walls of the passage, accurate temperature control is possible.

(b) Accurate control of staying time (reaction time)

The flow inside the flow microreactor can be maintained as laminar flow without causing turbulence as the passage is narrow. Therefore, by determining the passage length of the reactor or the flow speed of the fluid inside, it will be possible to control its staying time inside the reactor, i.e. the reaction time. Moreover, as it is a flow system, the product after the reaction is discharged outside the system quickly. Thus, it can also control the decomposition or side effect of the product.

(c) High speed mixing

Normally, mixing requires molecular diffusion, and the time required for molecular diffusion is in proportion to the square of the diffusion distance. Therefore, by radically shortening the molecular diffusion distance through redaction of the reaction container down to micro size, high speed mixing that cannot be achieved by conventional reactors becomes possible.

(d) Easy scale up

When increasing the scale by using flow microreactor, the output can be increased by increasing the number of flow microreactors after optimizing the reaction condition of one reactor. Thus, in principle, it will be easy to scale up without the chemical and industrial considerations required today.

While these characteristics are deemed to be useful for industrial production, the addition of supporting electrolyte necessary for electrolytic reaction is regarded to be undesirable from the perspective of clean chemistry. However, researches to significantly reduce the usage of supporting electrolyte by utilizing the fact that the distance between electrodes of micro-flow reactor is in micro order are ongoing[47)].

III. Scenario for realizing the vison of society

1. Dicipline/field and research problems in challenging research and development

PG is a system that ultimately achieves energy circulation, water circulation, and material circulation using only renewable energy, mainly solar power, from the outside in a closed space on a personal scale, and its detailed circulation integration process is shown in Figure 20. The core technologies of PG are electrochemistry (electrolysis), which is at the root of all circulation, and 3D printing, which creates shapes. The most upstream issue for the system to realize PG is the feasibility of energy balance: the electricity to be introduced to the entire PG is only from renewable energy sources, among which photovoltaic power generation is mainly suitable from the viewpoint of mobility. The amount of electricity generated by photovoltaic power generation is 14-15 kWh per day with an output of about 4.5 kW in the Japanese climate, assuming a personal living space of 20-36 m2. On the other hand, the average daily electricity consumption of a Japanese person is currently 6~10 kWh, depending on the estimation, and 4~9 kWh can be used for water circulation and material circulation. The wastewater treatment system using electrolysis currently available on the market consumes 0.5 to 1 kWh, and 0.8 to 1 kWh for drinking. Although there is an issue of downsizing the wastewater treatment equipment, it is possible to use 30~50% of the solar power generation for material circulation at this point, and further technological development is expected to improve performance and downsize the equipment.

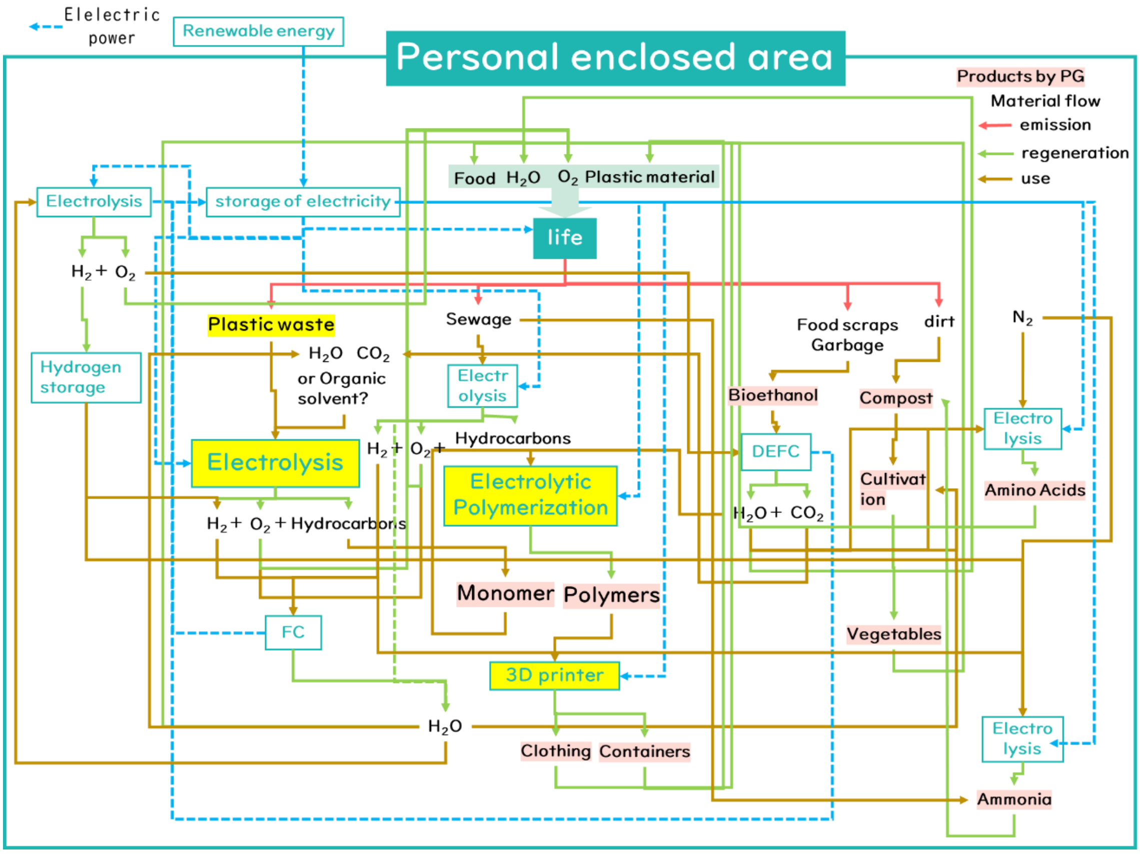


Figure 20 Details of the circulation integration process within a closed space in PG

