

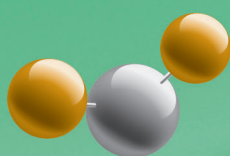
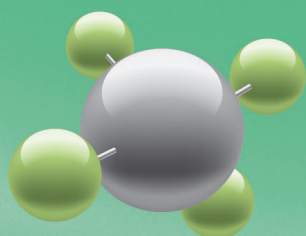
# Energy Outlook

International Institute for Carbon-Neutral Energy Research

November  
2018

## Building Japan's Energy System:

The Strategic Thinking We Need and Initiatives for Implementing It



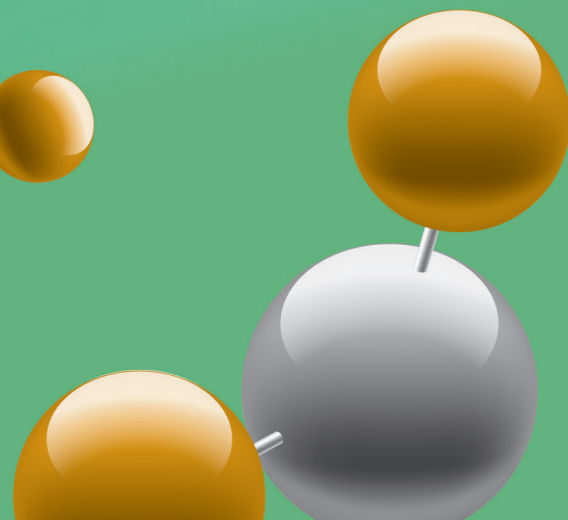
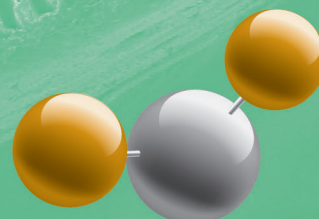
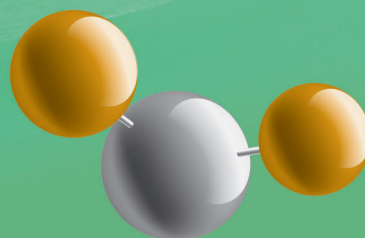
### Special Interview

**Shin-ichi Nakao**

Group Leader of Chemical Research Group / Director of the Inorganic Membranes Research Center  
Research Institute of Innovative Technology for the Earth (RITE)

**Ikuo Taniguchi**

Associate Professor  
CO<sub>2</sub> Capture and Utilization Division  
International Institute for Carbon-Neutral Energy Research (I<sup>2</sup>CNER), Kyushu University





# Special Interview

## Building Japan's Energy System: The Strategic Thinking We Need and Initiatives for Implementing It

Building an energy system with lower CO<sub>2</sub> emissions is an imperative priority. The Research Institute of Innovative Technology for the Earth (RITE) is a leading domestic research organization that is investigating topics such as CO<sub>2</sub> separation and sequestration to address that priority. In this special interview, Prof. Ikuo Taniguchi from I<sup>2</sup>CNER, who previously worked at RITE, discusses the current status and future direction of Japan's energy system in light of the latest technological trends with Dr. Shin-ichi Nakao of RITE, who gave a presentation in the I<sup>2</sup>CNER Seminar Series in 2014.



**Ikuo Taniguchi**

Associate Professor  
CO<sub>2</sub> Capture and Utilization Division  
International Institute for Carbon-Neutral Energy Research  
(I<sup>2</sup>CNER), Kyushu University



**Shin-ichi Nakao**

Group Leader of Chemical Research Group /  
Director of the Inorganic Membranes Research Center  
Research Institute of Innovative Technology for the Earth  
(RITE)

### The Role of Separation Membrane Technology in Reducing CO<sub>2</sub> Emissions

**Ikuo Taniguchi:** I'd like to get started by asking for your opinion on the importance of separation membrane technology in reducing CO<sub>2</sub> emissions.

**Shin-ichi Nakao:** When we look at reducing CO<sub>2</sub> emissions from the standpoint of separating and capturing CO<sub>2</sub> from large-scale sources, we can divide the associated technologies into three broad categories: liquid absorbents, adsorbents, and separation membranes. The performance of liquid absorbents has pretty much reached a limit, so there's not much room for improvement there. Similarly, adsorbents that use porous materials like zeolite<sup>1</sup> are also close to their limit. RITE is conducting research into a solid absorbent bearing amines<sup>2</sup>, but that also has its limits.

