Application for Academy Center Certification
World Premier International Research Center Initiative (WPI)

Host Institution	Kyushu University
Research Center	International Institute for Carbon-Neutral Energy Research (I^2CNER)
Host Institution Head	Tatsuro Ishibashi
Center Director	Tatsumi Ishihara
Administrative Director	Andrew Chapman

Please prepare this application based on the content of your Center's progress report and the progress plan you submitted for the Center's final evaluation. Summarize the Center's future plans with regard to the following 8 items **within five A-4 pages**. (Also fill out the appendices at the end of this form.)

1. Overall Image of Your Center

* Describe the Center's overall image including its identity.

I^2CNER's vision is to contribute to the creation of a carbon-neutral society through cutting-edge basic research underpinning technology that will address the energy challenge for Japan and the world, and establish a model international academic environment for the 21st century. In executing this vision, I^2CNER aims to enable energy technologies which, when deployed, lead to carbon neutrality by 2050. I^2CNER's mission and accomplishments are directly in line with Japan's vision for a robust energy future: energy security, economic efficiency, and environmental protection without compromising safety (3E+S). A unique and important component of I^2CNER is the Satellite Institute at the University of Illinois Urbana Champaign (UIUC), which facilitates complementary research activities and pioneers student and researcher exchanges.

We built our vision on a **balanced energy scenario** for Japan involving a combination of renewable energy deployment and carbon capture and storage technologies, with the addition of hydrogen into the energy system. I^2CNER's research efforts are intimately tied to this scenario because the short-, mid-, and long-term milestones of each of our **research project roadmaps** were established in consideration for the removal of the roadblocks in the development and deployment timing of the various promising technology options within the scenario. By necessity the research teams are composed of scientists and engineers from disparate disciplines and the research addresses phenomena that span many decades in spatial and temporal scales. I^2CNER's roadmaps and research portfolio updates are also informed by the Institute's scientific exchanges with a stellar list of distinguished scientists from 24 partnering institutions across the globe.

The relevance of the I^2CNER research efforts and objectives to enabling the green innovation initiative of the government of Japan is demonstrated by the large number (129) of collaborative projects in which its researchers have been involved with industry. A total of 63 projects resulted in technology transfer events. Since its inception, I^2CNER has applied for 387 patents and was granted 118 patents as of 2021.

Evidence of I^2CNER's international stature and relevance can be seen in its 3,769 publications since inception with a total number of 100,492 citations and an h-index of 127, on par or better than the h-index of peer institutes. Our researchers have joint publications with researchers from 959 institutions around the world, and 437 internationally recognized researchers visited I^2CNER for scientific interaction and exchange. The Institute's researchers are globally engaged and have been responsible for organizing, co-organizing, or serving on the scientific committees of 232 international conferences, 341 international conference sessions/symposia or workshops, and 86 I^2CNER international workshops. In addition, I^2CNER researchers have received a total of 364 national and international awards from various professional societies and institutions around the world.

I^2CNER provides a rich environment for young researchers to pursue transformative research in a non-traditional and highly multi-disciplinary and international setting. A vital interdisciplinary program is

the fusion of applied math with energy engineering, based on the Institute's burgeoning relationship with Kyushu University's (KU) Institute of Mathematics for Industry (IMI) and various departments at the UIUC. Of the 117 young researchers, 36 went on to take faculty positions at universities in Japan (excluding KU) and the world and 11 moved to positions within industry and national laboratories during the period of FY2010 to FY2021.

I^{2}CNER is spearheading KU's globalization efforts within the University Reform Revitalization Program, and I^{2}CNER faculty are instructors in the international programs of KU. I^{2}CNER's operational principles in research served as an example for the establishment of the Kyushu University Platform of Inter/Transdisciplinary Energy Research (Q-PIT) on October 1, 2016, an umbrella organization to integrate campus efforts in research and education on energy across its various units, including social sciences, economics, law, and political sciences.

In summary, I^{2}CNER is a highly successful research and education test bed. It is a national and global experiment that *tackles key scientific challenges along the path to providing Japan with carbon-neutral and sustainable energy supplies and the advancing of low-carbon energy transition despite limited energy resources* through internationalization of scientific research and education in Japan, the US, and the world at large. I^{2}CNER is unique as the only Japan-led multi-university institute in the world constructing the path to a carbon neutral society.

2. Mid- to Long-term Research Objectives and Strategies

* Describe new challenges in the Center's research objectives and plans after FY2020.

While I^{2}CNER's accomplishments have propelled Japan to the international forefront of carbon-neutral energy research and associated technology development, there are still major challenges ahead. Our focus continues to address basic science and engineering for energy with the overall goal of reduced CO_2 emissions and the realization of a carbon neutral energy society. In response to the Final Evaluation's Site Visit Report's advice/recommendation, our Energy Analysis Division (EAD) assessed the Technology Readiness Level (TRL) of each individual research project. We are using this assessment to make best use of resources and better focus our research directions in order to meet the long-term carbon-neutrality goals. As a result, I^{2}CNER streamlines its research portfolio by reshaping its strongest research themes and phasing out those that are less impactful according to their respective TRL. In addition, I^{2}CNER will continue to invest in disruptive, high-risk high-payoff science as well as directed, discovery research, such as the biomimetic activation of small molecules for the reduction of CO_2 and N_2 to produce hydrocarbons and NH_3.

Moving forward, the three streamlined thematic research clusters or '**Thrusts'** are **Advanced Energy Materials**, **Advanced Energy Conversion Systems**, and **Multiscale Science and Engineering for Energy and the Environment**. This structure allows us to capture our most relevant existing capabilities and to organize them for the best future impact. It also provides an efficient mechanism for top international and Japanese researchers to work interactively to accomplish common goals which cut across disciplines. I^{2}CNERl continues to rely on the central role of the current Energy Analysis Division (EAD) that was integrated in the Multiscale Science and Engineering for Energy and the Environment Thrust. This includes the continued use of Roadmaps to set research goals and assess progress for each individual research project within the thrusts, and estimate the contribution of I^{2}CNER research on future CO_2 reductions. *I^{2}CNER sees that this Research-Project Roadmap approach, which has proven highly successful in the past, should direct science and resource planning for the future*.

The **Advanced Energy Materials** Thrust combines the best features of the development of materials for hydrogen generation, transport and storage, and materials for efficient energy conversion, particularly for fuel cell and regenerative energy applications. More specifically I^{2}CNER is carrying out research on i) low cost high-strength, hydrogen-compatible stainless steels having yield strength 600MPa (current research status of TRL~4) by developing the next generation of hydrogen/fatigue and hydrogen/impurity interaction models, ii) highly selective catalysts for the conversion of CO_2 to hydrocarbons including alcohol (as an energy storage medium) and polymer electrolyte alcohol electrosynthesis cells aiming toward energy storage for carbon recycling with higher efficiency than batteries (TRL~4), iii) interface design of molecular and hybrid catalysts for artificial photo-synthesis for photoconversion devices that can provide low cost solar fuels with reasonable cost and efficiency (TRL~3); and iv) biomimetic activation of small molecules including nitrogen, NH_3 synthesis under mild conditions for the transport of hydrogen (TRL~3).

