2021

Annual Report of Center for Sustainability Science

CONTENTS

Foreword

Continuing into 2021, the COVID-19 pandemic remained a threat to human health and restricted international travel. The scientific community could only move forward by relying on virtual communications to achieve its collective mission of human sustainability. The year 2021 marked the mid-term goal of realizing the agenda set for 2030, namely the 17 Sustainable Development Goals (SDGs) adopted in 2015 by the United Nations Development Programme (UNDP). In fact, the impact of COVID-19 coincidentally happens to reflect the complexity of the sustainability problem: On the surface, it is linked to SDG #3 (Good Health and Well-Being), but has also exerted a profound influence on a variety of aspects related to other SDGs. Once again, this reminds us that transdisciplinary research work is urgently needed in order to attain the sustainability of human society.

In 2021, the Center for Sustainability Science (CSS) at Academia Sinica retained its momentum in promoting relevant research projects and international networking to align with global transdisciplinary cohorts and national demands. During the past year, three major missions were successfully achieved: 1) The Sustainability Science Research Program; 2) International Programs for Networking on Sustainability Science; 3) Policy Recommendations for National Sustainability Subjects.

Following the CSS' call for proposals in sustainability science, five new projects were approved based on three main themes: 1) Societal and Economic Transformations under Global Climate Change; 2) Community Health Impacts due to Environmental Deterioration; 3) Conservation of Water Resources and Ecosystems. These new projects have immense potential for providing relevant solutions to cope with societal sustainability problems nationally or even worldwide. In addition, this report presents cutting-edge findings from five recently-finished projects related to photovoltaic technology, agricultural emissions, bio-electro carbon dioxide conversion, and societal roadmaps for systems of sustainable consumption and production.

The CSS international program experiences a significant development leap in 2021 as well. Back in 2020, this program only consisted of three goals: 1) To support the National Committee, Future Earth Taipei in participating in the global Future Earth project; 2) To manage the Integrated Research on Disaster Risk, International Centre of Excellence (IRDR ICoE) at Academia Sinica, a virtual center contracted with the International Science Council (ISC); 3) To partner with the Ministry of Science and Technology in taking part in the Belmont Forum, a partnership of funding organizations, international science councils, and regional consortia committed to the advancement of transdisciplinary science. In 2021, Academia Sinica took a major step forward by applying for and being approved as one of the Global Secretariat Hub offices, with the CSS designated to host this office as its fourth international program. This represents significant progress in strengthening collaboration with other leading countries and promoting sustainability science on a global scale.

In 2021, the CSS was also assigned the task of launching a mission to work on the policy recommendation white paper entitled "National Pathway to Net Zero 2050". An advisory committee, formed by 18 members from various research fields, was chaired by the President of Academia Sinica to brainstorm the most suitable pathway for Taiwan to attain Net Zero in time. In addition to committee meetings, a number of specialist workshops were also organized by the CSS to collect sufficient information for decision making. Since the global mission of reaching the goal of Net Zero by 2050 is urgent, this white paper is expected to be published soon.

A better future requires appropriate efforts undertaken at present. The CSS at Academia Sinica is committed to carrying out this mission and moving forward. The new development of the CSS reflects the devotion of Academia Sinica to both national and global sustainability. Your constructive feedback to this report is most welcome.

Mei-Yin Chou
Chairperson, Center for Sustainability Science
Academia Sinica

Center for Sustainability Science

Introduction

With increasing global climate threats and environmental changes, humanity is facing tremendous challenges. We not only need to find solutions for various problems and transition to a more sustainable lifestyle, but also need to ensure that their desirable effects occur within reasonable time. The Center for Sustainability Science (CSS) was established in 2012 at the Academia Sinica, Taiwan's most prestigious academic institution. The CSS hopes to encourage more Taiwanese researchers to commit to research regarding sustainability and collaborate with international researchers.

