

World Premier International Research Center Initiative (WPI) Executive Summary (For Final Evaluation)

Host Institution	Kyushu University	Host Institution Head	Chiharu Kubo
Research Center	International Institute for Carbon- Neutral Energy Research (I ² CNER)	Center Director	Petros Sofronis

Instruction:

Based on the Center's Progress Report and Progress Plan, prepare this summary within 6 pages.

A. Progress Report of the WPI Center

I. Summary

As a result of I²CNER's current accomplishments and our projected future achievements, approximately 0.43% of the total required CO₂ reductions, and approximately 5.26% of the total 70% required reductions, respectively, can be realized by I²CNER technologies and innovations when they are applied to appropriate energy systems in Japan. Many metrics, such as I²CNER's numerous scientific discoveries and breakthroughs, its active engagement with industrial partners and transfers of innovative technology to industry, and the multitude of international universities seeking partnerships with I²CNER, demonstrate and quantify the Institute's scientific impact and international acclaim. The high-impact transformational reforms being instituted by the Kyushu University Administration that I²CNER has driven, as well as I²CNER's strategy for furthering technology-driven research, is positioning Kyushu University as a world-wide leader. The continual evolution of I²CNER's research themes is forging new partnerships with additional departments within Kyushu University, which are essential to ensure the vitality of the Institute and its ability to overcome the technological barriers preventing Japan from transitioning to a carbon neutral society. After nearly 10 years of unceasing effort, I²CNER is woven into the very fabric of Kyushu University and the overall international energy research landscape. Despite the advances made by I²CNER, many roadblocks remain, but through its partnerships with mathematics, political and social sciences, and economics, the Institute is prepared to address these complex challenges. I²CNER is already making vital contributions toward the development of a future carbon neutral society, and its plans for the future are calibrated precisely to ensure that Japan meets its energy needs while achieving its carbon reduction targets by 2050.

II. Items

1. Overall Image of Your Center

I²CNER's vision is to contribute to the creation of a carbon-neutral society (CNS) through basic research underlying 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, I²CNER aims to develop energy materials and systems which, when deployed, lead to a large reduction of greenhouse gas (GHG) emissions (70-80% by 2050 from 1990 levels). As a whole, we consider 3E+S (Energy security, Economic efficiency, Environmental protection, and Safety) as basic view points for the vision.

In pursuing our mission, we consider two major principles, efficiency increase (EI) in energy conversion and energy use, and lowering the carbon intensity (LCI) of fuel and electricity to adopt and develop future technologies. EI can be applied to existing systems, but is also achieved by replacing existing systems with new technology. LCI in electricity and fuel supply-use pathways is achieved using either renewables, nuclear, or carbon capture and storage (CCS). By prioritizing different LCI and EI technologies, renewables, and CCS, and by considering the ongoing energy transition occurring in Japan, I²CNER's vision is built on a most likely future energy system which involves a combination of renewable energy deployment and carbon capture and storage technologies, with the addition of hydrogen into the energy system, predominantly imported from overseas. To carry out its mission, I²CNER's research is driven by well-defined milestones and targets that are identified in roadmaps of the underlying technologies. Our roadmaps are developed by our Energy Analysis Division (EAD) and continuously updated through a close collaboration between the technical research clusters (divisions) and the EAD. By necessity the research teams are composed of scientists and engineers from disparate disciplines including chemistry, physics, materials science, mechanics, geoscience, biomimetics, applied math, economics, and social sciences, and the research addresses phenomena that span many decades in spatial and temporal scales. I²CNER's roadmap and research portfolio updates are also informed by the Institute's scientific exchanges with a stellar list of distinguished scientists from 25 partnering institutions across the globe, including the University of California, Berkeley; the University of Wisconsin-Madison; MIT; the National Fuel Cell Research Center at the University of California, Irvine; the State of California Air Resources Board (CARB) in the US; Imperial College, London in the UK; and the University of Göttingen in Germany.

I²CNER's mission is enhanced by its Satellite Center at the University of Illinois, which serves to advance an impressive number of collaborations across the USA, including top-tier US universities, prestigious national laboratories, and government agencies. In addition, the Illinois Satellite is enabling KU to execute its reform and revitalization program for the internationalization of its education and research missions.