The **Advanced Energy Conversion Systems** Thrust focuses on the development and evolution of systems which either lower carbon emissions, increase energy efficiency, or both: i) the high temperature electrolysis cell has the potential to take a large share in the electrolyzer market due to its

high efficiency and low cost. I²CNER's research will focus on electrode materials in relation to water-assisted phase separation, the quantitative prediction of oxygen reduction, and the degradation mechanisms for technological functional oxides (TRL~4), ii) the energy storage system utilizing reversible fuel cell / novel battery is a promising means to modulate/adjust supply and demand in electricity markets. We have developed an air-battery based on SOFC/SOEC concepts where H_2 is used to reduce hematite to metallic Fe thereby storing reducing equivalents as metallic Fe rather than H_2. Future research will optimize this device for higher roundtrip efficiency, capacity, and operating temperature (TRL~4), iii) Electrocatalytic system for CO_2-H_2O co-electrolysis for production of syngas which can be further converted to liquid fuel as a carbon free fuel (TRL~4), iv) I²CNER will advance the exciting photovoltaics technology of hybrid perovskite solar cells whose adoption in the PV markets can lead to drastic CO_2 reductions. I²CNER research will focus on increasing the efficiency of the lead-free systems we developed and found to exhibit promising durability (TRL~4).

The **Multiscale Science and Engineering for Energy and the Environment** Thrust pulls together the range of challenges facing Japan's and the world's energy transition, namely the transition from largely fossil fueled energy technology to a carbon-neutral or a carbon-free energy supply. In addition, this Thrust enables the coordination of carbon reduction technologies, energy efficiency technologies, and guidance for social, political, and investment strategies to coordinate this transition. Negative emission technologies, contributed to by our CO_2 separation and monitoring technologies, are expected to be supported by the public. I²CNER's research will focus on i) PVT measurements and accurate equations of state for new refrigerants for next generation adsorption heat-pumps that will penetrate our society as the energy demand due to air conditioning increases (TRL~4). Our research on activated carbons has already shown great promise for record adsorption capacity of ethanol and CO_2 (TRL~4). ii) Further development of nanosized CO_2 separation membranes (TRL ~4) and CO_2 monitoring technologies (TRL~7)—through improved understanding of the geophysics of CO_2 storage (TRL~1) and reservoir characterization (TRL~5)—will enable effective Carbon Capture and Storage (CCS) deployment. I²CNER will continue to explore the efficient and selective conversion of captured CO_2 into value added products (TRL~4). In addition, capitalizing on talent and resources across KU, we will invite new members (WPI Professors) to diversify I²CNER's expertise and research portfolio of the Thrust to include the integration of renewable energy with the grid, the interaction of the energy networks with the environment, and social and economic dynamics.

3. Management System of the Research Organization

* Describe the system of organizational management via which the center will execute the above-described research strategy and plan.
* In Appendix 1-3, list the Principal Investigators, enter the number of center personnel (researchers, research-support staff, and administrative staff), and provide a diagram of the Center's organizational management system.

To make best use of financial resources beyond 2020, I²CNER's research operations, international engagement, brain circulation, technology transfer, and socioeconomic outreach will be executed and advanced through the "*Three Thrust, Two Platform*" approach. The three research Thrusts, outlined in Section 2, will be interwoven with the **Platform for International Collaborations and Partnerships** for I²CNER to maintain its international identity and the **Platform for Societal Implementation and Industrial Collaboration** that will ensure technology transfer through the large and growing network of I²CNER's industrial interactions. In particular, we established the Mitsui Chemical Inc.- Carbon Neutral Research Center (MCI-CNRC) which is the platform between I2CNER and Mitsui Chemical Inc. from 2021 and the fundamental results will be transferred to industry for practical use. I²CNER will continue to operate under the strong leadership of the Director and is also supported by the President of Kyushu University, President Ishibashi. Administrative Director Chapman will continue the oversight of the Administrative Office.

I²CNER's research program beyond 2023 will be anchored on 25 PIs (24 presently in I²CNER, 6 PIs are resigned and 7 which have been newly appointed) and operate under the umbrella of three research thrusts with the following composition: i) Advanced Energy Materials: Tenured I²CNER PI Kubota; tenured I²CNER Associate Professors Yoon, Y. Takahashi, and KU PIs Ogo, Tsuchiyama, Sawae and Yamauchi. The research activities of the thrust will be supported by the international PIs Sofronis, Volkert and Somerday of the platform for international collaborations and partnerships, ii) Advanced Energy Conversion Systems: tenured I²CNER PIs Matsumoto, Staykov; tenured I²CNER Associate Professors, Matsushima, Watanabe and Edalati, and KU PIs Adachi, Ishihara and Fujigaya. The research activities of the thrust will be supported by the international PIs Skinner, Lippert, and Gewirth of the platform for international collaborations and partnerships, iii) Multiscale Science and Engineering for Energy and the Environment: tenured I²CNER PIs Fujikawa, Saha and Chapman; tenured I²CNER

Associate Professor Nguyen, and KU PIs Sugai, K.Takahashi and Tsuji(U. Tokyo); international PIs Kenis, Chakraborty and Stubbins will support the research activities of this Thrust.

I^{2}CNER's **Platform for Societal Implementation and Industrial Collaboration** will be tasked to accelerate impactful technology development and transfer to industry for practical application, and foster the advancement of interactions with national and international agencies. This platform will focus on the goals currently pursued by the Industrial Research Division, augmented with a societal dimension to advance the engagement of I^{2}CNER with industry and society at a broader institutional level. Several research laboratories collaborating with companies will also participate in this platform. Mazda established a collaborative research laboratory on energy storage for transport and a similar collaborative research laboratory is planned to strengthen collaboration with industry. Resources will be sought to staff the platform with an expert that can bring the I^{2}CNER research accomplishments to the attention of national and international corporations and help I^{2}CNER execute its mission as a resource to national agencies such as METI on the current state-of-the-art in energy research. With regard to the social implementation, I^{2}CNER's research will seek to deal with critical policy issues in Japan such as the aging, shrinking population with regard to low-carbon energy transition and will consider the impact of behavior, specifically the environmental and social equity impacts of household consumption and participation in the energy system.

The **Senior Advisory Committee (SAC)** will be newly established by reorganizing the previous External Senior Advisory Committee (EAC) with its role in advising regarding cutting-edge research and the ongoing management of I^{2}CNER. Some EAC members will remain and PI Sofronis will be the chair of this SAC. Previous international PIs, Kilner, Tuller, and Kirchheim will also be newly appointed as committee members. This committee will convene annually at the same time as the annual meeting of I^{2}CNER at KU.

The **Industrial Advisory Board** will continue on with its role in advising on research relevance and counseling on technology transfer. Lastly, this platform will be working with the PIs and faculty of the three thrusts to pursue joint research funding among national agencies of the government of Japan, e.g. JSPS, and counterpart international agencies, e.g. US NSF.

4. Plan for Promoting the International Circulation of World's Best Brains

* Describe your policy and concrete plan for promoting the international circulation of the world's best brains, which is an important function of the WPI Academy.