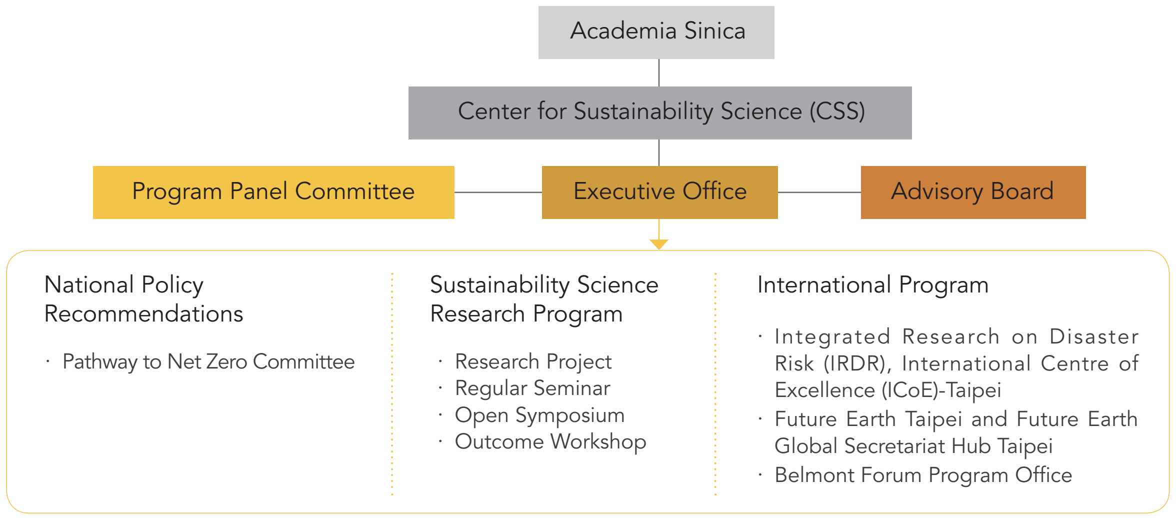
The CSS aims to promote transdisciplinary research on sustainability science that can bring together both researchers and stakeholders; this could enable scientific outcomes to potentially lead to real actions. To achieve this, the following objectives will be targeted:

(1) To plan, organize, and promote a Sustainability Science Research Program (SSRP) that is oriented towards problem-solving, transdisciplinary, and encourages stakeholder participation."

(2) To host the project office of three sustainability science-related international cooperation programs (i.e., IRDR-ICoE, Future Earth, Belmont Forum), and to act as a bridge between Taiwan's researchers and the global sustainability research community.

(3) To provide evidence-based policy recommendations regarding significant sustainability issues.

Organization and Task



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Dr. Lee-Yaw Lin
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Visiting Specialist	Dr. Liang-Yung Wei
Administration Chief of CSS Office	Dr. Shih-Yun Kuo
Science Officers of International Programs	Dr. Chia-Hsing Lee, Dr. Ying-Hsuan Lin, Dr. Yi-Chun Lin, Dr. Yu-Chun Chung, Dr. Han-Yu Chiu, Dr. Chi-Ting Peng
Program Managers	Yun-Han Chin, Chia-Hui Yen, Chia-Lun Kuo, Tzu-Hsun Chang, Ming-Shan Chiang, Yen-Yu Chou, Yen Yang

2021 Highlight

Based on our three missions, the CSS has already achieved several accomplishments in 2021. This annual report shows the key achievements of several SSRP projects (see page 30~63) and international programs (see page 10~29). As for our policy recommendation mission, here is the highlight of this task:

Launching the "Pathway to Net Zero Committee" and Deliberating Taiwan's Energy Options and Decarbonization Pathway towards the 2050 Net Zero Goal.

To combat global climate change and limit the warming to 1.5 degrees Celsius, scientists around the world have urged all countries to attempt to achieve a net-zero emission goal by 2050. President Ing-wen Tsai announced that Taiwan will be no exception and will commit to this goal. However, achieving it requires a clear pathway and a master plan to transition smoothly over the next three decades. Hence, Academia Sinica aims to provide evidence-based policy recommendations on these significant issues.

The president of Academia Sinica, James C. Liao, has invited 18 experts from various backgrounds to form a "*Pathway to Net Zero Committee*" to analyze this subject. The CSS serves as a working group to provide background information and develop cutting-edge technology to facilitate the committee's deliberation. Five committee meetings and a dozen specific-subject pre-meetings were organized in 2021. The topics of these discussions included various energy options (e.g., geothermal, bioenergy, hydrogen, energy storage, fuel cell), decarbonization options for the four main carbon emitting industries (steel, cement, petrochemical, and electronics) and sectors (transportation, residential and commercial, and agriculture and waste), innovative technologies for reducing carbon emmisions (carbon capture, utilization, and storage (CCUS), next-gen nuclear energy), and social and economic aspects. A policy recommendation report is planned to be released in 2022.