**Taniguchi:** Which means separation membranes have the greatest potential to fulfill expectations?

**Nakao:** There's certainly room for improvement, but the bottleneck is the energy needed to pressurize a gas that's being emitted at normal pressure so that it can be separated. If the technology is to best absorb liquids even after that energy cost is subtracted, it has to exhibit

extremely good permeability. CO<sub>2</sub> capture from natural gas, which is already at high pressure, and from pre-combustion exhaust gases in IGCC<sup>3</sup> (integrated coal gasification combined cycle) does not require pressurization, so separation membranes are ideal for those tasks.

**Taniguchi:** Since IGCC uses inexpensive coal, it seems well suited to use in places like emerging nations.

**Nakao:** If the goal is to promote separation membranes, a good approach would be to package construction of coal-fired thermal power plants with CO<sub>2</sub> capture systems. There's a large market for natural gas, and the technology could become a means of reducing CO<sub>2</sub> emissions that offers cost advantages.

**Taniguchi:** So separation membranes have a certain amount of promise...

**Nakao:** The problem is one of scale. Since the gas being targeted for separation is emitted in large volumes by facilities like thermal power plants, technologies such as PSA<sup>4</sup> (pressure swing adsorption) can't keep up, and that gives separation membranes an advantage.



## CCU/S Initiatives Being Pursued by I<sup>2</sup>CNER

**Taniguchi:** In its pursuit of basic research into separation membrane materials, I<sup>2</sup>CNER is focusing on efficient CO<sub>2</sub> capture using separation membrane methods, specifically CCU<sup>5</sup> and CCS<sup>6</sup> (carbon capture and utilization/storage). What can you tell us about the status of those technologies?

**Nakao:** The challenge with CCS is where to sequester the CO<sub>2</sub> and what it costs to do so. Separation membranes may provide a way to lower those costs.

**Taniguchi:** How about the direction of development in separation membranes?

**Nakao:** Membrane performance can be approached from the standpoint of permeability and selectivity. Although people are prone to think about the latter, it is permeability that's important from the standpoint of putting the technology to practical use. In that sense, polymeric membranes have lower gas permeability than inorganic membranes, but they have advantages when large surface area and cost are considered. The question is what we can do to maximize their permeability.

**Taniguchi:** So improving permeability is the key. What else can you tell us?

**Nakao:** If I<sup>2</sup>CNER is going to work to commercialize separation membranes, you need to study how permeability can be improved and then think about durability. You can have the best permeability in the world, but you won't be able to actually use the membrane if it lacks durability. Academic papers need only address performance, but if the technology is going to be implemented in the real world, customers are inevitably going to make an issue of durability. By the way, durability testing is truly difficult. Testing with actual gas requires a supply of gas. Commercial plants won't offer that supply, and testing at power plants is regulated by law.

**Taniguchi:** It's a problem that involves trade secrets.

**Nakao:** If you run tests at a commercial plant and there's a problem, you could be looking at an enormous damage claim. In reality, public entities, including the national government, ought to supply the equipment needed for testing, and in fact that's how it works in Europe and the U.S. In China, testing is carried out not at test centers, but at actual plants. Certainly, problems do occur but improvements are made quickly because the direction in which things must move to do so becomes immediately clear. The result is that the commercialization process is accelerating.

**Taniguchi:** It's truly a structural problem. When I was at RITE, we keenly felt the difference in our approaches every time we visited overseas researchers where they work.

**Nakao:** RITE's investigation of CO<sub>2</sub> separation membranes has reached the stage of testing with actual gases. However, since there aren't any entities that will supply that gas in Japan, we have to use facilities in the U.S. to carry out such testing. It's necessary to exercise caution to keep technology from leaking since you can tell a lot about the underlying approach just by observing the testing process.

## Future Approach to CCU/S

**Taniguchi:** Since demonstration testing is carried out using modules, it's necessary to enlist the cooperation of membrane manufacturers and engineering companies.