1.1 Energy circulation

Many projects have already been carried out to develop technologies in the energy circulation field, and roadmaps for 2050 have been established for each technology. Therefore, it is expected that the realization of the PG will strongly collaborate with other national projects in the field of energy circulation, especially those of NEDO.

1.1.1 Solar power generation

The photovoltaic roadmap (PV2030+) lists the following technical goals to be achieved by 2050: increasing the conversion efficiency to 40%, lowering the generation cost to 7 yen/kWh, improving the module and system lifetime, establishing high-purity silicon supply technology and silicon source unit reduction, and establishing technology for saving silicon and scarce resources. In addition, there is a need to establish reliability and to reduce the cost of power generation. In addition, it is considered essential to establish technical and social infrastructure, such as reliability and recycling/reuse systems. For the short-term technological development, industry will take the lead in optimizing the entire system and expanding applications based on existing technologies and materials. For the ultra-long-term technological development around 2050, a scenario in which universities and national laboratories conduct research to find seeds is presented.

1.1.2 Hydrogen production and storage technology

At present, steam reforming from fossil fuels such as naphtha and natural gas is the mainstream hydrogen production technology, and high-pressure hydrogen gas and liquefied hydrogen are the mainstream hydrogen storage technologies. However, by around 2030, hydrogen production technology from unused overseas energy sources such as by-product hydrogen and lignite will be developed and demonstrated, and hydrogen storage technology in the form of organic hydrides and liquefied hydrogen will be developed and demonstrated. By 2030, we will develop and demonstrate hydrogen production technology from unused overseas energy sources such as by-product hydrogen and lignite, and hydrogen storage technology in the form of organic hydrides and liquefied hydrogen. At the same time, development and demonstration of CO2-free hydrogen production using renewable energy will be carried out around 2040. Based on the above, the scenario is to start full-scale production and storage of CO2-free hydrogen around 2040.[48)]

1.1.3 Fuel Cell Technology

According to the NEDO's strategic roadmap for hydrogen and fuel cells, the development of innovative electrocatalysts with higher catalytic activity and durability is being promoted in order to enter a period of the widespread use of hydrogen stations and fuel cell vehicles after 2030. Since platinum is used in catalysts for both cathode and anode, the use of platinum may hinder the widespread use of fuel cell vehicles. Platinum-less or ultimately platinum-free catalysts must be developed.

1.1.4 Storage Battery Technology

Mass production of all solid-state batteries, mainly using sulfide solid electrolytes, is expected by 2025. At the same time, all-solid-state batteries composed of advanced sulfide and oxide electrolytes will be developed as the next generation. Basic research is also underway to develop innovative storage batteries composed of lithium-sulfur and lithium-air by around 2040. Through these research and development efforts, the storage batteries for automobiles and stationary applications will be developed in earnest.[49)]

1.1.5 Full-scale introduction of renewable energy into society

In Denmark, an initiative called the citizen wind turbine, where individuals erect wind turbines to obtain electricity through wind power generation. Possession of power generation facility at the individual level would greatly contribute to the realization of the PG. One of the factors of the success of this citizen wind turbine in Denmark is the careful maintenance system offered by the wind turbine manufacturer. The fact that the manufacturer offers good support in maintenance after the sales instead simply dumping wind turbines reassures the owners. Moreover, the manufacturer can continue to sell their product in the form of maintenance. Thus, it is a system that is beneficial to both parties[50)].

Energy decentralization initiatives are also ongoing inside Japan. For instance, Toyota-shi in Aichi Prefecture is working on the "Toyota-shi Smart Demonstration Project" whose theme is the local production and consumption of small-scale energy. The purpose of this project is to build a next generation provincial city-type low-carbon social system that can achieve the optimization of energy and traffic usage for the entire sphere of living comfortably without reducing the life quality and strain. It introduces fuel cells, domestic storage batteries and solar power to 67 newly build and sold houses, optimally control energy saving electric appliances using EMS and other means, and implements optimization of power supply to and device control at households[51)].

Digital grid is a power system that is freed from the frequency constraint and equipped with private power generation facilities such as renewable energy through application of BTB discussed in Chapter II, Section 1.1.5. In this digital grid, it will be possible to smoothly conduct multidirectional exchanges of electric power. Thus, it is believed to greatly contribute to the system stabilization during the large-scale introduction of renewable energy[3)].

1.2 Material circulation

In the material cycle, it is assumed that polymers, which are plastic products, will be depolymerized to monomers by electrolytic technology, go through the polymerization process again, and finally be formed into clothing and other products by a 3D printer. Fake meat is also formed by a 3D printer, originating from amino acid synthesis by electrolysis. Therefore, the polymerization technology by electrolysis and the 3D printer technology are very important elemental technologies in the material cycle.