Pathway to Net Zero Committee

April 20

Launch Meeting
Subject: Launch Meeting

June 8

2nd Meeting
Subject: Decarbonizing Energy

September 2

3rd Meeting
Subject: Decarbonizing Industry

October 12

4th Meeting
Subject: Decarbonizing Other Sectors (Transportation, Residential Commercial, and Agriculture and Waste) and Carbon Sinks

December 9

5th Meeting
Subject: Innovative Technology

Policy recommendation report is expected to be released in Q3, 2022.

2021 Activities

September 10

SSRP Seminar

Project: Sensing the Noise in Urban Areas and Evaluating its Potential Health Impact (PI: Ta-Chien Chan)

December 7

SSRP Seminar

Project: Development of Viable High Performance Thermoelectric Materials for Sustainable Energy Applications (PI: Kuei-Hsien Chen)

October 20

SSRP Outcome Workshop

Project: A Research Roadmap for Transitioning to Systems of Sustainable Consumption and Production (PI: Daigee Shaw)

November 18

SSRP Outcome Workshop on Air Quality and Health

- Project: Trans-disciplinary $PM_{2.5}$ Exposure Research in Urban Areas for Health-oriented Preventive Strategies (PI: Shih-Chun Candice Lung)
- Project: Assessing Health and Economic Benefits of Air Pollution Reduction Policies in Taiwan (PI: Jing-Shiang Hwang)

October 30

Academia Sinica Online Open Campus CSS Lectures

- Parley with Carbon: N0thing to Worry (by Dr. Shih-Yun Kuo)
- Future Earth Program – Tomorrow land after next inception (by Dr. Chia-Hsing Jeffery Lee)

November 11

SSRP Seminar on Sustainable Agriculture

- Project: New Strategies for Improving Rice Nitrogen Utilization Efficiency (PI: Yi-Fang Tsay)
- Project: Challenges of Water Conservation for Rice Cropping: Straw Decomposition, Nutrient Recycling and Yields (PI: Kuo-Chen Yeh)

IRDR ICoE-Taipei

Introduction

Humans currently face increasing risks due to extreme and emerging hazards and rising socioeconomic vulnerability. Many international programs have been established to adopt a more comprehensive, forward-looking, and multi-hazard approach to reduce risk and increase resilience in preparation for long-term sustainable social adaptation and transformation. These international efforts include the Sendai Framework for Disaster Risk Reduction (SFDRR), the United Nations Office for Disaster Risk Reduction (UNDRR), and the Integrated Research on Disaster Risk International Centre of Excellence (IRDR ICoE), which was launched in collaboration with both the International Council for Science (ISC) and UNDRR.

IRDR ICoE Taipei, established in 2010, is an international platform for disaster risk reduction (DRR) dedicated to capacity building as well as transregional collaborative research. The objectives of the program have been set as understanding the characteristics of hazards, vulnerabilities, and risks, exploring effective decision-making in complex and changing risk contexts, and containing losses through knowledge-based action. Its main tasks include 1) building capacity in the Asia-Pacific region by organizing training courses or workshops (here named Advanced Institute, AI); 2) promoting collaborative research among young scientists; and 3) creating a network to connect scientists, engineers, government officials, practitioners, and stakeholders. These tasks dovetail with the action priorities of the SFDRR. ICoE-Taipei will continue to work on keeping up with and contributing to major global agendas (Figure 1).