**Nakao:** Because RITE's mission extends to

the adoption of technology by industry, we're continually aware of the ultimate goal of commercialization even as we start with basic research. That's why engineering companies and membrane manufacturers have been part of the project from the beginning. We develop the materials, membrane manufacturers make the modules, and engineering companies carry out the tests. If the goal is to create membranes at a scale that presumes commercialization, the cooperation of membrane manufacturers is essential.

**Taniguchi:** So when the goal is commercialization, it's necessary to invest resources outside of material development as well.

**Nakao:** Cost is particularly problematic. We don't think about material cost at the research stage, but awareness of cost becomes vastly more pronounced and demanding as soon as membrane manufacturers become involved.

**Taniguchi:** So you've got to take cost into consideration while carrying out research and development (R&D). Although we focus on basic research at I<sup>2</sup>CNER, our goal is for basic technologies to be commercialized in the future, and in the field of fuel cells, there are researchers who are already working on demonstration testing. In addition to CCS research, I<sup>2</sup>CNER is also conducting research into CCU, in which CO<sub>2</sub> undergoes electroreduction to convert it into CO. If we can get to that stage then there are already technologies available for chemically converting it into a valuable resource. We already have enhanced recovery of oil and gas using captured CO<sub>2</sub> (EOR and EGR)<sup>7</sup>, but I wonder what your thoughts are about other CCU technologies.

**Nakao:** To answer that question, we have to determine the role of CCU. As a means of reducing CO<sub>2</sub> emissions, CCU is characterized by its extremely large scale. If the goal is to reduce CO<sub>2</sub> emissions, CCS, including EOR and EGR, is the only option. If we're talking about reuse, then there are methanation (methane formation) and methanolation (methanol formation). Since those substances can be used as fuels, if we capture and reuse the CO<sub>2</sub> that is emitted when they are burned, CO<sub>2</sub> emissions won't increase. However, methane conversion and methanol conversion require hydrogen, so the key question is how that hydrogen will be supplied.

## Initiatives to Realize a Hydrogen Society

**Taniguchi:** You founded the Inorganic Membranes Research Center at RITE. What is its goal?

**Nakao:** Basic research into inorganic membranes is being carried out in Japan at a fairly high level. However, that research has not led to commercialization or industrialization. I'm proud to have been involved in



a variety of initiatives addressing water treatment technology using polymeric membranes and to have played a part in the industrialization of those technologies. Having been involved with inorganic membranes for more than 20 years, I want to see that technology industrialized in one form or another. I founded the Inorganic Membrane Center because universities were not able to accomplish that goal on their own, and I felt we needed to create an organization that would bring together engineers from various fields and unite them in the goal of industrialization.

**Taniguchi:** In fact, you have an impressive roster of corporate members.

**Nakao:** However, unfortunately that roster does not include many inorganic membrane manufacturers. On the other hand, we have numerous companies who wish to use inorganic membranes thanks to the high expectations they have with regard to the technology. We receive a steady stream of requests from them but membrane manufacturers don't like sitting at the same table with competitors.

**Taniguchi:** The first issue is to create a market, so I imagine you see cooperation in that regard, but does that stance change when intellectual property becomes involved?

**Nakao:** There are other difficult areas as well. It's not possible to create or test prototypes without the cooperation of membrane manufacturers. Engineering companies also demand performance guarantees and durability when conducting tests. From the customer's point of view, it's not possible to use unproven membranes. Addressing these structural problems is another priority.

**Taniguchi:** These thoughts are valuable when it comes to implementing a technology in society. Let's turn our attention for a moment to the sweetening<sup>8</sup> of natural gas using inorganic membranes, an area where there has been a lot of R&D activity recently. What can you tell us about that?

**Nakao:** Difficult problems remain with capturing CO<sub>2</sub> at thermal power plants and other facilities at this point in time, but sweetening will likely expand going forward. Inorganic membranes offer good separation performance even at high pressure levels, and methane has value as a product, so the process is profitable.

