DENSO's Initiatives of CO_2 Capture and Utilization Technology toward Carbon Neutrality *

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DENSO started a pilot demonstration of on-site methanation as “CO_2 circulation plant” as proactive initiative for CO_2 capture and storage/utilization (CCUS) technologies toward achievement of carbon neutrality by 2035 in our own business. The CO_2 circulation plant was designed to capture CO_2 primarily generated by the plant and recycle it as an energy source of the facility. We also started work on the development of electric swing CO_2 adsorption (ESA) technology to achieve low-energy CO_2 capture.

Keywords :
Carbon neutral, CO_2 capture, methanation

INTRODUCTION

As the world’s second largest global manufacturer of automotive components, DENSO’s core business is the provision of various mobility products based on the principles of environment and safety. Regarding to the environment, we are contributing to the realization of the carbon neutrality through the electrification and other technologies that lead from mobility with core products of drivetrain and thermal systems. In addition, we have been developing non-in-vehicle technologies such as biofuel synthesis and stationary fuel cells for many years.

Through the integration of in-vehicle and non-in-vehicles technologies, we aim to increase our contribution to the realization and spread of sustainable communities and societies. We challenge to achieve carbon neutrality in our business activities by 2035 through the initiatives in the three area in addition to the acceleration of the conventional effort mentioned in Fig. 1; i.e., manufacturing, mobility products, and energy use.

In the conventional society with fossil-fuel-based energy, the majority of the composition is based on raw materials extracted from large-scale oil and gas fields and electricity generated by power plant, and each of which uses and emits CO_2. In response, DENSO has focused on how to use the energy much efficiently with low CO_2 emission on energy consumption in the factory and town.

On the other hand, as shown in Fig. 2, for the energy society in the future, it will be important to share, store and recycle the small-scale and dispersed energy as well as existing large-scale centralized one. For example, renewable energy such as solar and wind power exist widely and thinly around us. It seems necessary to make effective use of these resources in a way that completes them in a slightly smaller unit than in the past, such as a city or a region. In addition, we believe that CO_2 generated by the use of energy will likewise need to be captured in smaller units and recycled by energy consumers themselves.

Fig. 3 shows a concept of energy society based on renewable energy in the future. One of the issues of this new society is the way to use the renewable energy efficiently and conveniently with its fluctuations and surpluses. In order to solve this matter, the advanced technology of energy storage and recycle would be essential. DENSO is developing three key elements of storage technology: batteries, hydrogen and carbon-neutral fuels.

The electricity is most energy-efficient when stored in batteries, although its low energy density makes it larger and more expensive. Conversely, in spite of the loss of conversion efficiency, hydrogen and synthetic fuel can increase energy density, make it smaller and easier to transport [1]. In summary, it will be needed to use the mix of these technologies for smart use of renewable energy.

On the other hand, even with these advances in renewable energy storage and conversion technologies, some hard-to-abate industry sectors and life activities remain the emission of CO_2. These CO_2 need to be captured and recycled, as DENSO describes as a “recycle technology.” DENSO is also working on technologies to capture CO_2 in the atmosphere and exhaust, as well as to utilize captured CO_2 as CCUS [2]. We aim to establish and provide these “storage” and “recycle” technologies for society to realize energy utilization wherever and wherever they are needed.

Based on the above issues and challenges, DENSO is working for establishment of technologies for CO_2 capture and utilization through

(1) Proactive demonstration of CO_2 recycling for methanation

(2) Development of new CO_2 capture technology with electric swing adsorption (ESA) method.

Hereafter, we would introduce the background and objective, current status, and future plan of the above initiatives.