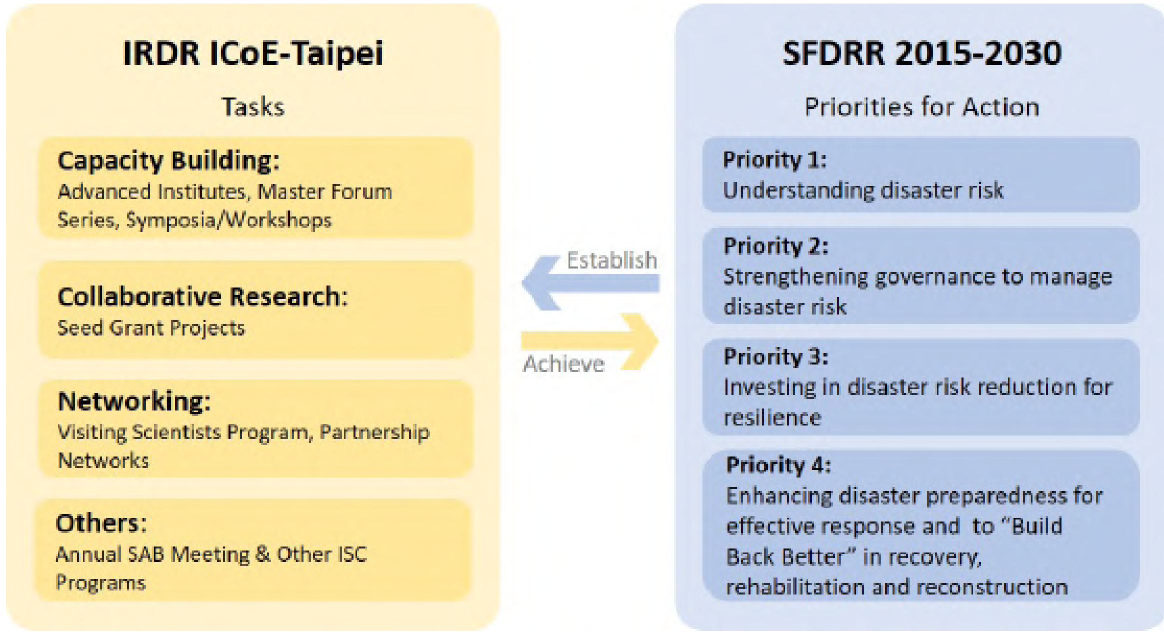


Figure 1. The tasks of IRDR ICoE-Taipei to match the priorities of SFDRR

Highlights in 2021

From 2020 to 2021, the world, affected by the COVID-19 pandemic, had the opportunity to consider many issues that have been taken for granted in the past from different perspectives. This global catastrophe has forced people to break out of their habitual thinking and accept new situations caused by the current changes in the world. Like many other research institutions, ICoE-Taipei is looking for a better way to organize events and exchange ideas and approaches with other communities. Hereafter, we describe the highlights of IRDR ICoE-Taipei for 2021.