1.2.1 Electrochemical depolymerization of plastic (Polymer to monomer conversion)

In order to realize carbon circulation within the PG, small-sale systems for the decomposition of polylactic acid, which can be used as the filler of 3D printers, and all-purpose plastics such as polyethylene are necessary. The converting plastics into oil requires a huge facility and large quantities of plastic wastes, which makes the current technology unsuitable for the PG. The development of plastic depolymerization (decomposition) technology that can be conducted at home is necessary. Electrochemical depolymerization has many advantages: easy reaction control (control of voltage application), easy maintenance (replacement of electrodes) and easy use of renewable energy. Thus, the electrochemical depolymerization system is the most promising candidate for the PG.

For example, electrolysis at the high temperature of 350°C is reported, where polypropylene is depolymerized at the anode and hydrogen is generated at the cathode. C1-C5 hydrocarbons are produced at approx. 68% conversion efficiency[52]. Although high temperatures are required in this experiment, called a solar thermal electrochemical process (STEP), lower reaction temperatures can, in principle, be realized by developing highly active electrocatalysts and optimizing experimental conditions. Another example is the electrochemical hydrogen generation coupled with decomposition of methyl pivalate, which is used as the model compound for electrochemical depolymerization of polymethyl methacrylate (PMMA)[53]. While progress of electrolysis on the surface of Pt electrodes of the model compound was observed, it requires methods to solubilize polymers including PMMA in the electrolyte solution and avoid poisoning caused by decomposed products. In addition, the electrochemical oxidization of lactic acid, which is both the material and hydrolysis product of polylactic acid, has been achieved using microoganisms[54] or iridium catalysts[55]. Furthermore, a photochemical decomposition system of microplastic made of low-density polyethylene using zinc oxide nanorod as the photocatalyst[56] has been reported, though it is not an electrochemical system. This implies that the depolymerization of plastic through photoelectrolysis using semiconductor electrodes is theoretically possible.

These recent reports suggest that depolymerization of polymers using electrochemical systems within the PG is reasonably realizable if the product selectivity of the electrode catalyst can be improved.

1.2.2 Ammonia Synthesis by Electrolysis

In PG, ammonia is intended to be used as fertilizer, and due to space constraints, electrolytic synthesis is the most suitable method. I. Amar et al. succeeded in producing ammonia from air and water at ambient temperature and pressure by using Nafion membrane as SPE. [57] Protons produced by electrolytic oxidation of water are reduced at the cathode and react with nitrogen adsorbed on the cathode electrocatalyst to produce ammonia. This is a highly energy-efficient electrolysis method that produces ammonia at a maximum rate of 1.6 V, a voltage equivalent to water electrolysis. In order to further improve energy efficiency and productivity, it is necessary to establish an ammonia synthesis method that satisfies the limitations of PG by improving catalysts and reactors.

1.2.3 Amino acid synthesis by electrolysis

Since amino acid synthesis is linked to the food supply in PG, it is necessary to ensure sufficient production. In recent years, Naito and co-workers have achieved the continuous flow synthesis of α-amino acids by using benzaldehyde and aniline as starting substrates, generating benzylamine in the system using a dehydrating agent, followed by electrocarboxylation in an electrolytic flow microreactor.[58] In order to reach the level where the reaction can be operated in a PG, further investigation of the electrolysis and catalyst conditions is necessary. Further investigation of electrolysis and catalyst conditions is necessary to reach an operational level in PG.

1.2.4 3D printer

It is difficult to protrude polymers and form them into fibers with thickness between 10 to 30μdirectly out of a nozzle without stretching is difficult overall, and not only for 3D printers. In order to shape clothing using this method, a new technology that can drastically change the physical character of polymers themselves or inventions such as integration of stretching mechanism inside the shaping head would be necessary.

In the MJT method, the material is discharged by using an inkjet (hereafter referred to as IJ) head. The diameter of the nozzle of the IJ head used in 3D printers are approx. 20μm, which is about the same as the desired diameter. In the MJT, monomer is normally extruded instead of polymer, which is hardened through UV irradiation immediately after it landed on the shaping surface. The liquid extruded from the IJ head is column-shaped immediately after the extrusion, and it becomes drop-shaped in a few dozen μ-seconds due to the fragmentation and condensation caused by the surface tension. The challenges in shaping fibers through this method are to harden the monomer while it is still in column-shape, and also to make the fibers flying through the space land and accumulate on the desired position, and then adhere to the previous layer.

If a method to disperse short fibers in the liquid and maintain that state is developed, there is a possibility that SL type 3D printing will become possible. However, this method is only capable of producing even fabrics. Shaping of highly functional fabrics unique to 3D printer, such as the aforementioned Nike Zoom VaporFly Elite Flyprint, will no longer be possible.

Meanwhile, shaping of fake meat is already seeing the start of commercial activities, as discussed above, and it is possible that it becomes widespread within 10 years depending on the social demand. However, its material is plant-derived protein, and it will be difficult to introduce synthetic materials to its production.

Especially because the act of eating meat has strong element of taste in addition to nutrition intake, it is necessary to create products that can satisfy the demands as luxury item such as flavor and aroma in addition to ensuring their safety.