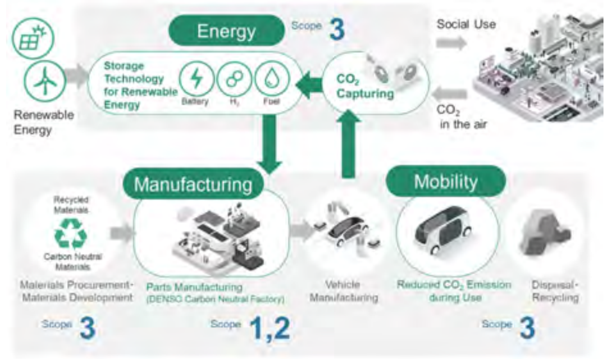


Fig. 1 DENSO’s primal theme for environmental initiatives toward carbon neutrality

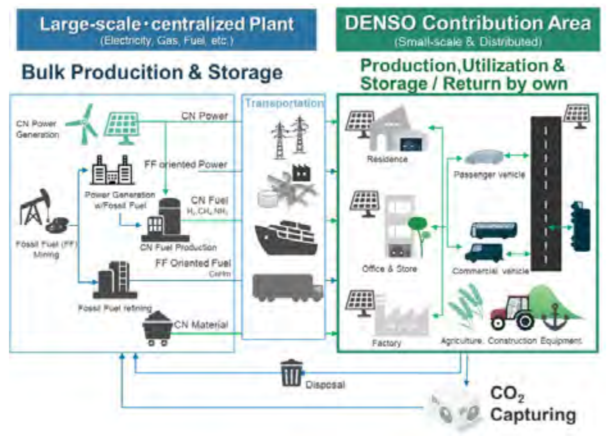


Fig. 2 DENSO’s scope of contribution for energy production, utilization, and CO_2 emission

＊（公社）自動車技術会の了解を得て，「2023 JSAE/SAE Powertrains, Energy, and Lubricants International meeting」発表論文より，一部加筆して転載

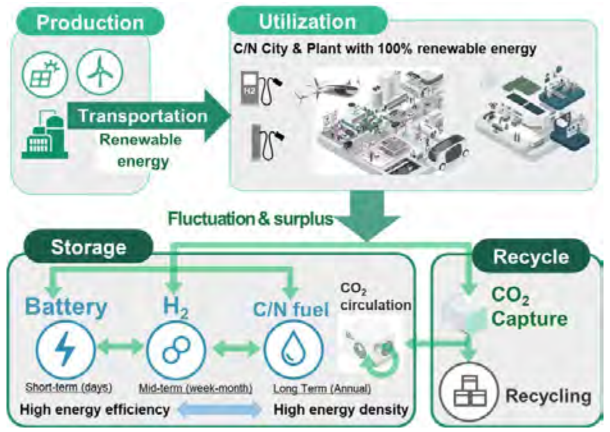


Fig. 3 Combination of energy storage and recycling technology for future energy society

Table 1 Gas engine specifications

Configuration	4-cycle water-cooled series
Fuel (normal)	City Gas (13) A or LPG
Combustion system	Mirror cycle lean burn system
Power output	5kW
Total displacement	0.699L

MAIN SECTION

(1) DEMONSTRATION OF CO_2 RECYCLING

(1)-1 Background and objective of demonstration

Fig. 4 shows the approach to realize a factory carbon neutrality. In 2020, our company's global operations emitted about 1.9 Mt of CO_2. A breakdown of CO_2 emissions shows that nearly half of total CO_2 emissions derives from the use of gaseous fuel for industrial furnaces and cogeneration systems. In order to achieve carbon neutrality in our company's energy use, it is an important issue to reduce CO_2 in Scope 1 by substituting carbon-neutral gas fuels as well as promoting further energy conservation and increasing the use of renewable electricity.

The synthetic methane (e-methane) is one of the promising candidates for carbon-neutral gas energy as well as hydrogen and ammonia. The advantage of e-methane is that the characteristic difference is small compared to conventional city gas, and existing transportation infrastructure and utilization equipment can be diverted. We also believe that methanation technology is effective not only for our own factories but also for achieving carbon neutrality in towns and industrial sectors where electrification and hydrogenation are difficult to achieve in society.

In light of the above background, we started a demonstration at the Anjo factory as a prior art of CO_2 capture and recycling for methanation.