In line with our energy system scenario and as a result of our current accomplishments and our projected future achievements, approximately 0.43% of the total required CO₂ reductions, and approximately 5.26% of the total 70% required reductions, respectively, can be realized by I²CNER technologies and innovations when they are applied to appropriate energy systems in Japan. Additionally, the relevance of the I²CNER research efforts and objectives to enabling the green innovation initiative of the government of Japan is demonstrated by the large number (122) of collaborative projects in which its researchers are involved with industry. A total of 53 projects resulted in technology transfer events. Since inception, I²CNER has filed for 239 patents and was granted 67 patents.

2. Advancing Research of the Highest Global Level

I²CNER's research activities are conducted within its technical divisions in partnership with the EAD, which ensures continuous assessment of the techno-economic relevance and feasibility of the research. Within the divisions, research is organized into projects, with each project having well-defined milestones on a roadmap toward a final target. Since inception, the Institute has realized 45 of the short-term and 7 of the mid-term milestones in our project roadmaps, reached 4 ultimate targets from our roadmaps, realized a NEDO Target in the Hydrogen Storage division, and established 14 international benchmarks. A selection of the Institute's breakthrough results/achievements are presented in terms of the milestones and targets of the respective project roadmaps.

Energy Analysis Division: In addition to developing division project roadmaps, the EAD carried out several technoeconomic studies on energy challenges for Japan and the impacts of I²CNER solution pathways for emission reductions. Collaborating with WPI Visiting Professor Hirose from Toyota Motor Corporation and using geographic information system analysis, the EAD investigated hydrogen station deployment, identifying optimal station locations to meet refueling demands from fuel cell vehicles. The analysis identified the optimal way to locate hydrogen stations so that the average distance between potential customers and stations is minimized. More hydrogen stations need to be located in internal city locations, especially in prefectural capitals. In addition, the EAD progressed the "people, technology and systems nexus" research for energy transitions. The link between Japan's relatively unambitious renewable energy deployment goals and progress toward a successful transition was identified. Building on these findings, an investigation of Japanese energy users identified three distinct tranches of consumer activeness toward energy system participation and reasoning to determine how a bottom-up approach might further Japan's progress. Finally, applying the participation preferences of "active" and "intermediate" households, it was found that this approach to transitions can have a marked impact on energy system transitions, security, and safety.

Molecular Photoconversion Devices: Photocatalytic hydrogen fuel production can support future transportation but is limited by the slow hydrogen evolution kinetics. To overcome this, by combining chemical synthesis, atomic resolution microscopy, and first-principles modeling, PI Ishihara's team demonstrated for the first time that dopant atoms embedded in titania can function as co-catalysts, yielding hydrogen production at rates up to ten times that of undoped systems. They also created the first direct comparison of measured activity across a spectrum of dopants to computational predictions, leading to the ability to engineer these catalysts. The most promising new photovoltaic energy generation technology is based on hybrid organic/inorganic perovskite semiconductors. PI Adachi was the first to realize that the increased number of hole traps lying above the valence band edge under solar illumination is responsible for the degradation in the devices when exposed to moisture. By controlling water and oxygen ingress, the perovskite devices exhibited reduced carrier recombination and suppressed formation of metallic lead, improving stability. The recently extrapolated 50%-lifetime is over 20,000 hrs and among the world's top reported values, thus making the device a strong contender for a successful product.

Catalytic Materials Transformations: The discoveries on biomimetic catalysis by PI Ogo are an exemplar of continuous progress toward roadmap milestones. The group first reported in *Science* a functional [NiFe]-based model of [NiFe]hydrogenase enzymes, which can heterolytically activate hydrogen to form a hydride complex. That work was followed by a successful development of a new synthetic [NiFe]-based catalyst for O₂ reduction via an O₂ adduct. This is the first example worldwide of a side-on iron (IV) peroxo complex of an O₂-tolerant hydrogenase mimic. These accomplishments underlie future developments of small molecule fuel cells that do not involve precious metal catalysts, and at the same time set the framework for small molecule activation, an area of crucial importance to energy technologies. PI Yamauchi's group developed highly selective electrocatalysts and a flow-type electrolyzer to directly produce transportable and storable alcoholic fuels with high volumetric energy density. The group also succeeded in generating power from alcoholic fuels without CO₂ emission via selective oxidation of alcohols, which is the first demonstration of CO₂-free power circulation using liquid fuels.