1.3 Water circulation

Considering that the water cycle is to be implemented in each living space, small, quick, low-cost, and maintenance-free systems are desired. In general, purification technologies are implemented using various filters, but they are not suitable for PG considering safety, system scale, cost, and maintainability. In particular, existing filtration technologies cannot decompose or remove pharmaceuticals and other substances, so they cannot be used for drinking or returned to the surrounding environment. Therefore, PG will focus on electrolysis technology, which is relatively compact, quick, and low-cost, as the core of water circulation technology.

1.3.1 Establishment of purification technology by electrolysis for domestic wastewater including manure and surrounding environmental water

The Ministry of Land, Infrastructure, Transport and Tourism (MLIT) reported in its 2030 edition of "Current Status of Water Resources in Japan" that the average per capita water consumption for domestic use in Japan is currently 284 L/day. This amount of water cannot be covered only by the technology to obtain drinking water from urine, which has already been developed. Therefore, in order to achieve 284 L/day, it is necessary to circulate all wastewater discharged from households, including manure. In addition, the wastewater purification system must be small enough to be installed in each living space, and it must be as maintenance-free as possible. Furthermore, the lifetime of the entire purification system should be more than 30 years.

In actual domestic wastewater, there are solids such as hair. Therefore, it is necessary to separate solids of a certain size using a filter. The separated solids are then recycled together with other organic wastes. Therefore, it is expected to purify inorganic ions, organic matter, bacteria, viruses, surfactants, inorganic ions, organic ions, and chemical substances contained in urine, pharmaceuticals, and domestic wastewater.

Currently, electrolysis is being investigated as a type of wastewater treatment[59- 61)], and some of it is in practical use. However, in most cases, plate metals and oxides are used as electrodes. However, in most cases, plate metals or oxides are used as electrodes. From these results, it is concluded that electrolysis can be used to purify wastewater, but further improvement of efficiency is necessary to introduce it into PG. Therefore, the development of a new electrocatalyst with a large number of reaction fields and excellent long-term stability is required to realize the water cycle in PG.

1.3.2 Electrochemical power generation and hydrogen generation using microbe

If organic waste can be used as fuel to generate electricity and hydrogen as energy electrochemically, it is expected to make a significant contribution to the realization of not only the water cycle in PG but also the energy cycle and material cycle.

For instance, it is possible to use microbial fuel cell that combines microbe used as catalyst and electrode for power generation. Water is obtained by collecting the electron emitted during the decomposition of organic matters by microbe at the anode and reducing oxygen at the cathode. Its introduction to sewage treatment is being examined, and achievement of power generation in average at approx. 0.7 W/m^3 with filling at MFC20% when connected to 27Ω resistor has been reported. [62)] Development of anode is ongoing, as well as development of electrode whose substrate is nano-carbon material such as graphene and carbon nanotube. [63, 64)] When using microbe, it generally decompose matters and discharge CO_2, though that depends on the type of the microbe, combination of direct air capture (DAC) technology that fixes emitted CO_2 and the flow-type CO_2 electrolytic reduction using the proton exchange membrane (PEM)[65] is necessary. At this point, as there is no example beyond the 1L scale and the cell structure that has been used for researches is not optimal, its practicability such as cost effectiveness is difficult to assess. In future, it is necessary to design optimal cell that reflects the knowledge in fuel cell and PEM water electrolysis cell and examine its practicability.

If the reaction at the cathode is seen as a hydrogen generating reaction (reduction of proton), it is possible to generate hydrogen in the same setup, though application of voltage (energy supply) is necessary. There is an example of electrolysis of simple organic matter such as glucose, excrement of domestic animals and the liquid fraction of pressed municipal solid waste (LPW).[66] In the electrolysis of LPW, approx. 60 mmol hydrogen was produced from 1g of decomposed organic matter. As it decomposed approx. 80% of the entered organic, its function as a biochemical waste treatment device was verified. If using microbe, there is the issues of their stability (securing of cultivation condition) and reaction speed. It is necessary to develop artificial electrode catalyst and improve its activity, product selectivity and durability based on the knowledge on microbe in order to realize the PG.

1.3.3 Direct electrolysis from seawater

The development of technology to produce hydrogen directly from seawater has been proceeding rapidly in recent years, as described in Chapter II, 1.3.3. The first challenge in developing this technology is to reduce the generation of chlorine or perchloric acid. Therefore, in order to realize hydrogen production from seawater, it is essential to develop an electrocatalyst that minimizes the influence of anion species present in the seawater and reduces the overvoltage. In addition, it is necessary to increase the reaction efficiency to save space. Therefore, the morphology of the electrocatalyst and the structure of the catalytic layer should be considered. In addition, the electrocatalyst must be durable enough to last for 30 years, even if it is assumed that it will be maintained because it will be used for PG water circulation.

In addition, it is necessary to consider the treatment and utilization of concentrated seawater, which is a by-product of direct seawater electrolysis. In addition, the inside of the electrolyzer and the connecting pipes must be made of materials with excellent corrosion resistance because of the distribution of concentrated seawater.

1.4 Miniaturization of Electrolyzer[67]

In order to complete the electrolysis reaction performed in the PG in a limited space, it is necessary to develop a reactor with a small volume and capable of continuous production. The microflow reactor is expected to be a space-saving reactor that enables precise synthesis due to the aforementioned characteristics, but the production volume per reactor is small. However, the production volume per reactor is low. To increase the production volume, a method called numbering-up has been devised. This is a method of connecting microflow reactors in parallel, but there are still problems in supplying raw materials to each microflow reactor. The problems include the size of the pump itself and the pressure drop due to the narrowing of the flow path by the precipitated products. The development of a micro-flow reactor with a structure that can be easily cleaned and disassembled will enable long-term operation, which will make it possible to use the reactor in PG.