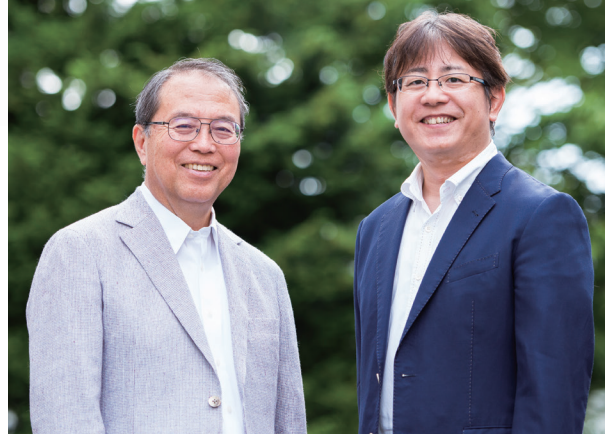
**Taniguchi:** You're also conducting research into hydrogen carriers as a way to isolate high-purity hydrogen from methylcyclohexane using a membrane reactor<sup>9</sup>. Hydrogen is an important topic for I<sup>2</sup>CNER as well so I am wondering what you can tell us about the potential for realizing a hydrogen society.

**Nakao:** When we talk about energy mix, we will probably end up using some amount of hydrogen. However, if we're going to limit our supply to renewable energy, Japan will need to import hydrogen from overseas. The key will be not to replace all coal, oil, and natural gas with hydrogen, but rather to search for the best mix of options.

## On the Need for a Strategic Energy Mix

**Taniguchi:** Japan has found itself in an extremely special energy situation since the Great East Japan Earthquake of 2011. What are your thoughts with regard to an ideal energy mix for the country?

**Nakao:** We're probably going to need to rely on imports for hydrogen. In that case, cost will become a problem. At current prices, we can't use large volumes of hydrogen, so we need existing thermal power plants. Although we need to factor in CCS for reducing CO<sub>2</sub>, fortunately there are locations



suitable for sequestering CO<sub>2</sub> all over Japan. Consequently, we can secure a certain amount of reduction by combining coal-fired power generation with CCS. With regard to natural gas, I believe EGR will be effective. Then we can increase solar and wind power. We can use those sources of electricity without converting it into hydrogen.

**Taniguchi:** How should we treat nuclear power?

**Nakao:** In general, I'm opposed to nuclear power. People often describe it being good for base load, but we can handle that with thermal. We just need to make up for fluctuations in renewable energy with thermal.

**Taniguchi:** Concerning coal-fired power generation, clean coal technology<sup>10</sup> is said to boost generating efficiency to levels in excess of 45%. Would that render costly technologies such as IGCC unnecessary?

**Nakao:** Generating efficiency is only a matter of temperature, so efficiency can be increased for even gas turbines by increasing temperature. That doesn't mean IGCC is unnecessary.

**Taniguchi:** In closing, what should researchers like us be working on in the area of energy issues?

**Nakao:** We need to create an energy system for Japan with an optimal mix of energy sources based on evidence in the form of exhaustive calculations. Then we need to clarify the role of the research being carried out by each researcher. Our current energy mix is nothing more than a means of avoiding eliminating nuclear power. Institutions consisting of experts should study an overall system that's designed to achieve an ideal level of energy efficiency. Technological development that is not guided by a strategy is unacceptable. First, we need to create institutions that can formulate a proper strategy, and then disseminate and implement that strategy. In the U.S., such an institution actually formulates strategy. Consequently, I believe that I<sup>2</sup>CNER also has an important role to play.

### Notes

- 1 Zeolite: A general name for crystalline aluminosilicates. In addition to molecular sieve effects that result from pores deriving from the material's skeletal structure, zeolites' characteristics include adsorptive capability.
- 2 Amine: A general name for compounds in which hydrogen atoms in ammonia are replaced by a hydrocarbon group or an aromatic atom group. Amines exhibit affinity with CO<sub>2</sub>.
- 3 IGCC (integrated coal gasification combined cycle): A power generation system that improves the efficiency of conventional coal-fired thermal power by gasifying coal as an input for combined-cycle generation.
- 4 PSA (pressure swing adsorption): A system that takes advantage of different adsorbents' gas adsorption characteristics to continuously separate a target gas by alternating high- and low-pressure operation.
- 5 CCU (carbon capture and utilization): The process of reusing captured and sequestered CO<sub>2</sub>.
- 6 CCS (carbon capture and storage): The process of separating and capturing CO<sub>2</sub> and then storing it underground.
- 7 EOR/EGR (enhanced oil/gas recovery): A technique for pressurizing CO<sub>2</sub> that has been separated and captured in order to improve oil and natural gas recovery efficiency.
- 8 Sweetening: The process of removing CO<sub>2</sub> and sulfides, which cause unpleasant odors and corrosion, from natural gas.
- 9 Membrane reactor: A system for synthesizing substances using membranes consisting of fixed catalysts and membranes with functionality for extracting products.
- 10 Clean coal technology: Technology for improving power conversion efficiency with reducing harmful substances such as CO<sub>2</sub>, sulfur oxides, and nitrogen oxides that are emitted when coal is burned.