Thermal Science and Engineering: PI Takata's foundational studies on phase-change heat transfer in nano-confined systems, as well as surface wettability due to hydrocarbon adsorption from the atmosphere, have led to a globally-unmatched fundamental understanding of phase change heat transfer. These accomplishments are re-writing the foundational knowledge base in the field of surface science and phase change heat transfer by quantifying the environmental effects on sample wettability and degradation. PI Saha's foundational studies on solid-vapor adsorption phenomena for the rational design of high-uptake adsorbent materials, as well as surface wettability due to hydrocarbon adsorption from the atmosphere, have led to the discovery of highly porous (> 3000 2/g) activated carbons with ultra-high ethanol uptake. The focus of Prof. Miljkovic's interdisciplinary research on novel micro/nanostructures for durable and scalable enhanced phase-change heat transfer has led to transformational efficiency enhancements in energy and water applications by fundamentally manipulating heat-fluid-surface interactions across multiple length and time scales.

Specifically, the discovery of the fundamental degradation mechanisms of hydrophobic coatings as well as their design criteria for low surface tension fluids, set the global benchmark for performance, and has immense technological impact on renewable and non-renewable power generation, thermal management, building energy, distillation, and separation technologies.

Electrochemical Energy Conversion: The main shortcoming of polymer electrolyte fuel cells and Li-O₂ batteries, which are key energy devices that are now in use and targeted for the future, is the degradation of electrodes that use carbon as the catalyst support. The “polymer-wrapped carbon” approach, developed by the team of Prof. Nakashima and PI Fujigaya, of covering the carbon catalyst support in polymer electrolyte fuel cells and Li-O₂ batteries dramatically stabilizes and strengthens the function of the carbon surface. This discovery provides a radically new technique for the manufacturing of fuel cell electrodes with high performance and long lifetime. The commercialization of electrochemical devices such as the solid-oxide electrolyzers is currently limited by the performance of the air electrode, as these typically experience rapid degradation under operation. Surface composition, surface reactions, and the degradation mechanism are longstanding puzzles that must be addressed for wide-scale technology adoption. Using the advanced surface analysis technique known as Low Energy Ion Scattering and atomistic simulations, the team of PIs Kilner, Ishihara, and Staykov discovered that pristine surfaces are inactive for oxygen adsorption, and that instead, such systems must rely on active site mediated mechanisms, known as vacancies, for adsorption to occur.

CO₂ Capture and Utilization: Industrial requirements for membranes for CO₂ separation over nitrogen require that the CO₂ permeance exceed 4,000 GPU. PI Fujikawa and his group succeeded in manufacturing high CO₂ solubility free-standing polysiloxane (PoliSil)-based nanomembranes with thickness less than 50nm and CO₂ permeance greater than 40,000, which is the world’s highest. When tested under atmospheric pressure conditions, modified versions of this membrane captured CO₂ from a CO₂/N₂ mixture with a CO₂ concentration of 1000 ppm. This finding expands the relevance of our research goals beyond the capturing of CO₂ at fire-powered plants to the entirely new area of direct CO₂ capture from the air. For the separation of CO₂ from H₂ at integrated gasification combined cycle (IGCC) plants, I²CNER developed alkanolamine-containing polymeric membranes. Specifically, the 2-(2-aminoethylamino)ethanol-containing membranes developed by Prof. Taniguchi exhibited CO₂ permeance of 155 GPU with selectivity of 10 at CO₂ pressure of 1.0 MPa and 80 % relative humidity. This permeance is the best reported in the open literature, although the selectivity needs to be improved. For the electrochemical reduction of CO₂ to value-added chemicals, ~90% of the overall energy required is consumed at the anodic reaction. Prof. Kenis’ group successfully found that CO₂ reduction with glycerol oxidation as the anodic reaction is associated with lower cell potential than with conventional oxygen evolution reaction. Due to the low cell potential, I²CNER holds the benchmark for lowest overall energy requirement for CO₂ electrolysis.