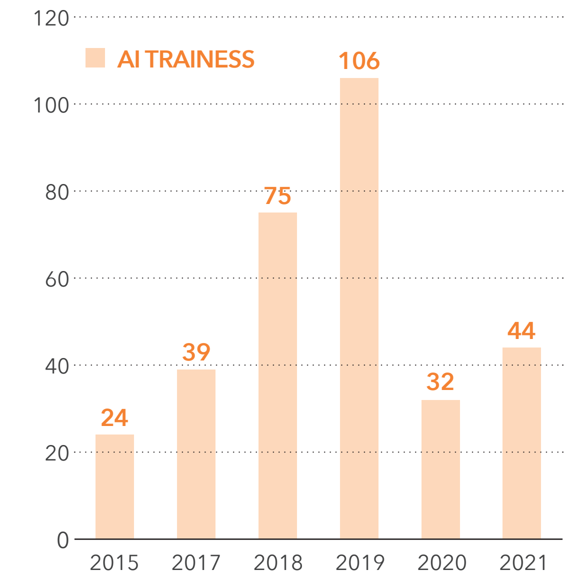


Figure 2. The Number of AI Trainees in 2015–2021

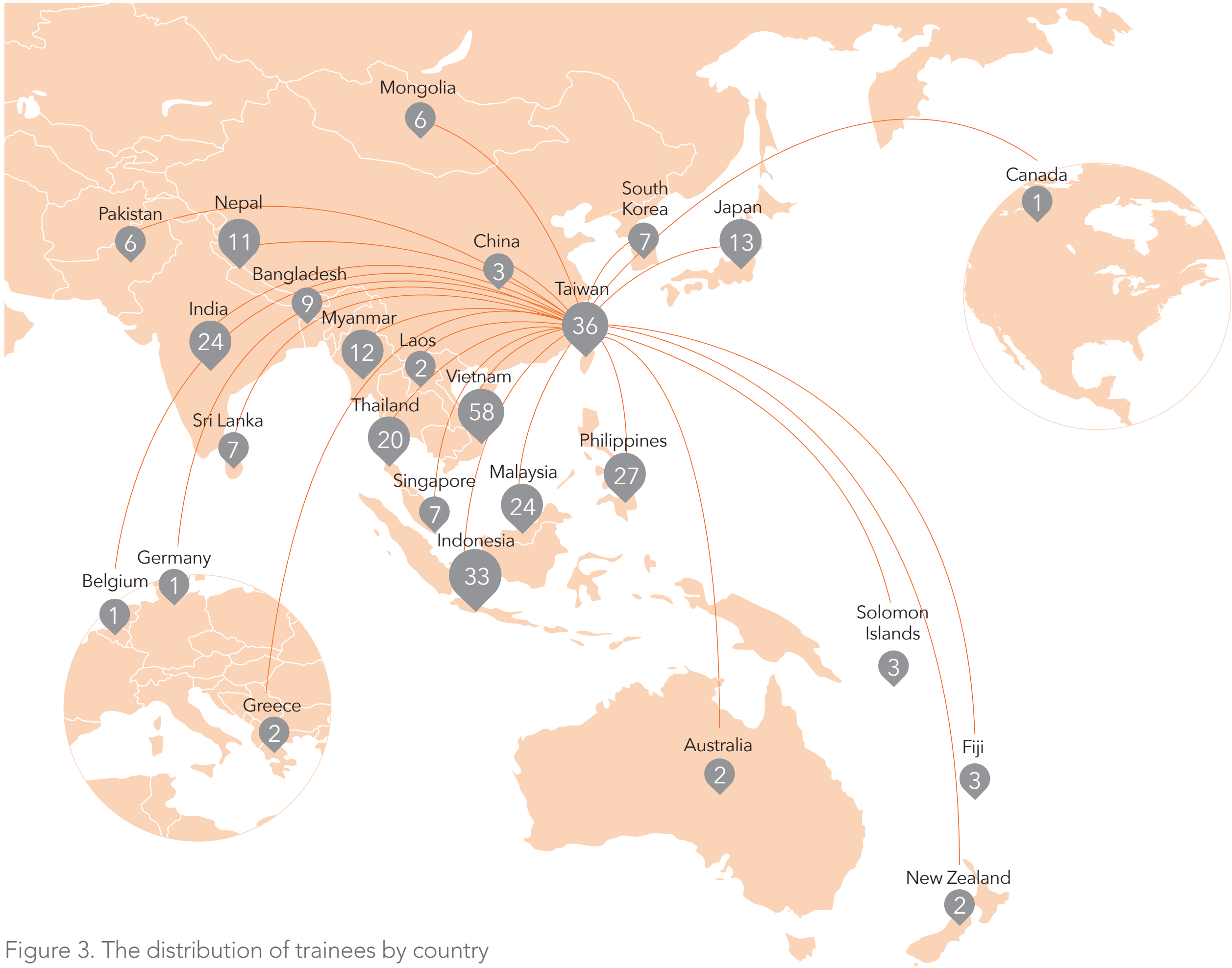


Figure 3. The distribution of trainees by country

1. Documenting the 10-year accomplishments of IRDR ICoE-Taipei

Over the past 10 years, ICoE-Taipei has followed the framework of SFDRR and the action plan proposed by the IRDR. Fifteen DRR capacity-building activities have been conducted, and numerous young scholars have been awarded seed grants in the Asia-Pacific region. Significant progress has been made in these areas. In 2021, IRDR ICoE-Taipei conducted a milestone review of its decade-long development and achievements since its establishment in 2010 and completed the "ICoE-Taipei 10-year Report." Based on the reflection and prospects in the report, IRDR ICoE-Taipei will continue to participate in and support IRDR initiatives. We will continue to work on this new IRDR research agenda. In the future, we expect that IRDR ICoE-Taipei will play a more diverse and flexible role in regional work connected with DRR and sustainable development.

2. Introducing and Developing Interdisciplinary Skills

With the increased complexity of global sustainability problems, it is crucial to promote transdisciplinary research (TDR), which can integrate many aspects and link science to action. However, not every researcher is capable of conducting TDR. ICoE-Taipei invited Professor Gabriele Bammer to give a talk—"What expertise do you need to tackle complex interdisciplinary problems?"—for the 2021 Online Master Forum. Professor Bammer describes the key aspects of expertise required to tackle complex societal and environmental problems. These include harnessing and managing diversity, synthesizing disciplinary and stakeholder knowledge, applying systems thinking, understanding and managing multiple unknowns, and appreciating the complexities of how change occurs. Bammer has developed a new discipline of integration and implementation sciences (see i2s.anu.edu.au). With the help of the online format, ICoE-Taipei successfully brought together experts from around the world. A total of 276 international participants were present at the online event, and the YouTube video reached 565 hits by the end of October 2021.