2. The targets to be achieved (milestone) in 2030, 2040 and 2050, the research and development for reaching the milestones and their ripple effects

Following are the technological targets to be achieved by 2030.

In the energy cycle, we aim to achieve a power generation cost of 7 yen/kWh for photovoltaic power generation, a conversion efficiency of 25% for practical modules, a power generation performance of 6 kW/L for fuel cells, and a system cost of less than 4,000 yen/kW. In addition, the secondary battery used in the HEMS will achieve 500 Wh/kg and a service life of more than 15 years. In order to achieve these goals, it is necessary to sublimate existing technologies, and it is essential to collaborate with the projects on photovoltaic power generation, fuel cells, and secondary batteries that NEDO is leading, not only for 2030 but also for 2040 and 2050.

In the area of material cycle, we aim to create a technology to decompose polymers other than PET resin into monomers. We also aim to establish amino acid synthesis technology using electrolysis technology. In addition, we aim to establish a small-scale ammonia synthesis technology. In order to achieve these goals, it is necessary to deepen our knowledge of the complete degradation of polymers. In addition, it is essential to develop suitable electrocatalysts for each electrolysis technology.

For water circulation, we aim to establish a water circulation system that can produce 100 L/day of drinking water from manure and domestic wastewater. We will also consider scaling down the system to a residential scale. In addition, we aim to establish hydrogen production technology by direct electrolysis from organic wastes and seawater, which are closely related to other cycles. In order to achieve these goals, it is necessary to develop electrocatalysts and electrolyzers suitable for each electrolysis technology.

Miniaturization of the electrolyzer and fuel cell and establishment of microreactor technology by using them on a personal scale with respect to PG systems. Establish systems for energy and water circulation, and demonstrate the principle of material circulation.

Following are the technological targets to be achieved by 2040.

In the energy cycle, we aim to achieve a conversion efficiency of 30-35% for the practical module, a power generation performance of 7-8 kW/L for the fuel cell, and a system cost of less than 3,000 yen/kW. In addition, the secondary battery used in the HEMS will achieve 600 Wh/kg and a long life of more than 15 years.

In the material circulation, we aim to establish a technology to decompose polymers other than PET resin to monomers by more than 95%. We will establish a polymer material cycle using recyclable 3D printer resin.

In water circulation, we aim to establish a water circulation system that can produce 200 L/day of drinking water. At the same time, we will examine the policy of technological development necessary to achieve scaling down to a residential scale, long-term durability, and low cost.

With regard to the PG system, we will establish a system of material circulation on a personal scale, achieve the operation of an integrated system of three circulations, and establish an energy balance.

Following are the technological targets to be achieved by 2050.

In the energy cycle, the goal is to achieve a conversion efficiency of 40% for the photovoltaic power generation module, a power generation performance of 9 kW/L for the fuel cell, and a system cost of less than 2,000 yen/kW. In addition, the secondary battery used in the HEMS will achieve 700 Wh/kg and a service life of more than 15 years. In order to achieve these goals, it will be difficult to sublimate existing technologies. For this reason, it is essential to develop elemental technologies that can be game changers.

In the area of material circulation, we will establish a technology that can freely convert polymers to monomers by using electrolysis technology. We will also use electrolysis technology to synthesize amino acids and ammonia, and establish a method to produce fake meat using a 3D printer.

In the area of water circulation, we aim to construct a small water circulation system on the scale of each living space. In order to achieve this goal, each elemental technology related to water circulation must be established at a level that can guarantee long-term durability, low cost, and maintainability.

We will commercialize the system by reducing the cost and packaging the system of three cycles on a personal scale with respect to the PG system.

3. Nature of the international cooperation for achieving the target

Since the nature of international collaboration varies greatly depending on the goals set, careful judgment is needed in international collaboration for PG.

If the reason for establishing the PG in Japan is to solve depopulation, decreasing birthrate, aging population and concentration of urban functions, there is no necessity to make extra efforts to promote international cooperation. As the research and development competitions in electrolysis and fuel cell, which are related to the water circulation, energy circulation and carbon circulation, are extremely fierce, these technologies will certainly progress. What important is how to unify these individual technologies to build the PG. Thus, if the main technologies were dominated by foreign companies through for instance patent, international cooperation would be unavoidable, but if Japanese technologies suffice the purpose, there is no particular need for international cooperation. However, the speed from starting a business to productization in the US is incomparably faster than what Japanese businesses are capable of. Thus, if the research and development led by ideas is to proceed with such fast speed, communication with international investors will be indispensable.

Moreover, if the PG is to be exported and sold internationally, or if a similar technology was independently developed abroad, international standardization and legislation of the PG may become necessary. The PG can provide comfortable home capable of circulations (PG) to people who are forced to leave their homes due to a natural disaster or a civil war, in addition to releasing people from limitation of the place of residence. Thus for instance, coordination with NGOs from warzone or refugee areas is worth examining.