Hydrogen Storage: In a collaborative effort, Prof. Akiba and PI Horita discovered that defect formation is the activation mechanism for hydrogen absorption of TiFe intermetallics by High Pressure Torsion processing. It should be noted that TiFe was abandoned as a renewable energy storage medium due to the fact that it was notoriously difficult to activate at room temperature and low pressure. The discovery already led to commercialization of the activation approach by cold rolling or mechanical milling. Pursuing this research further, Prof. Akiba obtained higher effectiveness of the high-pressure torsion (HPT) processing to activate TiFe-based alloys through the addition of Mn. In a parallel project, Prof. Akiba achieved hydrogen storage capacity of 9wt% and on-set temperature of 90°C through amide/hydride composites, which satisfied a NEDO target for on-board hydrogen storage applications.

CO₂ Storage: The coupled pore-scale flow dynamics of CO₂ and brine in geologic media represents a critical component of accurately predicting large-scale migration of injected CO₂. PI Christensen’s work in this area is the first quantitative study of liquid CO₂-water flow in both homogeneous and heterogeneous porous micromodels (inspired by real rock) at reservoir-relevant conditions, providing a detailed picture of the flow physics during the migration of the CO₂ front, the evolution of individual menisci and the growth of the dendritic structures, so called fingers. Velocity burst events, termed Haines jumps, were captured, during which the local Reynolds number was estimated to be up to O(100) in the CO₂ phase, validating the significance of inertial effects. Pore drainage events were shown to be cooperative, with a zone of influence that extends beyond tens of pores, confirming that Haines jumps are non-local phenomena. These advances imply that pore-scale models of liquid CO₂ migration must be modified to account for such dynamic flow processes, which can greatly alter macroscale migration of CO₂ in geologic reservoirs. The group of PI Tsuji developed a novel monitoring method to quantify CO₂ saturation in reservoirs, based on hydrologic and elastic characteristics of the reservoir rock. The method, which relies on a continuous and controlled seismic source, relates the CO₂ saturation with monitoring-derived seismic velocity. This monitoring system is currently deployed in an ongoing CO₂ sequestration project at a coal-fired power plant in Saskatchewan, Canada.

Hydrogen Materials Compatibility: Using state-of-the-art microstructural characterization and computational modeling, the groups of PIs Robertson (University of Wisconsin-Madison) and Sofronis (Illinois/Kyushu) discovered the link between hydrogen-enhanced plasticity and material failure. They found that the evolution of the material microstructure by hydrogen mediated plasticity in synergism with hydrogen-enhanced decohesion brings about material failure. For the first time, combining experiments and modeling, studies by the team of PIs Somerday, Kirchheim, Kubota, and Sofronis have revealed the physics governing inhibition of H₂-accelerated fatigue crack growth by ppm-levels of O₂. The significance of these development is in predicting the lifetime of metal components in a high-pressure hydrogen gas environment.

3. Feeding Research Outcomes Back into Society

The relevance of the I²CNER research efforts and objectives to enabling the green innovation initiative of the government of Japan is demonstrated by the large number (122) of collaborative projects in which its researchers are involved with industry. A total of 53 projects resulted in technology transfer. Since inception, I²CNER has filed for 239 patents and was granted 67 patents.