3. Building the DRR Capability of the AP region

During the second year of COVID-19, ICoE-Taipei organized two DRR online training sessions with a total of 44 trainees. The first was AI on the Health Impacts and Air Sensing in Asian Pollution (Hi-ASAP) program, which is co-organized with IGAC-MANGO. This is the third training course in a 5-year series focusing on slow-onsite air pollution. The second is the Advanced Institute on Knowledge-based Action (AI-KBA), a training session to practice and operate an online synthesis system (OSS)—an integrated system for promoting knowledge-based action. The session was co-organized with the National Research Institute for Earth Science and Disaster Prevention (NIED) (Japan) and the newly established ICoE-Japan. Both courses were designed to strengthen and integrate research capabilities across national boundaries. In addition to strengthening the participants' research and investigation capacity for disasters, the courses also focused on how to translate research outcomes and data into action or policy recommendations.

1) Organizing training course: 2021 Advanced Institute on Health Investigation and Air Sensing for Asian Pollution (AI on Hi-ASAP 2021) (12–15 and October 19, 2021)

ICoE-Taipei has been engaged in capacity-building training courses in Asia.

The Pacific region has been involved in air pollution investigation and public health assessment for several years, and the Hi-ASAP program, for example, has been endorsed as a Future Earth Asia activity. The main goal of the Hi-ASAP is to provide scientific evidence to support effective policy actions and reduce air pollution levels, particularly $PM_{2.5}$. Research groups from 13 different areas of the Asia-Pacific region participated in the Hi-ASAP. The first work timeline phase of the Hi-ASAP is from 2019 to 2023, with four steps: preparation (2019), launch (2020), intensive monitoring (2021), data analysis (2022), and publication (2023). After practicing courses in four sessions, all AI participants in 2021 were required to review and practice on their own and bring back feedback and questions in the fifth session. These data analysis methods are crucial in designing Hi-ASAP studies, and the collected data will be used as sample data files to facilitate future international comparisons.

2) Organizing training course: Advanced Institute on Knowledge-based Action (AI-KBA 2021), (December 7, 9, 14, and 16, 2021)

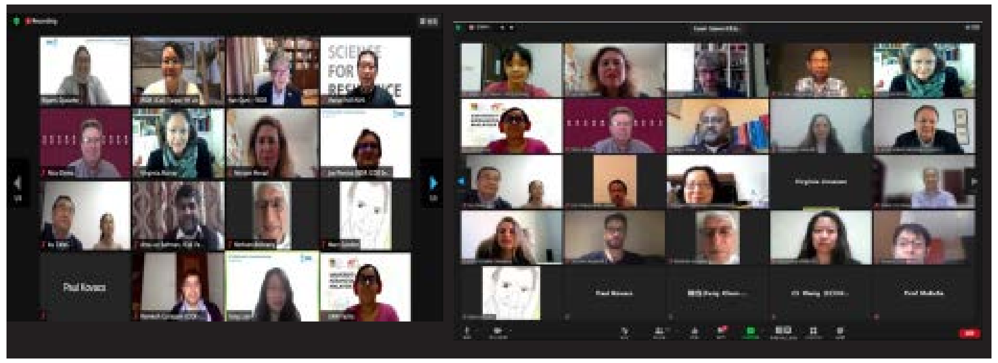
As a sequel of AI-KBA in 2017, the 2021 training workshop, co-organized by ICoE

Taipei, ICoE-Japan, NIED, the National Science and Technology Center for Disaster Reduction (NCDR), Academia Sinica, the ISC, and IRDR intended to present a systematic approach for disaster risk reduction knowledge-based actions. This approach is called online synthesis systems (OSS) for sustainability and resilience, a web-based knowledge integration system in which facilitators are designed to use on-site knowledge to solve stakeholders' problems as a means of strengthening resilience and promoting sustainable development. The 4-day workshop was held in a hybrid form, with speakers mainly from Japan teaching via online video devices; 25 trainees from Vietnam, Nepal, Sri Lanka, Indonesia, India, etc.; and ICoE staff attending online or in-person at Academia Sinica.