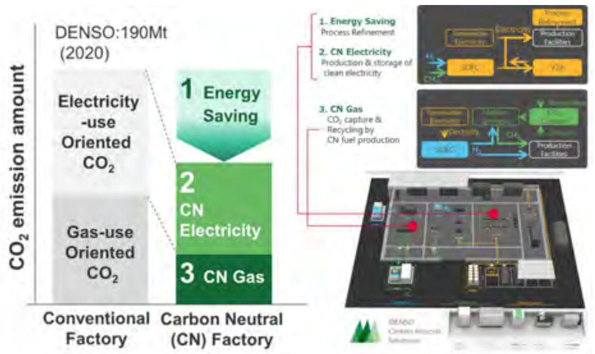


Fig. 4 Breakdown of factory CO_2 emission and concept of carbon neutral factory

(1)-2 Configuration of demonstration plant

The purpose of this demonstration is to realize a system that enables energy circulation by recycling CO_2 contained in the exhaust of gas equipment as shown in Fig. 5. The e-methane is synthesized by reacting captured CO_2 with green hydrogen, and used as a fuel for equipment without releasing CO_2 to the outside. The energy supplied to the demonstration plant is renewable electricity and the emissions are water, nitrogen and oxygen, making the system carbon neutral.

The demonstration plant has the appearance shown in Fig. 6. It consists of a single building measuring W9 x D12 x H4 m with main equipment and auxiliaries. The plant interior consists of 4 main components: a power generator that emits CO_2, a CO_2 capture system that captures CO_2 from the power generator exhaust, a hydrogen generator that generates hydrogen using renewable energy power, and a methanation reactor that synthesizes e-methane from CO_2 and hydrogen (Fig. 7). The following is an overview of each device.

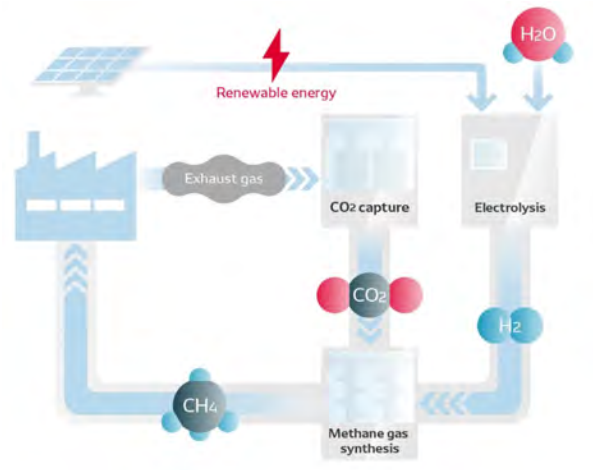


Fig. 5 Configuration of methanation demonstration

Fig. 6 Demonstration plant appearance

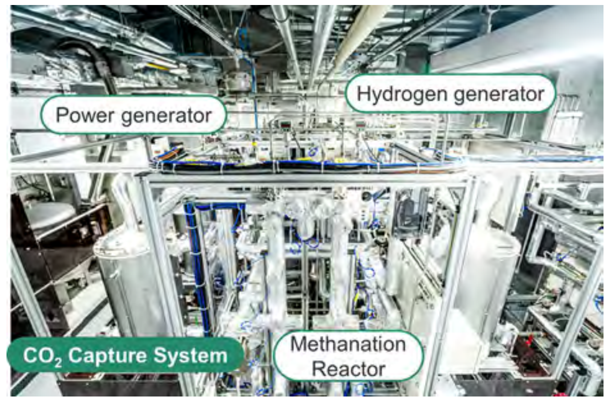


Fig. 7 Internal configuration of demonstration plant

• Power generator

As CO_2 emission facilities a gas engine with an output of 5kW that specification is listed in Table 1 and an in-house SOFC (Solid Oxide Fuel Cell) with an output of 5 kW are used in this demonstration. The emitted CO_2 concentration is about 5 to 8%.

These power generators are example of applications as facilities using gas fuel, and the process of CO_2 capture and methane synthesis of this plant can be applied to other facilities using gas fuel such as heat treatment furnaces and melting furnaces.