I^{2}CNER will maintain its international identity through the **Platform for International Collaborations and Partnerships.** This platform will involve Illinois, MIT, the Paul Scherrer Institut (PSI), Imperial College, London, University of Edinburgh, Göttingen, and other institutions from the list of our 24 partnering institutions, e.g., the Helmholtz Institute Forschungszentrum Juelich. Through this platform, I^{2}CNER will continue its successful program on graduate student and postdoc exchanges, and faculty sabbaticals. In addition, all 8 of our overseas Principal Investigators are world-class researchers who are actively involved in I^{2}CNER's research operations. They spend between one to seven weeks at KU and their ongoing relationships with the faculty of KU are having a transformative impact upon I^{2}CNER's overall research culture.

The Kyushu-Illinois memorandum of understanding (MOU) was renewed and went into effect on August 26, 2019 and a specific agreement for student exchange was signed on September 30, 2019. The revised MOU has cemented the strategic partnership between the two universities and broadened the collaborations to other colleges and departments (such as engineering, social sciences, humanities, economics, law, agriculture etc.). The Satellite Institute at the UIUC will continue to facilitate cooperative research activities and personnel exchanges as follows: i) Kyushu faculty, postdoc, and student visits to Illinois will be facilitated by departmental and university personnel that will assist with visas, visitor accommodations, and sabbaticals, ii) shared facilities and laboratory and office space will remain available, iii) Satellite office will be maintained, iv) tuition waivers will be explored for up to 4 PhD students from Kyushu if they come to Illinois to take courses, and engage in collaborative research.

Our international collaborations will be advanced by young researcher exchanges, travel, and sabbaticals. These operations will be supported by Gaisan Yokyu in the short term and for this purpose, the Center for Energy Systems Design (CESD) was established in 2022. Under an alliance between 7 institutes (Hokkaido University, Tohoku University, Tokyo Institute of Technology, RIKEN, National Institute of Materials Science, Kumamoto University, and KU), researchers can stay at each institute for a short period of time to conduct joint research. Under the activities of this center and I2CNER, young researcher exchange and travel be supported by Center funds. Some previous success stories include the

exchange of young researchers. Specifically, Prof. Chapman stayed at UIUC on a sabbatical utilizing the Progress 100 Program and there have been collaborations between PI Ishihara and PSI, Julich and Imperial college. Young researcher Kwati Leonard stayed in Julich for 3 months to work on making thin film electrolysis cell. PI Kubota has recently started international joint research with prospective foreign PI Volkert on hydrogen embrittlement using the support of JSPS. Also, I^{2}CNER researchers will leverage the established infrastructure, research culture, and international partnerships of the Institute to continue already established joint international programs such as the Core-to-Core Program with Imperial College London, PSI, and MIT. Lastly, I^{2}CNER will continue to work with the University of Göttingen to establish an International Research Training Group that can be co-funded by the German Research Foundation (DFG) and JSPS.

I^{2}CNER's annual international symposium and international thematic research workshops over the past decade have proven to be successful platforms for international engagement and exploration of new scientific directions as they have attracted hundreds of distinguished researchers from across the globe. I^{2}CNER will continue organizing this symposium and workshops within the Annual KU "Energy Week" event supported by KU's Platform Q-PIT. In addition, I^{2}CNER will continue to organize workshops with other WPI Centers and allied institutes. Lastly, the successful I^{2}CNER Seminar Series (Institute Interest Seminar Series, and I2CNER Webinar Series) will be utilized to engage key members of the international community from academia, national laboratories, industry, and government agencies (policy makers).

5. Plan for Disseminating the WPI Program Achievements

* Describe your policy and concrete plan for disseminating WPI center achievements both within the host institution and to other universities, especially their experience and know-how accumulated on establishing top world research institutes and advancing system reforms.

Drawing from its international research experiences and approach, I^{2}CNER will continue its central role within Q-PIT by helping to cross-pollinate a wide range of collaborations on energy research between KU research units of diverse disciplines including social sciences, economics, law, and political sciences. This will allow I^{2}CNER to capitalize on opportunities to broaden and enrich its energy portfolio while also helping Q-PIT advance its mission to catalyze interactions between disparate disciplines and units.

I^{2}CNER will continue its efforts to support the KU Administration's i) institutionalized cross-appointment employment system, and ii) Intra-University Faculty Transfer System. By way of example, in FY2023, 8 senior KU PIs from other KU units will be transferred to I^{2}CNER.

A significant mission of the **Platform for Societal Implementation and Industrial Collaboration** will be the engagement of the member corporations of the Japan-US Business Council (JUBC) with I^{2}CNER in the form of partnership and industrial investment through the model of open innovation whereby industry engineers are imbedded in I^{2}CNER laboratories. Such activities of the Platform will be a most demonstrable example of feeding the I^{2}CNER accomplishments back into society.

6. Plan for Sustaining the WPI Brand

* Describe your plan for sustaining and enhancing the WPI brand.

I^{2}CNER will sustain the WPI Brand by focusing on advancing outstanding research that sets international benchmarks, which brings international recognition, and by expanding global visibility.

In the area of scientific excellence, I^{2}CNER's research themes, outlined in the three Thrusts are the ones in which I^{2}CNER already set the international benchmark and will continue to do so in the future. As of March 31, 2022, the Institute's researchers were responsible for organizing, co-organizing, or serving on the scientific committees for 232 international conferences, 341 international conference sessions/symposia or workshops, and 86 I^{2}CNER international workshops. Our researchers have given 801 keynote, plenary and invited presentations in international conferences and fora. Indeed, this is solid evidence that I^{2}CNER will strive to expand on this record of recognized international engagement and global visibility. I^{2}CNER placed 45 of our researchers at various Japanese (excluding KU) and international institutions. I^{2}CNER will continue fostering its WPI culture for young researchers by maintaining and improving its WPI research environment which it has built over the past 10 years.

As stated in the Section 4, I^{2}CNER has launched two successful in on-line style seminar series: the Institute Interest Seminar Series (IISS), which invites young researchers to introduce their cutting-edge results, and the I^{2}CNER Webinar Series (ISS), which invites established and recognized speakers from

other institutes to encourage the younger researchers within I^{2}CNER. These seminar series are an excellent showcase of I^{2}CNER as a WPI institute.

7. Support by Host Institution

* Describe measures that the host institution will take to support and sustain your Center.

I^{2}CNER is a permanent research Institute of KU and at the center of the KU mid-term plan to "promote leading-edge research related to the carbon-neutral energy research domain in collaboration with the University of Illinois, which is conducted at the International Institute for Carbon-Neutral Energy Research (I^{2}CNER)." During the past 10 years, I^{2}CNER has been successful at winning and filling positions, and KU will make efforts to secure additional positions for the Institute. By the end of FY2022, I^{2}CNER filled a total of 7 Associate and 4 Full Professor positions. I^{2}CNER is also currently in the process of hiring 3 tenured Associate or Assistant Professors, and 1 tenure track Associate or Assistant Professor in FY2022.