Representative examples of technology transfer include: i) PI Ishihara's transfer of dual carbon battery technology for energy recovery from automobiles to Ricoh Co. Ltd., ii) PI Matsumoto's discovery of optimum chemical compositions of proton-conducting electrolytes and electrodes specifically suitable for steam electrolysis has been transferred to Nippon Shokubai Co., Ltd. for the development of a steam electrolyzer operating at 600°C for mass production of hydrogen from solar energy, iii) PI Takata's group have provided the Mitsubishi Heavy Industries, Central Glass Corp with fundamental data on thermophysical and transport properties, and heat transfer characteristics of newly developed refrigerants for the design of commercial products of high temperature heat supply heat pump, iv) Prof. Akiba worked with IWATANI Co. Ltd to develop high performance hydrogen absorbing alloys suitable for stationary hydrogen storage; v) PI Yamauchi's synthetic method for the preparation of atomically well mixed Fe-Ni nanoalloys has been transferred to Daido Steel, vi) PI Fujikawa's functional nanomembrane technology for gas separation has been transferred to Nanomembrane Technology Inc. for upscale development, vii) PI Tsuji's innovative continuous CO₂ monitoring system in collaboration with the Japan Oil, Gas and Metals National Corporation (JOGMEC) has been transferred and deployed in the ongoing CO₂ sequestration project in Saskatchewan, Canada, viii) PI Sugimura's studies of diamond-like carbon (DLC) coatings in collaboration with Kitz corporation on the wear of candidate coatings in the presence of hydrogen contributed to the development of 100 MPa hydrogen flow valve, which is now in practical use in hydrogen refueling stations; ix) The results of Prof. Itaoka's investigation on the hydrogen refueling stations and supply infrastructure for Japan have been submitted to the Ministry of Economy, Trade and Industry of Japan in the form of 73-page report in February 2017; x) PI Fujigaya received funding in FY18 from KU and the Fukuoka Bank for a **startup company** called FUJicat on novel electrocatalysts.

4. Generating Fused Disciplines

The Director has at his disposal "I²CNER Competitive Funding," which is intended to foster and advance interdisciplinary research. The Director has utilized the "Competitive Funding Initiative" to accelerate the Institute's strategic efforts and integrate applied math and economics into I²CNER's research portfolio. In FY15-FY17, a total of 13 applications were selected as "seed projects," and those projects are now a new interdisciplinary research direction of "Applied Math and Economics for Energy," which is and will be an important component of I²CNER. I²CNER's annual symposia are used as platforms to explore fusion of disciplines and come up with action plans for nurturing new cross-cutting interdisciplinary research directions and guiding new faculty hires. By way of example, major outcomes of the 2016 and 2017 symposia is that they helped in the respective establishment of computational science and applied math as integral components of I²CNER's research portfolio.

I²CNER provides unique opportunities for bottom-up research, giving researchers opportunities to create and establish new research directions. In particular, young researchers have formed an important part of I²CNER. For example, Assistant Professor Perry and Associate Professor Ertekin (Illinois) were awarded internal seed funding so that they could focus on combined computational and experimental studies of oxygen exchange on electrode surfaces, which laid the ground work for the NSF/JSPS sponsored PIRE (Partnerships in International Research and Education) project "Integrated Computational Materials Engineering for Active Materials and Interfaces in Chemical Fuel Production." The PIRE program is a high-visibility joint program of the US National Science Foundation and JSPS that seeks to foster international collaborations and support the development of global citizenry.

The disparate nature of the disciplines involved in the I²CNER research fields facilitates interdisciplinary work through collaborations across division boundaries. The work by PIs Kilner, Ishihara, and Staykov that led to the understanding of the oxygen surface exchange kinetics in solid oxide cells and involved a large number of postdocs and young faculty lies at the intersection of surface science, materials science, electrochemistry, and theoretical and molecular chemistry. Similarly, the collaboration of PI Somerday (Sandia National Laboratories) with PI Staykov that involved mechanical metallurgy and density functional theory calculations led to the understanding of how oxygen adsorbed on metal surfaces can inhibit hydrogen uptake, thus mitigating hydrogen accelerated fatigue, which is a severe degradation mechanism, as another collaboration between PIs Somerday, Kirchheim, and Sofronis has demonstrated.

5. Realizing an International Research Environment

The environment at I²CNER provides a rich platform to pursue transformative research in non-traditional and highly multi-disciplinary environments, bringing together researchers from domestic and international settings to address issues critical to Japan's transition to a carbon neutral society. Since inception, there have been a vast amount of international activities that enhanced I²CNER's global visibility. I²CNER has hosted 40 international symposia; held 143 seminars in the Institute Interest Seminar Series (IISS) with 256 speakers of which 158 were non-Japanese; 157 seminars in the I²CNER Seminar Series with 161 total speakers of which 105 were non-Japanese. The Institute's researchers were responsible for organizing, co-organizing, or serving on the scientific committees for 207 international conferences, 278 international conference sessions/symposia or workshops, and 68 I²CNER international workshops. Our researchers have given 565 keynote, plenary and invited presentations in international conferences and fora. In addition, our researchers have joint publications with researchers from 573 institutions around the world (38 new institutions in FY18) and hosted 343 internationally recognized researchers for scientific interactions and exchange. Lastly, since inception, of our 91 young researchers, 21 went on to take faculty positions

at universities in Japan (excluding Kyushu University) and the world and 7 moved to industry and national laboratory positions.