• CO_2 capture system

This system adsorbs and separates CO_2 contained in the exhaust of the power generators mentioned above. The CO_2 adsorption method is temperature-swing adsorption (TSA), and the system consists of four towers of identical capture units. Each unit adsorbs CO_2 at room temperature and desorbs CO_2 at a high temperature of about 120 degrees Celsius by thermal control. Referring to the system of TOYOTA CENTRAL R&D LABS., INC [3]., Zeolite 13X is used as the CO_2 adsorption catalyst.

Each of the four-tower units is assigned a process of adsorption, preheating, desorption and cooling at the same time, and the process is switched sequentially to achieve continuous capture and desorption of CO_2. The oil is used for thermal control, and heat from the methanation reactor, described later, is used to raise the temperature of the oil.

• Hydrogen generator (PEM electrolyzer)

A commercial **polymer electrolyte membrane** (PEM) electrolyzer (Kobelco Eco-Solutions HHOG) is used as hydrogen generator. The electricity used is supplied by a solar power generation system installed on the roof of the plant adjacent to the demonstration plant, so the hydrogen generated is green hydrogen that does not emit CO_2. The maximum hydrogen production is 5 Nm^3 per hour.

• Methanation reactor

This equipment synthesizes methane by catalytic reaction from CO_2 captured by the aforementioned CO_2 capture system and hydrogen generated by a hydrogen generator. The reactor consists of two columns in series, and the water generated by the reaction is removed at the outlet of the first column, and then the reaction is carried out at the second column to achieve a high conversion rate.

Since the methane synthesis is an exothermic reaction, the temperature during the reaction is controlled by oil and heat is recovered through oil. The heat recovered from the methanation reactor is used as heat for desorption in the CO_2 capture system to improve overall demonstration system efficiency.

Other than the four main components mentioned above, the system includes auxiliary equipment such as a dehydrator to remove water contained in power generator exhaust, a CO_2 tank to temporarily store CO_2 desorbed from the CO_2 capture system, a methane tank to store methane synthesized in a methanation reactor as fuel, and a pump to pressurize gas for storage in each tank.

The dehydrator has two-column configuration with y-type zeolite that switches dehydration and regeneration, which is operated to ensure the dew point less than -15 degree Celsius.

The concentration of unburned fuel NOx and other by-product gas from engine combustion is less than 1%. This level is considered to have little effect on performance of CO_2 capturing and methane synthesis, and any post-processing of exhaust gas is not introduced except for dehydrator.

(1)-3 Performance of demonstration system

The installed TSA CO_2 capture system can capture 1.4 kg of CO_2 per hour. This makes it possible to capture more than 99% of the total CO_2 emitted from power generator. The amount of CO_2 captured is equivalent to the amount of CO_2 emitted when 10 small passenger cars travel 30 km.

The captured CO_2 is supplied to the methanation reactor at the later stage with a purity of 97% or higher. The captured CO_2 is converted into methane of up to 0.7 Nm^3 per hour by synthesis with hydrogen produced by the aforementioned hydrogen generator.

Fig. 8 shows the gas composition at the outlet of the engine, CO_2 capturing system, and methanation reactor when the gas engine is operated at a steady load of 1 kW. Fig. 9 shows the characteristics of the methane synthesized by captured CO_2 from exhaust gas when the gas engine was operated continuously for 6 hours at a steady load of 1 kW. The average engine outlet CO_2 concentration during operation is 7.5%. The purity of the synthesized methane is more than 98% during operation of power generator. This has achieved a level of direct use as power generator fuel. In addition, the recycling rate of CO_2 in the exhaust gas exceeds 97% which is captured and converted methane, indicating that the targeted recycling system has been established.