# Technology Transfer

## ~Aiming at "I<sup>2</sup>CNER x Company = Contribution to Society"~

At I<sup>2</sup>CNER, several diverse research achievements in fundamental scientific fields have been transferred to various industries. Turning groundbreaking research results into products and businesses, and sharing them with society, is one of the most important missions for universities and research institutions. For this, close cooperation with the industrial community is essential. This section introduces various joint research and technology transfer projects that I<sup>2</sup>CNER has been working on with industry collaborations.



**Miho Yamauchi**  
Professor

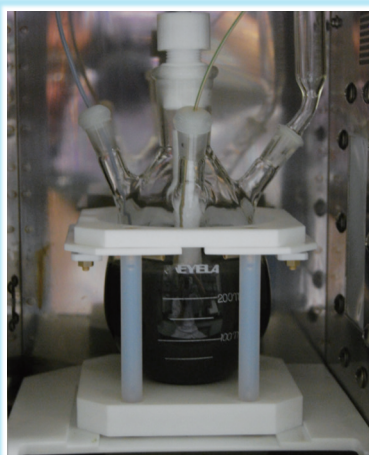
Principal Investigator  
Catalytic Materials  
Transformations Division



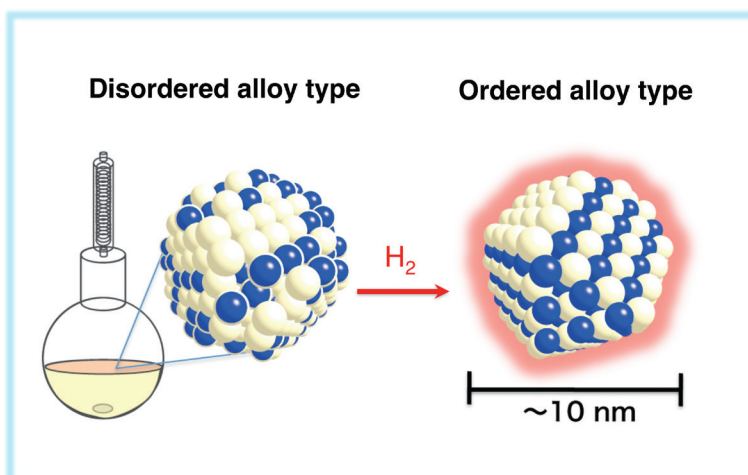
### UBE INDUSTRIES, LTD.

The Ube Group operates in five main business segments: chemicals, pharmaceuticals, cement and construction materials, machinery, and energy and environment.

## Description of Research



Alloy nanoparticles prepared in solution



Production of ordered alloy nanoparticles by hydrogen treatment

Catalysts<sup>1</sup> enable mitigation of reaction conditions for the progress of chemical reactions. Alloy nanoparticles having a diameter of several to several tens of nanometers<sup>2</sup> are known to exhibit high catalytic abilities. Alloy nanoparticles produced via chemical reduction of metal ions in a solution usually show a disordered structure in which constituent metals are randomly mixed. Recently, Prof. Yamauchi's group succeeded in preparing alloy nanoparticles with an ordered structure and with metal elements regularly arranged in the lattice by treating the disordered alloy nanoparticles under a hydrogen atmosphere. The newly prepared ordered alloy nanoparticles potentially exhibit novel catalytic activities, and the technology of the ordered alloy particles was transferred to Ube Industries, Ltd. Future research is expected to find further utility of ordered alloy nanoparticle catalysts in chemical synthesis process.

### Technical Terminology

- 1 Catalyst: Substances that affect the reaction rate of chemical reactions but do not change themselves.
- 2 Nanometer: Unit representing one billionth of a meter.