As part of its commitment to fostering globally-aware researchers starting from the undergraduate level, I²CNER sends approximately 6 undergraduate students from KU to carry out research in the laboratories at the University of Illinois on an annual basis. The Institute also hosts 6 undergraduate students from the US (Illinois, Northwestern, and the University of California, Berkeley) who participate in summer research programs in I²CNER laboratories.

The I²CNER Administrative Office is in close communication with the existing KU International Student and Researchers Support Center, and offers full-time support to overseas researchers in the invitation procedures, including visa application processing and accommodations on campus. To help overseas researchers adapt smoothly into the new culture and research environment, the Administrative Office i) offers additional training and workshop opportunities, ii) introduced an English version of various application forms, guidelines, and university regulations, and iii) introduced an English version of the Web Safety Training Module, which all new I²CNER researchers are required to complete prior to conducting experiments in the laboratory. Additionally, the Administrative Office provides extensive living assistance with medical checkups, off-campus accommodations, travel arrangements for family members, and introduction to the Japanese social insurance system.

6. Making Organizational Reforms

These can be summarized as follows: i) the University of Illinois was designated as a collaborating institution on leading-edge research related to the carbon-neutral energy research, ii) Director Sofronis was given full authority for all I²CNER operations by President Kubo, iii) the cross-appointment employment system was institutionalized and applied throughout KU, iv) the Intra-university faculty transfer system was established, v) I²CNER faculty involvement with teaching is increasing, vi) KU introduced I²CNER's merit-based salary system across all units, vii) I²CNER's flexibility with travel expenses of renowned visitors from overseas was adopted across KU, viii) KU provided support in the form of administrative personnel, building infrastructure, tenured faculty positions, ix) administrative staff have a good command of English, x) KU undergraduate students were sent to the University of Illinois for research experiences, xi) Adopting I²CNER as a model concept for the internationalization of research and education, KU established the Platform of Inter/Transdisciplinary Energy Research (Q-PIT), xii) EVP Wakayama led the efforts to expand I²CNER's collaborations with other units, e.g. IMI, xiii) faculty council regulations were changed dramatically, and xiv) KU switched to the Academic Quarter (4-term) System to enable faculty cross-appointments (from KU and overseas)

7. Others

Evidence of I²CNER's international stature and relevance can be seen in its 2,022 journal publications since inception, of which, 142 were published in journals with an impact factor greater than 10. In fact, the Institute's rate of productivity continues to remain high (53, 150, 263, 318, 308, 316, 316 and 298 publications in CY2011, 12, 13, 14, 15, 16, 17, and 18 respectively). Since its inception, 386 of the Institute's publications have been cited between 10 and 19 times, 184 have been cited 20-29 times, 89 have been cited 30-39 times, 41 have been cited 40-49 times, and 128 have been cited 50 or more times.

Additionally, a delegation of 11 executives and faculty from various KU departments visited Illinois on May 8-10, 2019 to work on a joint vision statement for the future of the Kyushu-Illinois Strategic Partnership. The purpose of the KU delegation's visit is to build a strategic partnership between UIUC and KU that broadens the collaborations to other Colleges and departments. August 26, 2019 has been set as the date for the signing ceremony of the revised MOU between the two universities. KU's president, Prof. Kubo, will be visiting Illinois to sign the agreement alongside Illinois' Chancellor, Prof. Jones.

B. Progress Plan

1. Mid- to Long-term Research Objectives and Strategies Based on the Center's Research Results to Date

I²CNER has amassed a remarkable record of accomplishments over the past 10 years. It has defined and embraced the development of the science to dramatically reduce Japan's CO₂ emissions while strengthening Japan's energy security. I²CNER's many accomplishments have been built on the development and growth of extremely strong research teams at Kyushu University and at the Satellite Center at the University of Illinois at Urbana-Champaign. The capabilities of these research teams are further strengthened by a high level of engagement with other of the world's best scientists in I²CNER's areas of technical expertise. I²CNER's mission and accomplishments are directly in line with Japan's vision for a robust energy future which optimizes energy resources in concert with Japan's overarching energy vision: energy security, economic efficiency, and environmental protection without compromising safety (3E+S). I²CNER has moved its science accomplishments forward through large scale interactions with industry where I²CNER developments can be directly implanted for use in society.