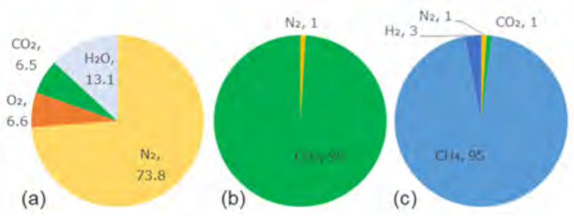


Fig. 8 Outlet gas composition of (a) engine, (b) CO_2 capturing system, and (c) methane reactor

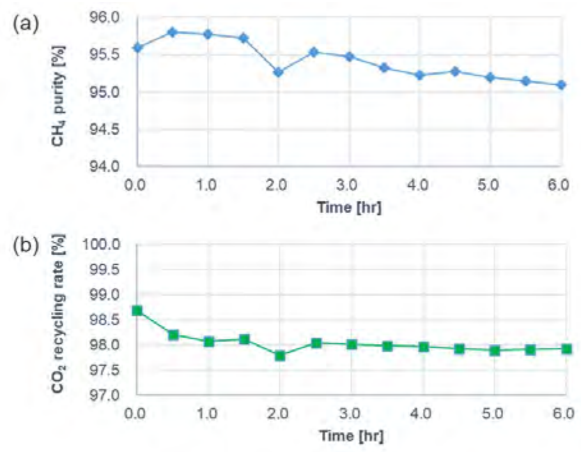


Fig. 9 Methane synthesis profile during gas engine operation; (a) methane purity, and (b) CO_2 recycling rate

(1)-4 Future plan

The current demonstration plant is a small-scale prototype, and there is still much room for improvement in performance aspects such as energy efficiency and physical size of methanation devices.

It is also necessary to scale up the plant component equipment to the scale corresponding to each facility in order to implement it in industrial furnaces, etc., as described above. In addition, it is important to achieve stable capture of CO_2 from the exhaust and supply of synthesized methane, depending on the operating status and characteristics of the equipment (CO_2 concentration and other components of exhaust gas).

In the future, the technology will be developed using the demonstration plant, and the application of the technology to plant equipment will be studied to promote the practical application of technologies such as CO_2 capture and methanation.

(2) DEVELOPMENT OF ESA CO_2 CAPTURE TECHNOLOGY

(2)-1 Background and objective

As seen in the demonstration mentioned above, CCUS technology including methanation requires a process to capture CO_2 and to convert the captured CO_2 into energy/engineering material. We are mainly focusing the former of the two.

Fig. 10 shows the classification of CO_2 emission source and corresponding CO_2 capture technologies. For CO_2 emission facilities with high concentration and large-scale, such as coal power and steel plant, their CO_2 capture is mainly driven by technological development and maturation of heavy industry manufacturers. In contrast, such technology has not been the practical way for capturing CO_2 emitted from small, distributed industries and towns. Although the low-concentration, distributed sources of CO_2 have low individual CO_2 emissions, they are widespread in the world, with total emissions are almost equivalent to those of large and concentrated systems.

In general, there is a trade-off between CO_2 concentration and capturing energy. Several start-up companies are working on CO_2 capture from the atmosphere (DAC; Direct Air Capture) [4], although the energy required is large and it has yet to be fully commercialized.

With above background, DENSO develops technology to capture low-concentration CO_2 with low energy consumption and a compact body, aims for a world where CO_2 can be captured wherever and wherever it is needed.