4. Nature of the interdiciplinary/sector cooperation for achieving the target

The PG consists of three different circulations, namely the energy circulation, the material circulation and the water circulation. Therefore, it is not a technology that can be realized within single field, unlike previous research subjects. Especially in the material circulation, it would be necessary to build a new academic field in order to proceed with the research. Thus, it is necessary to collaborate with researchers with wide-ranging knowledge, for instance in electrochemistry or biology, in addition to knowledge in polymer chemistry. Furthermore, as the PG is a system to be installed in individual household, contribution from system engineers who can design the system to integrate the three circulations will also be necessary. Thus, the realization of the PG is not possible without cooperation across fields and sectors.

5. ELSI (Ethical, Legal, Social Issues)

(Ethical, legal and social challenges that need to be addressed in order to achieve the target, and their solutions)

There are several social issues to be solved in order to implement the PG composed of the three circulations of energy, materials and water.

In the energy circulation, a system that is capable of stable energy provision for each living space through solar or hydrogen power generation combined with storage battery will be built. To build this system, it will be necessary to solve issues related to power generation cost, feed-in tariff (FIT), power transmission network, local power management, etc., in addition technological issues.

As represented by Zero Energy House (ZEH), energy supply and demand within a household is progressing. However, in order to supply the amount energy required by the three-circulation system envisaged for the PG, it is necessary to set a new feed-in tariff (FIT) for supporting the renewable energy cost during the transitional period. As the PG is at once an energy-consuming sector and an energy-producing sector, setting up of the system that adjust the energy supply and demand balance between PGs and IGs, as well as regional an electric power company that manages this system will be necessary.

In the materials circulation, a system that will enable recycling of clothing and plastic products, fake meat production through amino acid synthesis, cultivation of agricultural products through utilization of organic wastes, etc., that uses CO2 in the atmosphere as one of the materials will be built. To achieve this, size reduction of the recycling system, which is one of social infrastructures, and shift of agricultural, food and plastic industries to intellectual property industry will be necessary in addition to solving technical problems.

The PG will lead to elimination of organic wastes, old clothing and plastic wastes from the household sector. However, treatment/recycling system of other types of wastes from the household sector is not considered in this project. Thus, it is necessary to discuss how responsibilities should be shared between the PG and existing waste treatment system, as well as the transition process from one to the other. Moreover, food and clothing will be produced within each PG based on the data such as cultivation method, recipe and design. Thus, purchase of these products from outside the PG will be limited, and industries connected to these will shift to intellectual property industry. However, cultivation of agricultural products and food production within natural resources have multidimensional functions including ecosystem conservation and formation of local culture. Thus, division of functions between them and the PG must be done through social consensus while taking the technological developments into account.

In the water circulation, a safe water circulation system that can secure safe drinking water and eliminate discharge of wastewater will be built. For its realization, it is necessary to shift from the current massive waterworks/sewer facilities in addition to solving the technological issues.

In the Japanese society where the population is decreasing, the increasing maintenance cost and water intake cost from waterworks and sewer, as well as the size of inequality in their usage cost between regions and generations, are becoming serious problems. The PG, which is a stand-alone decentralized social infrastructure is a new type of social infrastructure that can solve these problems. However, shifting from the massive waterworks/sewer system, including dams, water intake facilities, water purification facilities and water supply/wastewater networks, built for metropolitan areas to the system built around the PG will incur large cost to the society. For this to happen, it is necessary to proceed with the shift while taking the costs for maintenance, update and removal, as well as how these costs are distributed, into account. Moreover, dams for instance have multiple functions, including in disaster prevention and power generation, in addition to their function as waterworks. Thus, examinations from multiple perspectives will be necessary when shifting to the PG.

The three-circulation system realized by the PG will be the new social infrastructure and industrial foundation for the people to live comfortably regardless of where they are living, their occupation, age, family structure or income without burdening the environment. It will enable dispersion of living spaces, and at the same time, enable creation of the networked urban structure in the urban areas consisting of a grid of stand-alone social infrastructures. In order to proceed with the shift from the existing social infrastructure to the new social infrastructure based on the PG, multidimensional simulation on the grid scale, its function, its effect on the environment, the safety of living in it and its life cycle cost at the areas where the PG are to be introduced is necessary. At the same time, it is essential to share the information among the stakeholders such as the local residents, the government and the business owners in order to form a social consensus.

IV. Conclusion

As the new target examination vision for the Moonshot Type Research and Development Project, this research study proposes realization of a society where everyone can obtain a stand-alone living space where each person can personally circulate energy, materials and water by 2050. For its realization, we propose a concept called "Personal Grid" which will contribute to the building of the decentralized society. The PG and the decentralized society it aims to create will provide harmonization of human life and the environment, protection of life from external disasters and guarantee of options to choose cultural freedom.

The history of last 30 years in scientific technology and human society progressed toward personalization. In principle, scientific technology does not move backward. Therefore, it is expected that this trend will develop further and accelerate over the next 30 years. PG is a system that is inevitably required in the trend of the times. Japan is currently the world leader in electrolysis technology and fuel cell technology, which are at the core of PG, and system integration is one of the technologies in which Japan excels. In addition, system integration is one of the technologies in which Japan excels, so Japan is well-positioned to lead the world in PG technology.