From the very beginning, I²CNER recognized the need for the development of roadmaps with milestones and targets to guide its science initiatives toward the long-term 2050 CO₂ emissions reduction goal. Each division's progress is tracked by continuous assessment of research efforts toward their research milestones. This approach has guided the use of I²CNER's resource allocations which enabled a research portfolio that includes high-risk high-payoff science balanced with science with clearly identifiable directions and outcomes. *I²CNER sees that this approach, which has proven highly successful in the past, should direct the science and resource planning for the future.*

Our vision for the future will also ensure that Japan remains at the forefront of international science addressing the energy challenge and carbon emissions. Additionally, it ensures that Japan will lead

the technology transfer process to implement the best new developments to reduce carbon impact. Engaging the world's best scientists in this mission is critical to success. I²CNER has earned an international reputation for involvement of the best scientists to address an issue of major importance to all of humanity. The future I²CNER efforts will continue to develop and grow these relationships as a central, overarching element of all future activities.

To make best use of resources, I²CNER will streamline its research portfolio by reshaping its strongest research themes and phasing out those that are less impactful. Our focus continues to address basic science and engineering with the overall goal of reduced CO₂ emissions. Moving forward, the three streamlined thematic research clusters or **Thrusts** will be **Advanced Energy Materials, Advanced Energy Systems, and Energy Future and Environment**. This structure allows us to capture all of the 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. I²CNER will continue to rely on the central role of the current Energy Analysis Division that will be integrated in the Energy Future and Environment Thrust, in close cooperation with the other two Thrusts, to set near, medium, and long-term goals to meet I²CNER's mission. *This includes the continued use of Roadmaps to set research goals and assess progress.*

The Advanced Energy Materials Thrust combines the best features of the development of materials for hydrogen transport and storage, materials for selective CO₂ capture, and materials for efficient energy conversion, particularly for fuel cell and regenerative energy applications. The Advanced Energy Systems Thrust combines the efforts of multiple I²CNER researchers to develop systems approaches and capabilities for efficient energy conversion and applications. Progress in these areas requires systems-level approaches which can also make use of new materials developed in the Advanced Energy Materials Thrust. The Energy Future and 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. This Thrust enables the coordination of carbon reduction technologies, energy efficiency technologies, and guidance for social, political, and investment strategies to coordinate this transition.

The three research Thrusts will be interwoven with the **Platform for International Collaborations and Partnerships**. This platform is intended to maintain and foster I²CNER's international identity. The members of this platform, who are world experts, will continue to collaborate with I²CNER's researchers from all three Thrusts. Since the Platform for International Collaborations and Partnerships and the three Thrusts are interwoven and the Thrusts' themes overlap, this will be an effective way to promote interdisciplinary collaborations across the institute and the world. I²CNER currently has 25 partnering institutes and these collaborations will continue to grow. More specifically, the aim is to expand on the substantive collaborations that already exist with institutes such as: Illinois, MIT, Paul Scherrer Institute at ETH, Imperial College, London, Goettingen, and the University of Edinburgh. Given I²CNER's portfolio on non-engineering aspects of energy, some of these partnerships may then grow into strategic partnerships with Kyushu University to involve various departments (e.g. Economics, Law, Humanities, and Mathematics).

The three major Research Thrusts will all contribute directly to the transition of future I²CNER science advances to applicable technology transfer through a large and growing network of I²CNER industrial interactions. The **Platform for Societal Implementation and Industrial Collaboration** will ensure this high level of tech transfer. This coordination with Japan's energy and transportation industries will also have an impact on Japan's international markets, where carbon-reduction technologies are lagging behind Japan's efforts. The future I²CNER Platform for Societal Implementation and Industrial Collaboration will also provide policy guidance for science and technology investments, as well as addressing possible social acceptance and social impact issues. With its strengths in both advanced energy science and energy analysis, I²CNER will provide critical direction and support to Japan's energy transition over the next 30 years to meet the 2050 carbon reduction goals with minimal social and economic disruptions.