The university will grant I^{2}CNER Building I for the time being and Building II constructed with WPI funds for 10 years (total floor space of 4,236 m^2 and 5,014 m^2, respectively) free of charge to provide I^{2}CNER researchers with the requisite environment to continue their cutting-edge research. The space provided by this support significantly exceeds the space allotment per researcher under the university's regular policy

KU will support the salaries of the required staff members and administrative office members, thus securing the successful operation of the "*Three Thrust, Two Platform*" I^{2}CNER organization.

8. Resource Allocation Plan

* Describe your plans over a 5-year period for allocating resources acquired from both the host institution (e.g., financial resources and positions) and from external research funding to execute the Center's functions and activities described above.

* In Appendix 4, enter concrete numbers in the Resource Allocation Plan.

Financial resources and positions to be acquired from the host institution and their allocation have been listed in the preceding Section 7. Regarding external resources, our vision is that I^{2}CNER can remain strong and agile by developing cores of embedded centers funded by external agencies (both industrial and governmental) and securing industrial projects. Drawing from the experience gained from the establishment of the NEXT-RP Center, I^{2}CNER will intensify its efforts to establish similar internal research centers in response to national initiatives by government agencies such as NEDO, METI, RIKEN, JSPS, and JST. With regard to establishing internal research centers, I^{2}CNER will i) rely on input from the Senior Advisory Committee to create new ideas that will attract funding from international foundations, ii) utilize the Platform for Societal Implementation and Industrial Collaboration to attract industrial projects for collaborative efforts in the form of open innovation on topics of mutual interest, such as the ongoing project with Mazda Motor Corporation (Mobile Energy Storage for Low-Carbon Society) and Mitsui Chemical Inc. (MCI-CNRC, carbon neutral technologies). Our ability to obtain industrial funding to support our research operations is demonstrated by the 129 collaborative projects we have had with major corporations (see Section 1) and the 63 projects that resulted in technology transfer events. The award of 118 Patents are also an important resource for I^{2}CNER toward the future and this number of patents will increase over time.

I^{2}CNER will intensify the ongoing dialogue with the Japan-US Business Council (JUBC) for potential investment in I^{2}CNER. In general, it is our plan that all our projects in the three Thrusts will seek industrial support to underpin both research activities and human resources.

WPI Academy Center

Form 2 FY 2023 List of Principal Investigators

NOTE:

*Underline names of principal investigators who belong to an overseas research institution.
*Indicate newly added researchers in FY 2023 (2023.4.1-2024.3.31) in the "Notes" column.
*Enter the host institution name and the center name in the footer.

<Principal Investigators at the end of FY 2023> **Principal Investigators Total: 25**

Name	Age	Affiliation (Position title, department, organization)	Academic degree, Specialty	Effort (%)*	Starting date of participation	Status of participation (Describe in concrete terms)	Note
Tatsumi Ishihara	62	Center director Prof., International Institute for Carbon-Neutral Energy Research, Kyushu University	Dr. of Engr., Catalyst and solid state electrochemistry	95%	2010, Dec. 1st	・Directs and administers the Institute ・Located at I^2CNER ・Leads research activities of his group	
Masanobu Kubota	54	Prof., International Institute for Carbon-Neutral Energy Research, Kyushu University	Dr. of Engr., Mechanical property of materials, Hydrogen brittlement	100%	2019, Apr. 1st	・Located at I^2CNER ・Lead PI of the Advanced Energy Materials Thrust	
Miho Yamauchi	50	Prof., Department of Applied Molecular Chemistry Institute for Materials Chemistry and Engineering/ International Institute for Carbon-Neutral Energy Research, Kyushu University	Dr. of Science, Chemistry	90%	2012, Jan. 1st	・Located at I^2CNER ・Leads research activities of her group	
Brian P. Somerday	55	Adj. Research Assistant Prof., University of Illinois at Urbana-Champaign, USA/ International Institute for Carbon-Neutral Energy Research, Kyushu University	Ph.D., Materials Science and Engineering	40%	2010, Dec. 1st	・Leads research activities of his group ・Research collaboration with Kubota	
Petros Sofronis	66	Prof., Department of Mechanical Science and Engineering University of Illinois at Urbana-Champaign, USA/ International Institute for Carbon-Neutral Energy Research, Kyushu University	Ph.D., Micromechanics of materials, Environmental degradation of materials	90%	2010, Dec. 1st	・Chair of Senior Advisory Committee ・Leads research activities of his group ・Research collaboration with Kubota	
Yoshinori Sawae	55	Prof., International Institute for Carbon-Neutral Energy Research, Kyushu University	Dr. of Engr. Biotribology, Polymer tribology	80%	2023, Apr. 1st	・Located at I^2CNER ・Leads research activities of his group	Newly Added

Cynthia A. Volkert	62	Prof., Institute of Materials Physics at the University of Göttingen/ International Institute for Carbon-Neutral Energy Research, Kyushu University	Ph,D., Physics	50%	2023, Apr. 1st	・Leads research activities of her group ・Research Collaboration with Kubota	Newly Added
Seiji Ogo	60	Prof., International Institute for Carbon-Neutral Energy Research, Kyushu University	Dr. of Science, Green Chemistry	95%	2010, Dec. 1st	・Located at I^2CNER ・Leads research activities of his group	
Toshihiro Tsuchiyama	52	Prof., International Institute for Carbon-Neutral Energy Research, Kyushu University	Dr. of Engr. Materials Science and Engineering	80%	2023, Apr. 1st	・Located at I^2CNER ・Leads research activities of his group	Newly Added
Hiroshige Matsumoto	57	Prof., International Institute for Carbon-Neutral Energy Research, Kyushu University	Dr. of Engr. Solid state ionics, Electrochemistry	100%	2010, Dec. 1st	・Located at I^2CNER ・Executes duties of Associate Director ・Lead PI of Advanced Energy Conversion Systems Thrust ・Chair of Faculty Recruiting Committee	
Stephen Skinner	51	Prof., Department of Materials, Imperial College London/ International Institute for Carbon-Neutral Energy Research, Kyushu University	Ph,D., Materials Chemistry	30%	2023, Apr. 1st	・Leads research activities of his group ・Research Collaboration with Ishihara	Newly Added
Andrew A. Gewirth	64	Prof., Department of Chemistry, University of Illinois at Urbana Champaign, USA/ International Institute for Carbon-Neutral Energy Research, Kyushu University	Ph.D., Chemistry	40%	2012, April. 1st	・Leads research activities of his group ・Research Collaboration with Ishihara	
Tsuyohiko Fujigaya	47	Prof., International Institute for Carbon-Neutral Energy Research, Kyushu University	Ph.D. Engr., Polymer chemistry	90%	2018, Apr. 1st	・Located at I^2CNER ・Leads research activities of his group	
Chihaya Adachi	60	Prof., International Institute for Carbon-Neutral Energy Research, Kyushu University	Dr. of Engr., Materials science and device physics	70%	2010, Dec. 1st	・Located at I^2CNER ・Leads research activities of his group	
Thomas Lippert	61	Prof.,Department of Chemistry and Applied Biosciences,Laboratory of Inorganic Chemistry, Swiss Federal Institute of Technology Zurich, and Paul Scherrer Institut, Thin Films & Interfaces Group, Villigen-PSI, Switzerland/ International Institute for Carbon-Neutral Energy Research, Kyushu University	Dr. of Science, Physical Chemistry	40%	2016, Aug. 1st	・Leads research activities of his group ・Research Collaboration with Ishihara	