### *Message from Prof. Yamauchi*

Our joint research with Ube Industries, Ltd. enables us to find new potentials of nanoalloys that we could not envision. If companies and university researchers deepen their understanding of their own technologies and have more opportunities to focus on wisdom and advance research, the possibility of creating innovative technologies will largely increase. More intimate collaboration between industries and academia can contribute to solving CO<sub>2</sub>-related environmental issues.





## 1

### Effect of amine structure on CO<sub>2</sub> capture by polymeric membranes

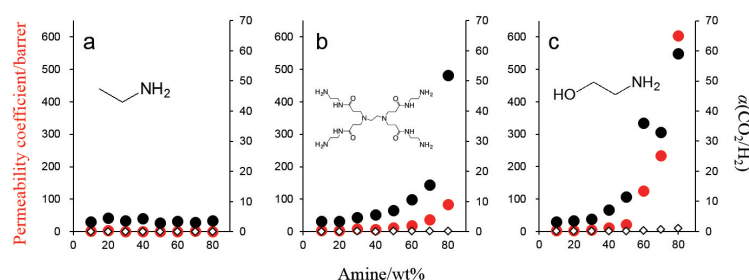
Ikuko Taniguchi, Kae Kinugasa, Mariko Toyoda, and Koki Minezaki

Science and Technology of Advanced Materials  
DOI: 10.1080/14686996.2017.1399045

Development of effective CO<sub>2</sub> capture technologies is one of the fundamental topics to suppress climate change, and membrane separation attracts much attention as the next generation of CO<sub>2</sub> separation technology. Amines have been incorporated in the membranes to enhance CO<sub>2</sub> separation performance. Poly(amidoamine) (PAMAM) immobilized membrane exhibits good CO<sub>2</sub> separation properties, but the gas permeability can be improved.

Polymeric membranes consisting of monoethanolamine, one of alkanolamine, and polyvinyl alcohol showed higher CO<sub>2</sub> transport properties than PAMAM membranes. In the membranes, CO<sub>2</sub> turned to bicarbonate under humidified conditions, which gave much greater diffusivity.

The obtained results would provide useful information to develop membranes for pre-combustion CO<sub>2</sub> capture at integrated gasification combined cycle plants to mitigate CO<sub>2</sub> emission.



Effect of amine content on gas permeation properties of (a) EA- and (b) PAMAM and (c) MEA-containing PVA membranes at 313 K and 80 % relative humidity ( $\Delta p(\text{CO}_2) = 63$  kPa).  
 $\bullet$ :  $P(\text{CO}_2)$ ;  $\circ$ :  $P(\text{H}_2)$ , and  $\blacktriangle$ :  $\alpha(\text{CO}_2/\text{H}_2)$ .

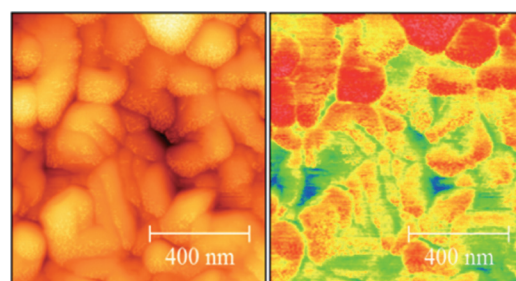
## 2

### Grain boundary engineering of halide perovskite CH<sub>3</sub>NH<sub>3</sub>PbI<sub>3</sub> solar cells with photochemically-active additives

Nastaran Faraji, Chuanjiang Qin, Toshinori Matsushima, Chihaya Adachi, and Jan Seidel

The Journal of Physical Chemistry C, 122 (9), 4817–4821, 2018  
DOI: 10.1021/acs.jpcc.8b00804

Metal halide perovskites are promising for efficient solar power conversion. However, low operational durability of perovskite solar cells is an issue that must be overcome for practical applications. In this study, we show that operational durability of solar cells is greatly enhanced by adding benzoquinone (BQ) into perovskite films, along with a 1.5-fold enhancement of power conversion efficiency. The half-lifetime, where efficiency reduces to half of the initial under continuous solar illumination, is 10,000 h for BQ-added solar cells. Results of the Kelvin probe force microscopy reveal that BQ addition reduces potential barriers at grain boundaries of perovskite films, which is the source of solar cell performance degradation (Figure). These results are directly consistent with I<sup>2</sup>CNER's mission and contribute toward a reduction of CO<sub>2</sub> emissions and fossil fuel consumption.