I²CNER has built an effective, world-leading research and technology program that exemplifies the WPI vision. Additionally, I²CNER increased diversity, provided a new culture for young scientists to thrive independently and to foster collaborations for interdisciplinary research around the world. This altogether is directed toward solving Japan's energy and carbon challenge. This is the goal around which I²CNER coalesced from the very early stages, and the goal toward which I²CNER has taken great strides over the past 10 years. The drastic reduction of carbon emissions in concert with the 3E+S remains the Grand Challenge which will require a continued, concerted, focused effort to meet that goal. Japan's leadership in this area will open new international markets and have a positive impact on international societal evolution to a more carbon-free world. *The support for this effort through I²CNER's induction into the WPI Academy is critical to fulfilling this Grand Challenge.*

2. Management System of the Research Organization

I²CNER will continue to operate under the strong leadership of Director Sofronis, who will be reporting to EVP Inoue on a monthly basis (see Section 6.1 of the Progress Report (for Final Evaluation)). Beginning in FY20, the organizational structure will be revised to the "*Three Thrust, Two Platform*" approach. I²CNER will maintain its international identity through the *Platform for International Collaborations and Partnerships*. This platform will involve the academic institutions of the international PIs, namely Illinois, MIT, Paul Scherrer Institute at ETH, Imperial College, London, Goettingen, Tsinghua, and institutions with which we developed research interactions and collaborations during the past 10 years of operation, e.g. the University of Edinburgh. *I²CNER's Platform for Societal and Industrial Implementation* will be tasked to accelerate impactful technology development and transfer to industry, and advance the engagement of I²CNER with the society at a broader institutional level.

A number of experts in applied math, social sciences, and economic systems from other units of KU will be invited to join I²CNER as WPI Professors in order to diversify the population and expertise of I²CNER, and expand its research portfolio.

3. Center's Position within the Host Institution, and Measures Taken by Host Institution to Provide Resources to the Center

I²CNER's Permanent Position within Kyushu University

Effective April 1, 2013, with the revision of the "Regulations of Kyushu University," I²CNER's position is clearly defined as a permanent Research Institute of KU without regard to the length of the WPI Program.

Kyushu University Platform for Inter/Transdisciplinary Energy Research (Q-PIT)

The Q-PIT was inaugurated on October 1, 2016 to bring together green-energy engineers with unexpected partners such as mathematicians, political scientists, social scientists, and economists to "solve the global challenges necessary to achieve a balance between emissions caused by humans and the removal of greenhouse gasses in the second half of this century," as President Kubo announced. Drawing from its international research experiences and approaches, I²CNER will play a central role in this new organization by helping to promote and advance a wide range of collaborations on energy research with other KU units. This will allow the Institute to capitalize on opportunities to broaden and enrich its energy portfolio while also helping Q-PIT advance its mission to catalyze interactions between diverse and disparate disciplines and units. I²CNER's Director Sofronis is member of the strategic committee of Q-PIT.

Securing and Filling I²CNER Tenured Faculty Positions

KU implements the "University Reform Revitalization Program" to encourage its units to actively review and reform their structure to revitalize the University. The President's Vision for tenured PIs in I²CNER is that the units compete for tenured positions through annual proposal submissions. In line with this policy and the President's Vision for tenured PIs in I²CNER, I²CNER competes for tenured positions through this program through annual proposal submissions, and will make continued efforts to secure additional tenured positions. I²CNER has been successful at winning and filling positions. By the end of FY18, I²CNER filled a total of 6 Associate and 4 Full Professor positions, and 2 tenure-track assistant professors on applied math for energy jointly with IMI.

I²CNER's Place in Kyushu University Infrastructure

The university will grant I²CNER Building II (a total floor space of 5,014 m²) free of charge to provide the I²CNER 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.

Kyushu University Administration Support of I²CNER Administrative Office

KU will support the salaries of the required staff members, thus securing the successful operation of the "*Three Thrust, Two Platform*" new I²CNER organization.