Aleksandar Staykov	45	Associate Prof., International Institute for Carbon-Neutral Energy Research, Kyushu University	Ph.D., Physical and theoretical chemistry	100%	2018, Apr. 1st	・Located at I^2CNER ・Leads research activities of his group	
Shigenori Fujikawa	53	Prof., International Institute for Carbon-Neutral Energy Research, Kyushu University	Dr. of Engr., Nanoscience and engineering	100%	2013, June. 1st	・Located at I^2CNER, ・Executes duties of Associate Director ・Lead PI of the Multiscale Science and Engineering for Energy and the Environment Thrust	
Takeshi Tsuji	44	Prof., Depatment of Systems Innovation, Graduate School of Engineering, The University of Tokyo/ International Institute for Carbon-Neutral Energy Research, Kyushu University	Dr. of Science, Geophysics, Digital rock physics, CCS, Geothermics	40%	2013, June. 1st	・Leads research activities of his group ・Research Collaboration with Sugai	
Yuichi Sugai	48	Prof., International Institute for Carbon-Neutral Energy Research, Kyushu University	Dr. of Engr., Petroleum Engineering	80%	2023, Apr. 1st	・Located at I^2CNER ・Leads research activities of his group	Newly Added
Bidyut B. Saha	58	Prof., International Institute for Carbon-Neutral Energy Research, Kyushu University	Dr. of Engr., Thermal Engineering	100%	2010, Dec. 1st	・Located at I^2CNER ・Leads research activities of his group	
James Stubbins	75	Prof., Department of Nuclear, Plasma and Radiological Engineering, University of Illinois Urbana-Champaign/ International Institute for Carbon-Neutral Energy Research, Kyushu University	Ph.D., Energy Materials	20%	2020, Apr. 1st	・Leads research activities of his group ・Research collaboration with Chapman	
Andrew Chapman	43	Associate Prof., International Institute for Carbon-Neutral Energy Research, Kyushu University	Ph.D., Socio-Environmental Energy Science	100%	2021, Jan. 4th	・Located at I^2CNER ・Administrative Director ・Leads research activities of his group	
Koji Takahashi	59	Prof., International Institute for Carbon-Neutral Energy Research, Kyushu University	Ph.D., Thermophysical Engineering, Nanotechnology, MEMS	80%	2022,Jan. 1st	・Located at I^2CNER ・Leads research activities of his group	
Paul J.A. Kenis	52	Professor, Department of Chemical and Biomolecular Engineering, University of Illinois Urbana-Champaign/ International Institute for Carbon-Neutral Energy Research, Kyushu University	Ph.D., Microchemical Systems, Electrochemical Engineering, Reactor Engineering	40%	2023, Apr. 1st	・Leads research activities of his group ・・Research collaboration with Fujikawa	Newly Added

Anutosh Chakraborty	48	Associate Prof., Cluster Lead, TFME Division,School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore/ International Institute for Carbon-Neutral Energy Research, Kyushu University	Ph.D., Adsorption, Thermodynamics and Heat Transfer	40%	2023, Apr. 1st	・Leads research activities of his group ・Research collaboration with Saha	Newly Added

*Percentage of time that the principal investigator devotes to his/her work for the Academy center vis-à-vis his/her total working hours.

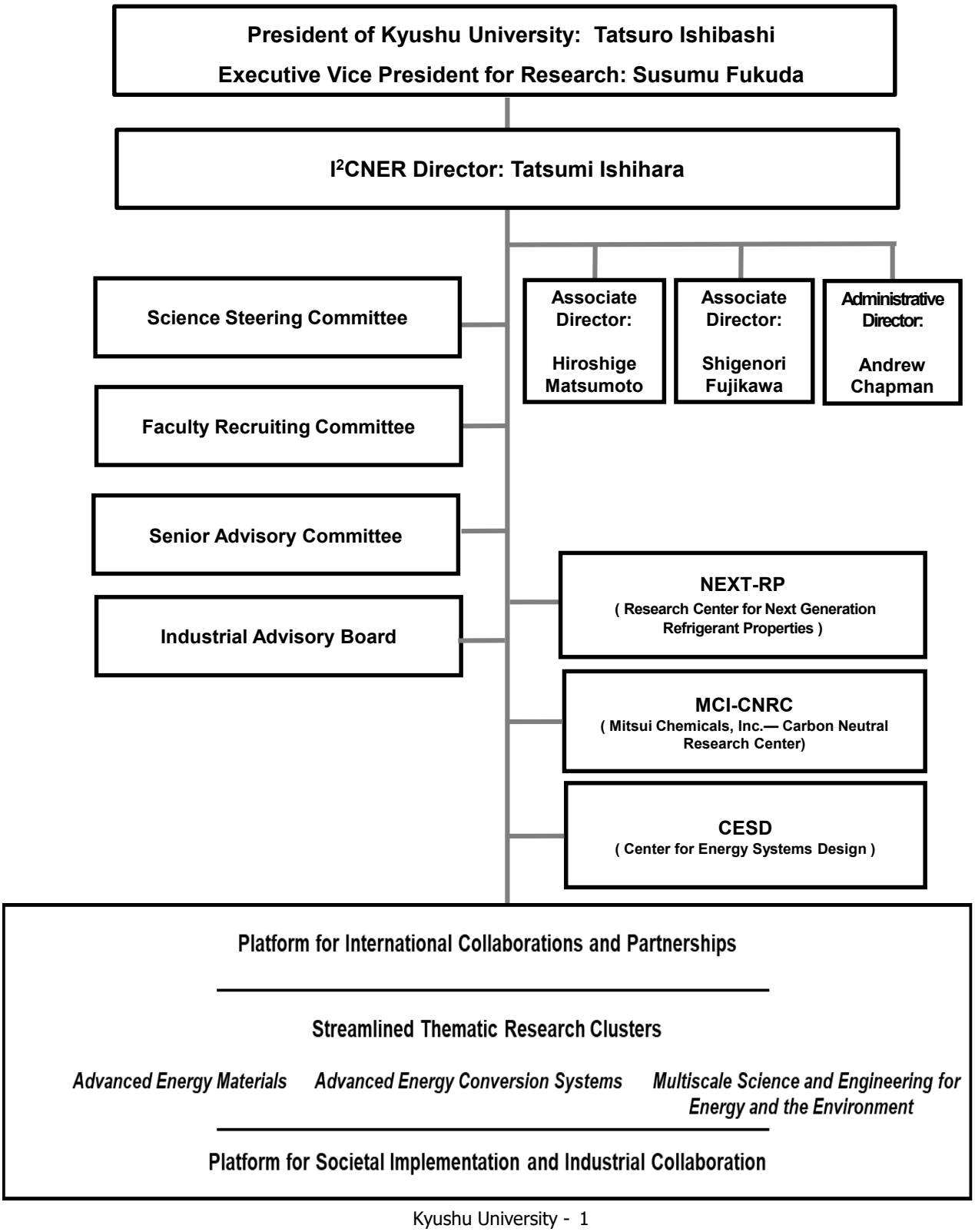
Principal Investigators resigned since FY 2023