V. Reference

1. Incorporated Administrative Agency, New Energy and Industrial Technology Development Organization, NEDO White Paper on Renewable Energy, 2nd edition, pp. 59, 142-151, 199-201, Morikita Publishing Co., Ltd. (2014).
2. Kazuhiro Takausu, Compiled cases of hydrogen produciton/transportation/storage technology and material development, pp. 5-186, Technical Information Institute Co., Ltd. (2019).
3. Rikiya Abe, Digital Grid, pp. 94-101, Energy Forum Inc. (2016).
4. Nomura Research Institute, Ltd., Disruptive Innovations in the Energy Industry, pp. 17,73-7, Energy Forum Inc. (2018).
5. Toru Morotomi, Reform of Power System and Renewable Energy, pp. 10,45-54, Nippon Hyoron Sha Co., Ltd. (2015).
6. Plastic Waste Management Institute, "Basic Knowledge in Plastic Recycling 2020".
7. Naoki Hosaka, Kaiyo Plastic, KADOKAWA Shinsyo.

8. Plastic Waste Management Institute, “Thoughts on LCA”.
9. R. Geyer, J. R. Jambeck, K. L. Law, Sci. Adv., 3, e1700782 (2017))
10. PlasticsEurope, Plastics–the Facts 2020
https://www.plasticseurope.org/en/resources/publications/4312-plastics-facts-2020
11. Y. Ashida, K. Arashiba, K. Nakajima, Y. Nishibayashi, Nature, 568, 536 (2019).
12. Ed. Masataka, Sugawara, Latest Development in Water Treatment Technology, CMC Publishing; Ed. Hideto Matsuyama, Cutting-edge of Membrane Development for Water Treatment, CMC Publishing.
13. “Compilation of wastewater/used water treatment technology, vol. 2”, NTS.
14. Ministry of the Environment Environmental Technology Demonstration Project Public Relations Booklet Natural Area Toilet Urine Treatment Technology
http://www.env.go.jp/policy/etv/document/index4.html
15. Shizuoka Prefecture Official Homepage, Fujinokuni, Current Mt. Fuji Toilet
http://www.pref.shizuoka.jp/kankyou/ka-070/fujisanpage/toile/present.html
16. GatesNotes THE BLOG OF BILL GATES, Why the world deserves a better toilet, November 05, 2018.
https://www.gatesnotes.com/Development/Sanitation-showcase
17. THE WALL STREET JOURNAL, "Future Toilet" Challenged by Bill Gates, November 12, 2018.
https://jp.wsj.com/articles/SB11632224690678093907204584588870414334030
18. Japan Aerospace Exploration Agency, Space Station / Kibo Public Relations / Information Center, Leonardo (Multi-Purpose Logistics Module)
https://iss.jaxa.jp/iss/ulf2/mission/payload/mplm/#wrJunichi Imura, Tatsuji Hara, Theory on next generation power system design, p.3, Ohmsha, Ltd. (2019).
19. Junichi Imura, Tatsuji Hara, Theory on next generation power system design, p.3, Ohmsha, Ltd. (2019)
20. Yo Nishimura, Naoki Tatsumi, Maruwakari Denryoku Kakumey Keywords 250, pp. 27-32, General incorporated association, Denki Shimbun, Japan Electric Association (2018).
21. Plastic Waste Management Institute, “2019, State of production/disposal/recycling/treatment of plastic products”.
22. JEPLAN, INC. TECHNOLOGY,
https://www.jeplan.co.jp/technology/
23. Hiroaki Nagayama, Political Economy of Renewable Energy Main Power Supply and Power System Reform, pp. 73, pp. 97-98, Toyo Keizai Inc. (2020).
24. PRTIMES, P&G / Keio University Hiroya Tanaka Laboratory "Recycled Plastic to Face Shield" S. Approximately 10,000 donated to deaf schools nationwide in cooperation with Lab Co.,

Ltd./Tanseisha / Terracycle / Nanodax, June 12, 2020
https://prtimes.jp/main/html/rd/p/000000031.000031986.html