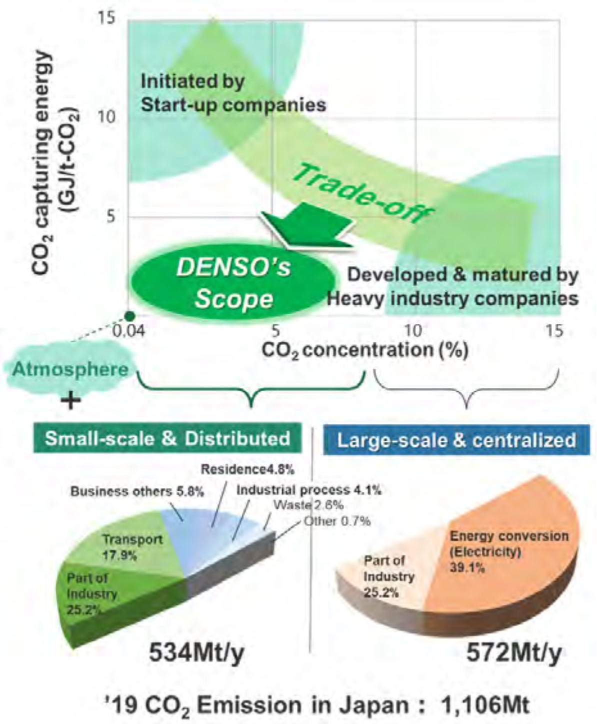


Fig. 10 DENSO focus area for CO_2 capture

(2)-2 Principles, configurations, and feature of ESA CO_2 capture system

As a means to achieve the aforementioned low-concentration CO_2 capture with high efficiency and compact size, DENSO is developing an electric swing adsorption (ESA) CO_2 capture system.

Fig. 11 shows the working principle of ESA CO_2 capture. This system uses the principle that voltage is applied to electrode cells stacked inside the collector, electrons are supplied to the cell surface, and CO_2 is adsorbed on the electrode surface by the Coulomb force of the electrons. The adsorbed CO_2 can be desorbed by switching the voltage.

Ideally, each CO_2 molecule adsorption is possible by supply of the same number of electrons. Thus, in principle, this CO_2 capture method can be performed with very low energy and small size.

In order to approach above ideal, it is necessary to thoroughly reduce the overvoltage generated by the resistance and the reaction of the path of electrons and CO_2. Aiming to achieve this, DENSO is working to design the materials that make up the electrode cells used in the system and to establish how to make them. In addition, in parallel with the development of materials, we are also developing the structure of electrode cells and systems equipped with multiple electrode cells. Furthermore, the enhancement of durability of its products and demonstration are in the scope of development, with the aim of identifying issues for practical applications and solving them at the early stage. Fig. 12 shows an example of idea of factory methanation system with an ESA CO_2 capture system realized by combining these development items.

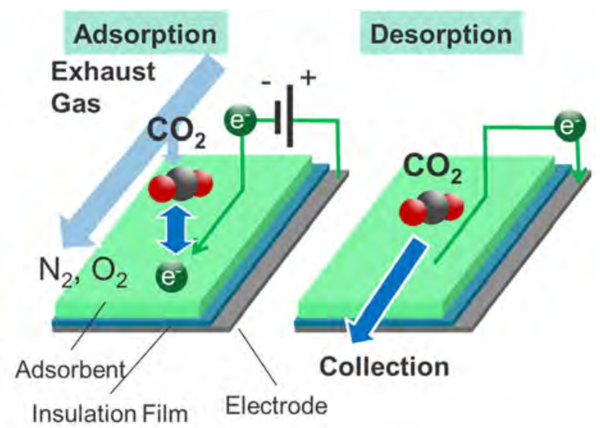


Fig. 11 Principle of ESA CO_2 capture

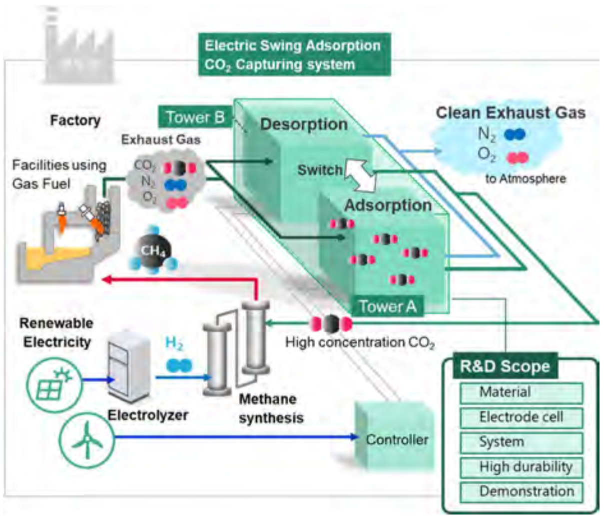


Fig. 12 Concept and R&D scope for methanation system with ESA CO_2 capture system