Atomic force microscope (left) and Kelvin probe force microscope (right) images of perovskite films with BQ additive



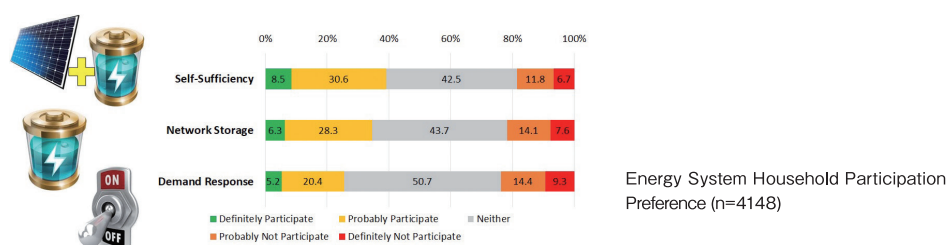
## 3

## Strategic and user-driven transition scenarios: Toward a low carbon society, encompassing the issues of sustainability and societal equity in Japan

Andrew Chapman and Nugroho Agung Pambudi

Journal of Cleaner Production  
DOI: 10.1016/j.jclepro.2017.10.225

This research investigates two approaches to energy transitions in Japan. The first approach is the strategic, top-down approach employed by the Japanese government with carbon reduction targets and renewable energy deployment goals specified by national policy and strategic plans. The second approach is the bottom-up approach to energy transition, by investigating household behavior, energy technology preference, and participation in energy system activities such as the deployment of solar PV, household battery storage, and demand response. The findings of this paper demonstrate how a combined bottom-up and strategically driven top-down approach to energy transitions can engender a desirable and equitable future energy system while meeting strategic goals. The findings are relevant to I<sup>2</sup>CNER in informing and influencing future Japanese energy policy by incorporating household energy system participation.



## 4

## Seismic and strain detection of the heterogeneous spatial distribution of CO<sub>2</sub> in high-permeable sandstone

Keigo Kitamura, Osamu Nishizawa, Kenneth T. Christensen, Takuma Ito, and Robert J. Finley

International Journal of Greenhouse Gas Control  
DOI: 10.1016/j.ijggc.2018.03.005

Recently, several cases have been reported of CO<sub>2</sub> behavior that was not observed by seismic monitoring in a high-quality aquifer. In this study, we injected supercritical CO<sub>2</sub> into the highly permeable Mt. Simon sandstone and measured the CO<sub>2</sub> behavior by P-wave velocity ( $V_p$ ) and surface strain. Our experimental results suggest that CO<sub>2</sub> makes a large cluster and heterogeneous distribution in low-capillary number cases ( $Ca$ ) and it is difficult to monitor the CO<sub>2</sub> behavior with only  $V_p$  under low- $Ca$  flow conditions. This result well explains the case of unmonitored CO<sub>2</sub> behavior in high-quality reservoirs because the strain measurements showed an expansion trend with an increasing injection volume.

These results indicated that permeability and  $Ca$  are controlled by CO<sub>2</sub> behavior, reservoir distribution, and the possibility of seismic monitoring. This study also indicates the importance of having multiple monitoring methods for CO<sub>2</sub> behavior in deep reservoirs.

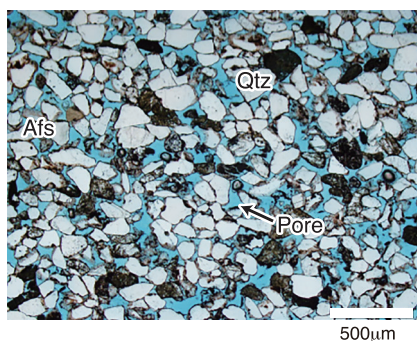


Fig.1: High permeable sandstone (Mt. Simon sandstone)

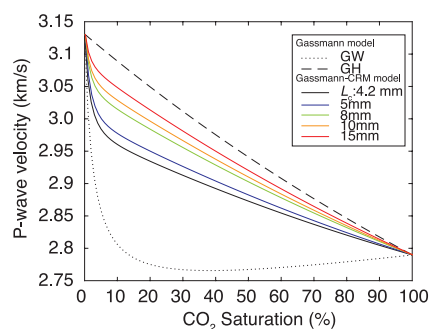


Fig.2: The relationship between CO<sub>2</sub> cluster size, CO<sub>2</sub> saturation and P-wave velocity.