25. CANON News & Topics, Originally developed two types of filaments for 3D printers made of 100% recycled plastic, November 19, 2020
https://ecology.canon/news/201119.html
26. CleanTechica, Humans Worth Their Salt? The Price Of Desalination = Brine Disposal, January 17, 2019
https://cleantechnica.com/2019/01/17/humans-worth-their-salt-the-price-of-desalination-brine-disposal/
27. MIRAI PORT, Desalination of seawater-its by-products are a big problem, June 13, 2019
https://www.mirai-port.com/planet/225/
28. R. Amann, W. Ludwig, K. H. Schleifer, Microbiol. Rev., 59, 143 (1995).
29. Y. G. Adewuyi, Environ. Sci. Technol., 39, 3409 (2005).
30. G. Chen, G. E. Hoag, P. Chedda, F.Nadim, B. A.Woody, G. M.Dobbs J. Hazard. Mater., 87, 171 (2001).
31. H. Hori,　A. Yamamoto, E. Hayakawa, S. Taniyasu, N. Yamashita, S. Kutsuna, H. Kiatagawa, R. Arakawa, Environ. Sci. Technol., 39, 2383 (2005).
32. J. S. Clements, M. Sato, R. H. Davis, IEEE Trans. Ind. Appl., IA-23, 224 (1987).
33. Collection of Wastewater Treatment Technology, NTS, vo1. 2, pp 254.
34. C. Li, H. Wang, D. Lu, W. Wu, J. Ding, X. Zhao, R. Xiong, M. Yang, P. Wu, F. Chen, P. Fang, J. Alloys Compd., 699, 183 (2017).
35. K. R. Reyes-Gil, D. B. Robinson, ACS Appl. Mater. Interfaces, 5, 12400 (2013).
36. S. Dresp, F. Dionigi, M. Klingenhof, P. Strasser, ACS Energy Lett., 4, 933-942 (2019).
37. Special Issue on "Precious Metal Saving Electrodes for PEM Water Electrolysis“Toshiba Review Vol. 73, No. 3, May 2018.
38. “Basic Plan for "Development of Innovative Plastic Recycling Process Technology", Environment Department, New Energy and Industrial Technology Development Organization (NEDO), Japan.
39. Y. Ito, T. Nishikiori, H. Tsujimura, Electrochemistry, 86, 21 (2018).
40. X. Fan, X. Gong, M. Ma, R. Wang, P. J. Walsh, Nat. Commun., 9, 4936 (2018).
41. FASHION UNITED, Materialise: How 3D printing will bring flexibility to the fashion industry, March 8, 2019
https://fashionunited.uk/news/business/materialise-how-3d-printing-will-bring-flexibility-to-the-fashion-industry/2019030842041
42. KELLER SPORTS, NIKE FLYPRINT: AN UPPER MADE WITH A DEM 3D PRINTER
https://www.keller-sports.com/guide/nike-flyprint/

43. UNRESERVED FOOD& DINING, 3D-Printed Steaks to Rival Impossible Foods in the Fake Meat Industry, Fake it til you make it, January 16, 2020
https://www.unreservedmedia.com/3d-printed-steaks-impossible-foods-fake-meat/
44. M. Atobe, Electrochemistry, 83, 463 (2015).
45. B. P. Mason, K. E. Price, J. L. Steinbacher, A. R. Bogdan, D. T. McQuade, Chem. Rev., 107, 2300 (2007).
46. Shigenori Togashi, Nobushige Endo, Ryo Miyake, Process Innovation and Environmental Burden Reduction with Microreactor, Joho Kiko (2010).
47. Watts, K.; Baker, A.; Wirth, T. J. Flow Chem. 2014, 4, 2.
48. NEDO Hydrogen and Fuel Cell Strategy Roadmap, 2016 revised edition.
https://www.hkd.meti.go.jp/hokne/hydrogen/roadmap_gaiyou.pdf
49. Katsuya Hayashi, Annual Report of NTT Facilities Research Institute, 31, 43 (2020).
50. Yo Yasuda, Maintenance and risk management of renewable energy, p.13, Impress Holding, Inc. (2017).
51. Yasuo Suzuoki, Cutting-edge of effective usage of renewable energy, pp. 268-269, General incorporated association, Japan Society of Energy and Resources (2016).
52. T. Jiang, X. Zhao, D. Gu, C. Yan, H. Jiang, H. Wu, B. Wang, X. Wang, Sol. Energy Mater. Sol. Cells, 204, 110208 (2020).
53. N. Grimaldos-Osorio, F. Sordello, M. Passananti, P. Vernoux, A. Caravaca, J. Power Sources, 480, 228800 (2020).
54. I. Shitanda, K. Takamatsu, A. Niiyama, T. Mikawa, Y. Hoshi, M. Itagaki, S. Tsujimura, J. Power Sources, 436, 226844 (2019).
55. C. Chen, J. Zhang, L. Li, K. Wang, G. Luo, Ind. Eng. Chem. Res., 56, 3560 (2017).
56. T.S. Tofa, K. L. Kunjali, S. Paul, J. Dutta, Environ. Chem. Lett., 17, 1341 (2019).
57. I. A. Amar,　R. Lan, C. T. G. Petit, S. Tao, J. Solid State Electrochem., 15, 1845 (2011).
58. Yuki Naito, Y. Nakamura, N. Shida, H. Senboku, K. Tanaka, M. Atobe, J. Org. Chem., (2021). https://doi.org/10.1021/acs.joc.1c00821
59. G. Vlyssides, P. K. Karlis, N. Rori, A. A. Zorpas, J. Hazard. Mater., B95, 215 (2002).
60. L. Chen, Y. Zhang, C. Ma, Chem. Eng. J., 393 124514 (2020).
61. H. Feng,　Z. Chen, X. Wang, S. Chen, J. Crittenden, Chem. Eng. J., 413, 127492 (2021).
62. K. Iida, K. Mastubara, M. Ito, A Mugita, N. Yoshida, Y. Genda, M. Sakoda, Koei Forum, 28, 1 (2020).
63. Kenji Kano, Recent Progress in Biofuel Cells, CMC Publishing (2011).
64. Kazuya Watanabe, The cutting-edge wastewater treatment system using microbe fuel cell, NTS (2013).
65. Irkham, S. Nagashima, M. Tomisaki, Y. Einaga, ACS Sus. Chem. Eng., 9, 5298 (2021).

66. X. Xie, G. Yu, N. Liu, Z. Bao, C. S. Criddle, Y.Cui, Energy Environ. Sci., 5, 6862 (2012).
67. A. Mutoh, Japan Society for Chemical Engineering, 77, 778 (2013).