(2)-3 System configuration and features

As shown in Fig. 13, a small prototype system equipped with a stack of multiple electrode cells has been constructed in the development so far. Fig. 14 shows the CO_2 concentration profile when atmospheric CO_2 is captured by the prototype ESA system as a functional verification. When a voltage is applied to the electrode, CO_2 adsorption starts in a short time, and the CO_2 concentration at the system outlet decreases. After the end of the voltage application ($t = 570$ s), CO_2 adsorption stops and the outlet CO_2 concentration gradually recovers. In the case of atmospheric CO_2 capture, it is considered as negative emission if more CO_2 can be captured than that is generated to create the energy used for CO_2 capturing. In addition, attempt of capturing all CO_2 from the air introduced into the system leads to a decrease in energy efficiency and an increase in system size. For these reasons, a part of CO_2 in the total passing air is captured in this test, so the lowest CO_2 concentration in the passing air is about 200 ppm.

Apart from above verification, we also conducted a performance evaluation of single cell used for prototype system. A simulated dry air (CO_2 concentration: 500 ppm) is supplied to the cell with a constant flow rate. In this test, approximately 1.15 cc of CO_2 under normal conditions is captured each cycle, and about 18 J of electricity is consumed by cell, which corresponds to 8 GJ/tCO_2.

The adsorbed CO_2 is separated and collected by the system which combines the pressure vessel enclosing above cell stack and vacuum pump. Fig. 15 shows the results of GC-TCD analysis of the gas composition separated and captured from the atmosphere in a stack consisting of 44 cells on a bench simulating the system configuration. The purity of the captured CO_2 is more than 80%. The CO_2 purity of this collected gas is limited by the small CO_2 yield relative to the dead volume of the system due to the small size of the proto-sample tested. It is expected that the CO_2 purity of the collected gas could be more than 95% through design improvements combined with scale-up of the system.

In the future, we try to achieve lower energy consumption of the system and higher purity of collected CO_2 by improving the electrode materials and the system configuration. In addition, more CO_2 could be captured in less time by optimizing applied voltage and current patterns, and homogenizing and promoting gas supply to the cell.

Since this system adopts a hierarchical structure with stacked flat cells and modules of multiple stacks, it has advantages such as flexible choice of system size and arrangement according to required amount of CO_2 capture in the applicable factory or commercial facility. Furthermore, this system requires only electricity as input, making it easy to connect to existing equipment.