Name	Next Affiliation (Position title, department, organization)	Period of participation
Harry L. Tuller	Member of Senior Advisory Committee Prof., Department of Materials Science and Engineering, Massachusetts Institute of Technology,USA	2010, Dec. 1st-2023.Mar.31st
John A. Kilner	Member of Senior Advisory Committee BCH Steele Chair in Energy Materials, Department of Materials, Imperial College, London, UK	2010, Dec. 1st-2023.Mar.31st
Reiner Kirchheim	Member of Senior Advisory Committee Prof., The Institut für Metallphysik, University of Göttingen, Germany	2011, Apr. 1st-2023.Mar.31st
Kazunari Sasaki	Prof., Department of Mechanical Engineering, Faculty of Engineering, Kyushu University	2010, Dec. 1st-2023.Mar.31st
Joichi Sugimura	Undetermined	2010, Dec. 1st-2023.Mar.31st
Hiroaki Watanabe	Prof., Department of Advanced Environmental Science and Engineering, Interdisciplinary Graduate School of Engineering Sciences, Kyushu University	2018, Oct. 1st-2023.Mar.31st

World Premier International Research Center Initiative (WPI)
Diagram of Organizational Management System

- Diagram the Center's organizational management system and its position within the host institution in an easily understood manner.

I²CNER Organizational Structure



Director's Vision

International Institute for Carbon-Neutral Energy Research

—Realizing a Carbon-Neutral Energy Society Rooted in Renewable Energy Via Hydrogen Carriers—

December 22, 2022

ISHIHARA Tatsumi, Professor, Kyushu University

Overview

From the perspective of climate change and global warming, it will be important to dramatically reduce CO_2 emissions by proliferating the use of renewable energies. However, to meet the strong demand for carbon neutral environments, just proliferating renewable energies will not be sufficient; it will also be necessary to reevaluate energy-usage systems and totally redesign them. Toward achieving carbon neutrality by 2050, new and innovative technologies must be developed to enable the use of hydrogen as an energy carrier of renewable energy.

Strategies for capturing and storing CO_2 or converting it to useful fuels will not be sufficient to achieve carbon neutrality. It will also be imperative to establish highly effective and efficient systems for producing and transporting renewable energies to hydrogen gas. In responding to this requirement, research that crosscuts various space and time scales (from picoseconds to kilometers, from nanoseconds to tens of thousands of years) is required but will not by itself be sufficient; also needed will be a paradigm shift to an approach that involves research carried out in a cooperative and complementary manner, one in which researchers in fields different than conventional modes of chemistry, materials science, earth sciences and biology, etc., gather together, merge ideas, and collaborate. To this end, the International Institute for Carbon-Neutral Energy Research (I^2CNER) was established in 2010. Since then, I^2CNER has built the infrastructures, environments and systems for advancing innovative research conducted by top-level researchers in such diverse fields as chemistry, physics, materials science, thermofluidic dynamics, earth sciences, and biometrics who work together and stimulate each other. The consistent results achieved by I^2CNER in basic research on carbon-neutral energy have elevated the institute to the level of a full-fledged WPI center. Considering, however, the changes that have occurred in the energy environment over the past decade, a growing need has emerged to create societies in which substances are circulated starting with renewable energy that is not as geographically limited.

This will necessitate the creation of various new, basic theories that serve as foundations for innovatively establishing safe and reliable systems in areas of hydrogen production, storage and utilization, as well CO_2 capture, storage, and conversion to useful substances. Recent challenges, such as inability to inject widely fluctuating renewable energy into power grids (output suppression), highlight the importance of innovative, cross-disciplinary systems and concepts for storing and circulating substances. Given the new trends in energy that have emerged since the establishment of I^{2}CNER, there is an increasing need to address socially significant challenges such as conducting fused research on green hydrogen for carbon circulation, on converting CO_2 to hydrocarbons or alcohols, and on environmentally friendly NH_3 synthesis. Moreover, to address these complex and weighty challenges and to contribute to ongoing technological and societal transformation, there is a need to cultivate the next generation of researchers and to provide them to both Japan and the international community. In this context, it's I^{2}CNER aim to establish newly fused sciences that span multiple fields in its effort to elucidate, control and manipulate physiochemical and dynamics mechanisms at the interface of hydrogen, CO_2, and substances.

Elucidating these mechanisms, I^{2}CNER seeks to create innovative technologies such as for CO_2 emission-free hydrogen production, hydrogen storage materials, hydrogen embrittlement-resistant materials, efficient fuel cells, effective CO_2 capture, underground storage, and efficient conversion of CO_2 to useful compounds, as well as artificial photosynthesis. I^{2}CNER's ultimate vision is to contribute through scientific innovation and multidisciplinary researcher development to the realization of a carbon-neutral energy society, driven by new green innovation.

The University of Illinois, with which I^{2}CNER has had an agreement for student and faculty exchange since 2008, is also a strategic partnership school of Kyushu University, so Kyushu University will continue to establish a satellite institution at the University of Illinois in the U.S. to accelerate exchange. Concurrently, I^{2}CNER is strengthening its exchange with institutions in Europe including Imperial College and Juelich National Research Institute. And by strengthening Center for Energy Systems Design (CESD), constructed with a focus on alliance with seven institutes within Japan, I^{2}CNER is working to advance both domestic and international brain circulation.

1. First of all

Given the current challenges of climate change and rising energy prices, there is a strong public desire for renewable energy to be used to make the transition to a carbon-neutral

society. Global efforts are underway to achieve carbon-neutral societies, relying on widespread adoption of renewable energy. While the adoption of renewable energy is a trend that suggests achieving carbon-neutral society is possible, reliance on renewable energy alone, as seen in Europe, engenders issues such as unstable power sources and reduced reliability. To realize carbon-neutral societies, it will be critical to be able to efficiently convert renewable energy into primary energy, store it in energy carriers, and build societies that circulate and utilize this energy.