## 5

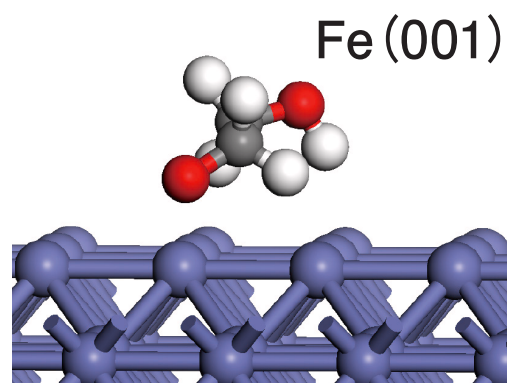
### First-principles calculation of activity and selectivity of the partial oxidation of ethylene glycol on Fe(001), Co(0001), and Ni(111)

Nobuki Ozawa, Shigeki Chieda, Yuji Higuchi, Tatsuya Takeguchi, Miho Yamauchi, and Momoji Kubo

Journal of Catalysis

DOI: 10.1016/j.jcat.2018.03.017

We are developing a novel alkaline fuel cell fueled with ethylene glycol, which is a liquid fuel exhibiting excellence in storability and transportability. We have demonstrated electric power generation using an Fe-based nanoalloy catalyst without CO<sub>2</sub> emission via highly selective partial oxidation of ethylene glycol into oxalic acid. In this research, we have revealed the mechanism of the highly selective oxidation of ethylene glycol on the nanoalloy catalyst as a collaboration work with Profs. Momoji Kubo and Nobuki Ozawa from Tohoku University. CO<sub>2</sub> production progresses via the dissociation of the C-C bond of ethylene glycol. Therefore, the activation energy for an elementary reaction on Fe(001), Co(0001), or Ni(111) was calculated. We found that activation energy for cleaving the O-H or C-H bond on Fe(001) is much smaller than that for C-C bond cleavage, suggesting that CO<sub>2</sub> generation hardly occurs on Fe(001). These results show that selectivity of oxidation reaction of ethylene glycol is controllable by the catalyst composition, which enables power generation with less environmental impact.



Glycolic acid molecules interacting with Fe(001)

## 6

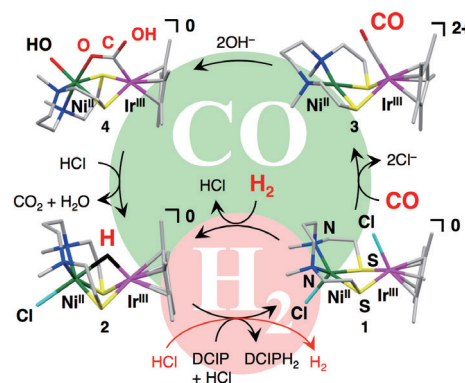
### One Model, Two Enzymes: Activation of Hydrogen and Carbon Monoxide

Ogo, Seiji; Mori, Yuki; Ando, Tatsuya; Matsumoto, Takahiro; Yatabe, Takeshi; Yoon, Ki-Seok; Hayashi, Hideki; Asano, Masashi

Angewandte Chemie International Edition

DOI: 10.1002/anie.201704864

The Ogo group has invented a catalyst for fuel cells that can use both hydrogen and carbon monoxide combined as a fuel. This research outcome is positioned in the short- and mid-term milestone of Project 1, “development of H<sub>2</sub> activation catalyst”, in the Catalytic Materials Transformation division roadmap. The platinum catalyst used in hydrogen/oxygen fuel cells that are expected to serve as clean, next-generation power-generating devices is poisoned by the minuscule amounts (on the order of parts per million) of carbon monoxide contained in hydrogen gas. Consequently, development of a catalyst that is not poisoned by carbon monoxide has been a key priority in the fuel cell field. To date, scientists have not succeeded in developing a catalyst for fuel cells powered by a 50:50 mixture of hydrogen and carbon monoxide gases (a synthesis gas). This research outcome can contribute to the practical use of hydrogen/oxygen fuel cells.



Scheme illustrating the activation of both H<sub>2</sub> and CO by the new bifunctional catalyst