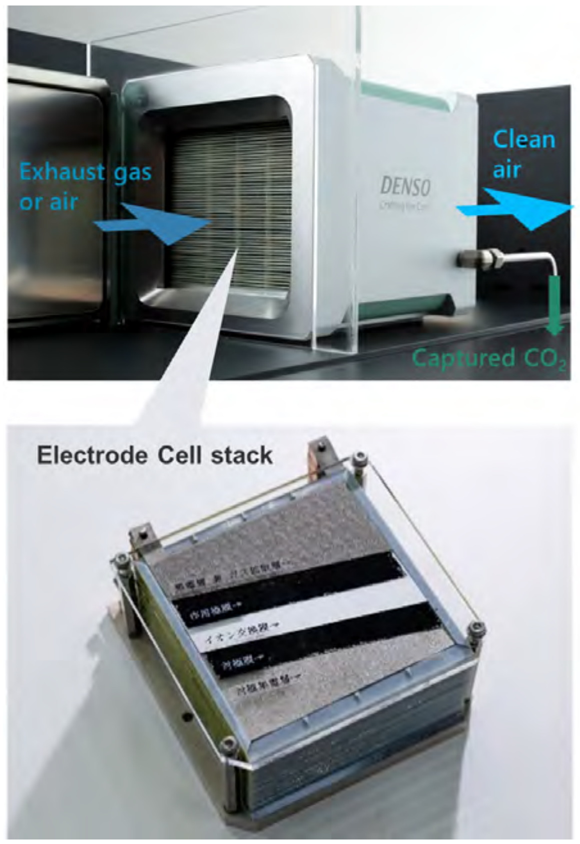


Fig. 13 Prototype of ESA CO_2 capture system

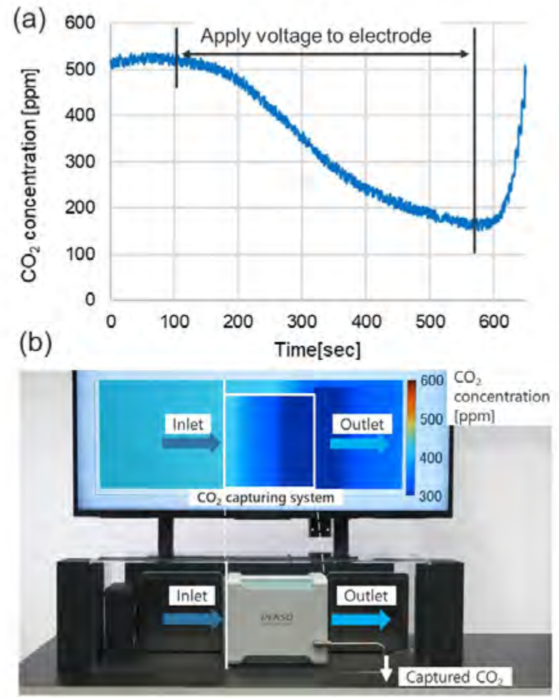
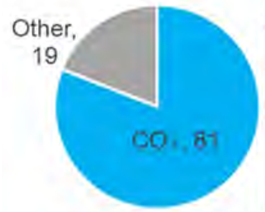


Fig. 14 Concentration profile of CO_2 during ESA operation
(a) Time variation of the system exit
(b) Spatial distribution at t = 400 s



Measurement condition

Input gas		Dry air
Input gas low rate		67 L/min
Duration per cycle	Adsorption	15min
	Desorption	25min

Fig. 15 Composition of collected gas by ESA from atmosphere

Conclusion

As an initiative for establishment of technologies related to CCUS and introduction of them, DENSO conducts demonstration of CO_2 capture and recycling for methanation and develops an electric swing adsorption CO_2 capture technology.
In each case, the principles and functions are verified first, and the technology is established to identify problems and solve them for practical use in the future.
Taking CO_2 capture and e-methane synthesis as an example, the current demonstration is completed in-house as described above. However, it is also anticipatable that CO_2 could be captured individually or collectively at factories and commercial facilities in the region and integrated in gas plants to produce synthetic methane. In this case, the captured CO_2 needs to be transported, but the expansion of infrastructure and trading systems will enable carbon-neutral partnerships from the region to the world (Fig. 16).
DENSO will continue to contribute to realization of CCUS technology with expectation for wide collaboration across the CCUS supply chain to accelerate the movement toward carbon neutrality.

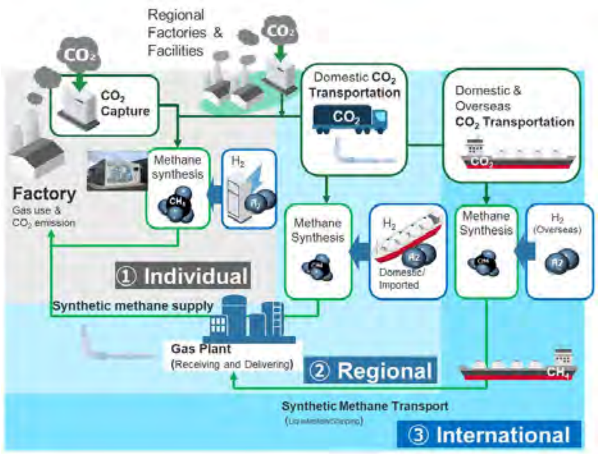


Fig. 16　Regional collaboration to promote methanation

ACKNOWLEDGMENTS

In the methanation demonstration TOYOTA CENTRAL R&D LABS., INC. cooperated in the design and construction of a CO_2 capture system, and a system combining a methanation reactor and hydrogen generator.
A part of the technology for electric swing adsorption CO_2 capture system is under development as Green Innovation Fund Project “Technology development and demonstration of small-and medium-scale CO_2 separation and capture from factory exhaust gas, etc.” established by the Ministry of Economy, Trade and Industry, and executed by New Energy and Industrial Technology Development Organization [5].

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