In Japan, with its limited in landmass and natural environment marked by many days of strong and seasonal winds including typhoons, there are limitations to the widespread adoption of renewable energy. Accordingly, I^{2}CNER's vision for Japan's future involves importing energy carriers produced using renewable energy from overseas and using them for materials and energy within Japan. Currently, hydrogen is considered a potential energy carrier for this purpose, and while its direct use in fuel-cell vehicles is expected, challenges exist in the storage and transport of gaseous hydrogen. Given such challenges, I^{2}CNER is exploring the synthesis of liquid fuels by reacting green hydrogen with CO_2, which is well-suited for transportation and matches existing infrastructure. Given this situation and with a goal of realizing a carbon-neutral society, I^{2}CNER considers liquid fuels synthesized by reacting CO_2 with green hydrogen important as it is suitable for the kind of transportation needed to realize a carbon-neutral society and is well-matched to in-place infrastructure. In addition to the conventional approach of directly using hydrogen, I^{2}CNER considers it important to comprehensively develop carbon-neutral energy, including technologies needed for CO_2 reuse, in contributing to the overall development of carbon-neutral energy. Synthesis of valuable compounds from CO_2 with renewable energy will make a significant contribution to reducing CO_2 in materials transformation. In addition to pioneering advances in carbon-neutral technologies since its establishment, I^{2}CNER is working to create a new research domain that merges concepts from cross-disciplinary fields such as catalysis, electrochemistry and biochemistry for the purpose of attaining CO_2 recirculation. I^{2}CNER is accelerating its effort to tackle challenges related to developing innovative processes and materials, such as creating a synthesis method using NH_3 in solar energy as a carrier for storing and transporting renewable energy, which has not been traditionally pursued.

As illustrated in Figure 1, I^{2}CNER places focus on high-temperature electrolysis technology for efficiently storing solar energy to hydrogen. On the other hand, high-temperature electrolysis enables high-efficiency not only in the electrolysis of CO_2 but also in the co-electrolysis of CO_2 and H_2O. We are working to achieve resource recycling by leveraging this high-efficiency, high-temperature electrolysis process. Subjecting the process to

hydrogeneration, we are expanding it to fuel production. While traditionally addressing the capturing of CO_2 from the air, we are also considering the use of artificial photosynthesis with a photocatalyst as the most effective means of recycling diluted CO_2. We are focusing on biocatalysts such as enzymes as effective catalysts, and expanding this research into new domains.

With a slogan of "university that drives social change with integrative knowledge," Kyushu University has positioned itself as a green innovation hub in the fundamental fields of "decarbonization, medicine & health, and environment & food." Starting with the development of innovative technologies, the University makes policy recommendations on such things as building models for a decarbonized society, while cultivating highly skilled individuals who can lead innovation. I²CNERs vision of a carbon-neutral energy society aligns well with the strategy of the Kyushu University; it leverages the university's strength in the field of decarbonization, an area in which it is easy to obtain University's support.

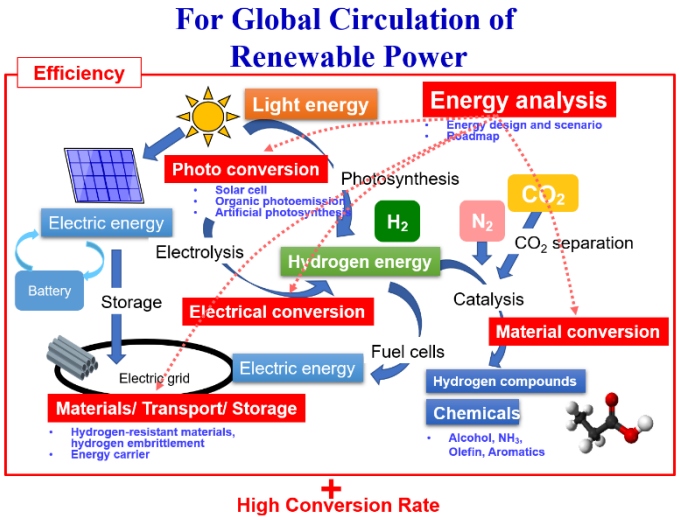


Figure 1, Research Areas Pursued by I²CNER

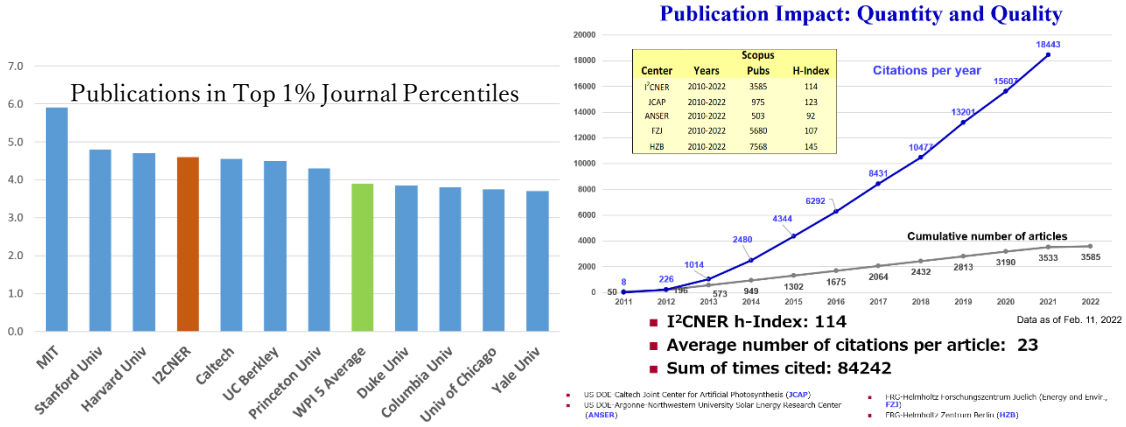


Figure 2, Evaluation of I²CNER's Results

2. Key research areas

Since its establishment, I2CNER has been engaged in developing innovative cross-disciplinary technologies for the production, transport, and utilization of hydrogen, as well as securing excellent researchers around the world and promoting brain circulation.
As shown in Figure 2, the center has achieved impactful results as a world-class research center in the fields of hydrogen production and effective utilization, and innovative conversion technologies of materials. However, with the rapid spread of renewable energy and with the emergence of new situations related to energy, such as output control in renewable energy sources like solar power, designing models for the comprehensive use of energy in energy-usage systems, including for the effective use of energy, has become critical. On the other hand, it is impossible to build a society based on only renewable energy. As is currently the case with oil and natural gas, there is a need to address issues related to the storage, transport and utilization of renewable energy on a global scale. This necessitates the transport of substances such as green hydrogen produced using renewable energy or hydrogen-storage media such as methanol or ammonia, which are created by further reacting green hydrogen with carbon or nitrogen. For such substance transformation, I^{2}CNER is working on consolidating a wide range of expertise across disciplines such as physiochemistry, catalysis chemistry, electrochemistry, mechanical engineering, materials science, earth science, and biochemistry in its work to generate innovative processes.

3. Research overview

I^{2}CNER's approach to achieving a carbon-neutral energy society involves creating a new domain that integrates chemistry, physics, materials science, mechanics, earth sciences and biochemistry with a focus on interface phenomena between substances. In other words, by scientifically integrating information across various time and spatial scales, from the atomic level to the global macro scale, we are working to spur the advancement of interdisciplinary research across a wide spectrum of related fields. This is a global challenge, and to tackle it, we will need to accelerate international brain circulation while further developing our center as a global leader in carbon neutralization. I^{2}CNER's goal is to achieve an environmentally harmonious and sustainable carbon-neutral energy society. To address global warming and develop alternative energy systems to fossil fuels, we have established and are advancing research on the following themes.

1) Producing hydrogen through artificial photosynthesis, such as photocatalytic water splitting—Aimed at producing green hydrogen

2) Producing hydrogen-compatible structural materials—Aimed at designing a safe and reliable hydrogen society infrastructure
3) Producing next-generation fuel cell materials—Aimed at establishing foundational principles for high-energy conversion and creating new devices
4) Elucidating fundamental thermal properties and heat-transfer characteristics of high-pressure environments such as hydrogen and CO_2 (e.g., 100Mpa)—Aimed at elucidating interactions between hydrogen and substances under a wide range of temperature and pressure conditions and also at the stability of supercritical CO_2
5) Conducting advanced chemical conversion and catalysis—Aimed at establishing substance-conversion methods that do not generate waste
6) Establishing advanced CO_2 separation and concentration processes—Aimed at developing efficient CO_2 separation and concentration technologies
7) Investigating CO_2 subsurface storage and stability—Aimed at elucidating the behavior of CO_2 in the subsurface and its stability in tri-phase coexistence with rocks and water
8) Analyzing and designing energy-utilization methods—Aimed at establishing a carbon-neutral society

In addition to these themes, we are strengthening our research on the following initiatives in response to current changes in the energy environment and society.

9) Developing high-efficiency solar cells and luminescent materials—Aimed at attaining efficient energy conversion of solar power and developing low-power luminescent devices
10) Developing advanced CO_2 conversion technologies—Aimed at chemical storage of green hydrogen through synthesis of green fuels
11) Synthesizing NH_3 as a hydrogen carrier under mild conditions—Aimed at hydrogen transport through the nitrogen cycle

By fusing theories and sciences in the field of machine learning and using materials informatics, we are accelerating research in addressing these themes.

4. I^{2}CNER's organization and its collaborations with affiliated organizations

I^{2}CNER's organization and its collaborations with affiliated organizations are illustrated in Figure 3, which depicts the center's operational framework. I^{2}CNER is structured into three research clusters or 'Thrusts' for each research theme with researchers belonging to three interdisciplinary thrusts. This setup facilitates the generation of innovative science and technology by advancing research in interdisciplinary knowledge domains. The units are as follows:

1) Advanced Energy Materials

Based on new sciences of surface, interface and microstructure for the use of hydrogen, water and CO_2, this thrust works to develop molecular, nano, and structural materials. It also achieves material circulation as a hydrogen carrier.

2) Advanced Energy Conversion Systems

This thrust conducts research on energy conversion and systems with a focus on reducing CO_2 emissions and improving energy efficiency

3) Multiscale Science and Engineering for Energy and the Environment In transitioning from a society centered on fossil fuels to a carbon-neutral one, this thrust comprehensively considers and addresses various-scale challenges facing Japan and the world.

In these fields, we are introducing machine-design methods as a new approach to enhancing research efficiency. Concurrently, we are restructuring our External Advisory Committee into a Senior Advisory Committee to provide guidance to the center and advice on new research directions. In addition, to further strengthen international collaboration and brain circulation, we have established the Platform for International Collaborations and Partnerships and will facilitate the employment of outstanding young talents from around the world and to promote exchange with internationally renowned researchers. Moreover, we have established the Platform for Societal Implementation and Industrial Collaboration to accelerate the societal implementation of our research results and to promote collaborative research with domestic and international industries. In particular, we have established a comprehensive partnership with Mitsui Chemical Inc.— Mitsui Chemical Inc.-Carbon Neutral Research Center (MCI-CNRC) with the aims of promoting the societal implementation of carbon-neutral technologies, quickly disseminating our research results to society, and advancing the center's research from the vantage point of its societal implementation.

We established the Center for Energy Systems Design (CESD) to promote the circulation of talented researchers and boost collaboration with I^2CNER's surrounding research institutions. Currently, CESD is carrying joint research activities with six domestic research institutions: Hokkaido University, Tohoku University, Tokyo Institute of Technology, RIKEN, National Institute of Materials Science, and Kumamoto University. It is strengthening domestic center collaborations not only through joint research but also via initiatives to foster young, multidisciplinary researchers. As we continue our satellite partnership with the University of Illinois, we are advancing international joint research with European institutions engaged in energy and materials research, while promoting international brain circulation with them by inviting their researchers to our center and

sending ours to theirs.

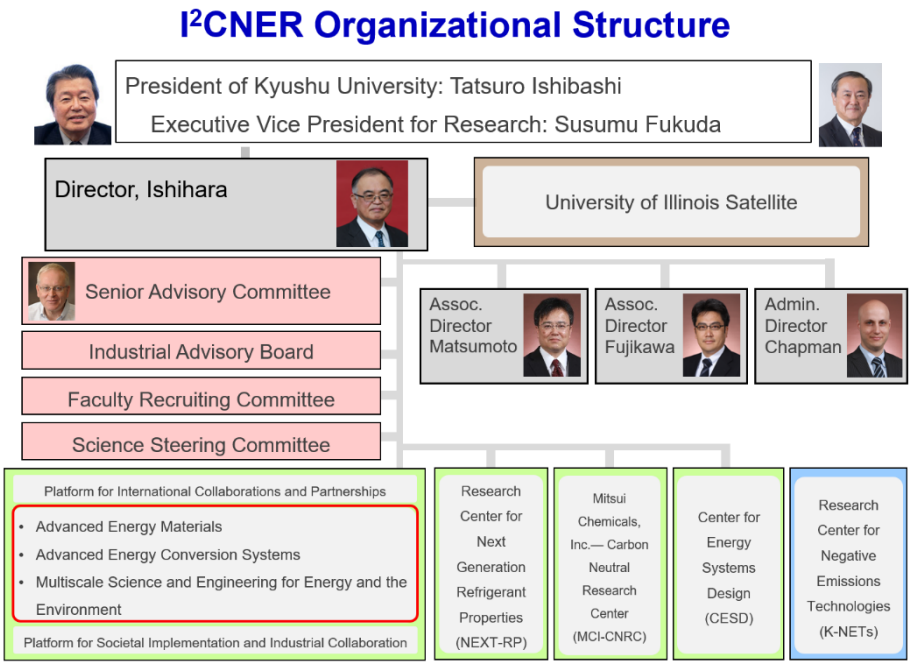


Figure 3, I²CNER Organizational Structure

5. Concluding Remarks

As part of I²CNER's current reorganization, we are drawing upon our achievements in research and management over the past 13 years to further ensure the center's sustainability. In reorganizing our team of PIs, we are placing expanded emphasis on advancing fields of chemistry, most particularly on chemical conversion of CO_2 into useful substances and on synthesis of NH_3 under mild conditions, both of which will be of increasing future importance. Expanding research in these fields is considered not only important but also essential to realizing a renewable energy-driven carbon-neutral society in the future. I²CNER will carry out its operations at the highest world scientific level, as judged and promoted via rigorous evaluations conducted by leading domestic and international experts. To maintain and elevate I²CNER's status, we are reorganizing our External Advisory Committee into a Senior Advisory Committee, which will convene once a year to provide the center advice on its plans, results and other matters. It's our strong expectation that the innovative scientific discoveries and research advances to be achieved by I²CNER will contribute significantly to the realization of the widely hoped-for carbon-neutral energy society of the future.