2021 Activities

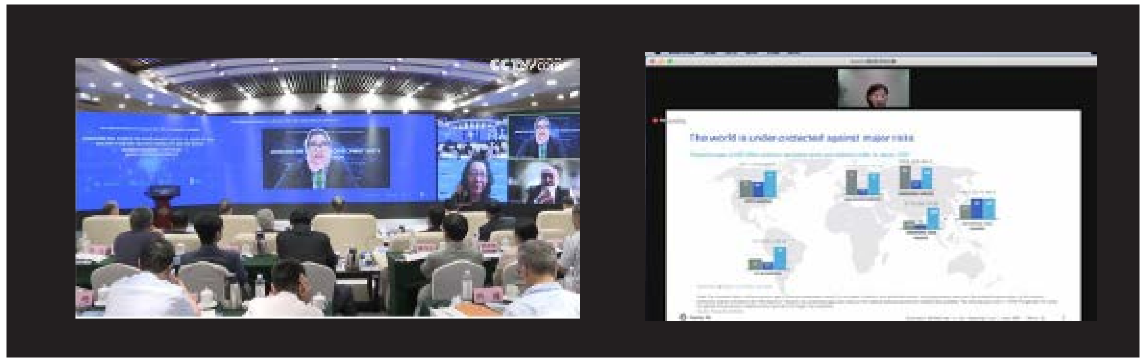
March 30

Participating in IRDR 25th SC video meeting



June 8-10

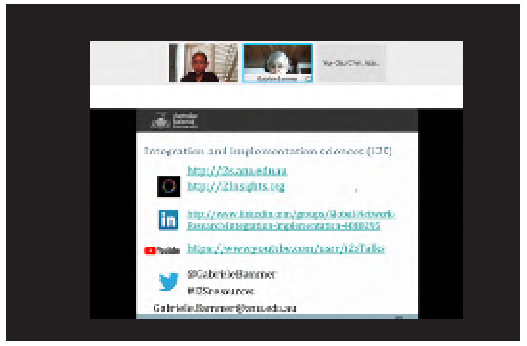
Participating in IRDR's online 10-year conference



May 19

Organizing the online Master Forum with Professor Gabriele Bammer

On May 19, the IRDR ICoE-Taipei organized a Master Forum inviting Professor Gabriele Bammer. Prof. Bammer gave a talk entitled "What expertise do you need to tackle complex interdisciplinary problems?" The online event registered 276 international participants, and the video on YouTube reached 565 hits by the end of October 2021.



June 14

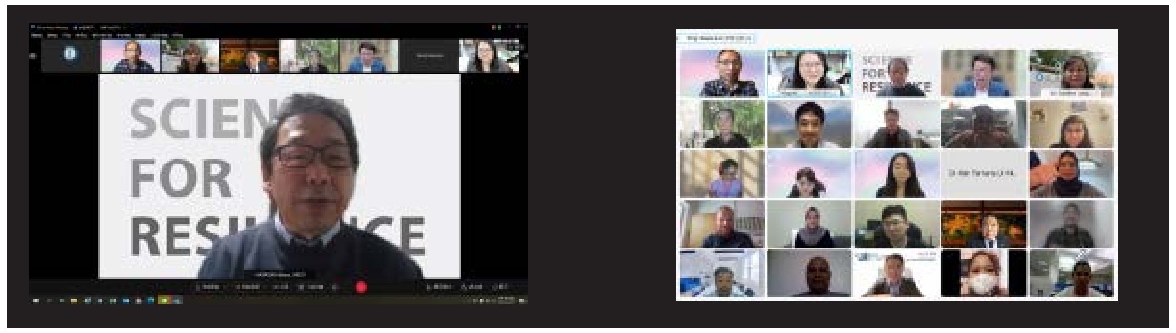
Organizing a special session at the SRI 2021 conference

The IRDR ICoE-Taipei organized a special session at the SRI 2021 conference "A Dialogue Forum: To Distill from Experiences of Stakeholders, Scalable Strategies for Disaster Risk Reduction and Societal Resilience Building." A number of scholars around the world had been invited to the conference, including Hassan Virji (USA), Stephen Dovers, and John Handmer (Australia), Haruo Hayashi (Japan), Yue-Gau Chen, and Wei-Sen Li (Taiwan). The session aimed to bring experienced stakeholders together to share their knowledge and wisdom through open discussion so that effective strategies and best practices could be exchanged and disseminated.

December 7, 9, 14, and 16

Organizing online training course: Advanced Institute on Knowledge-based Action

The AI-KBA was co-organized by ICoE-Taipei, ICoE-Japan, NIED, and the NCDR, and it was sponsored by Academia Sinica, the ISC, and IRDR. The training session targeted the issue OSS and facilitator with a total of 25 international trainees (mainly from the Asia-Pacific region).



October 12–15 and 19

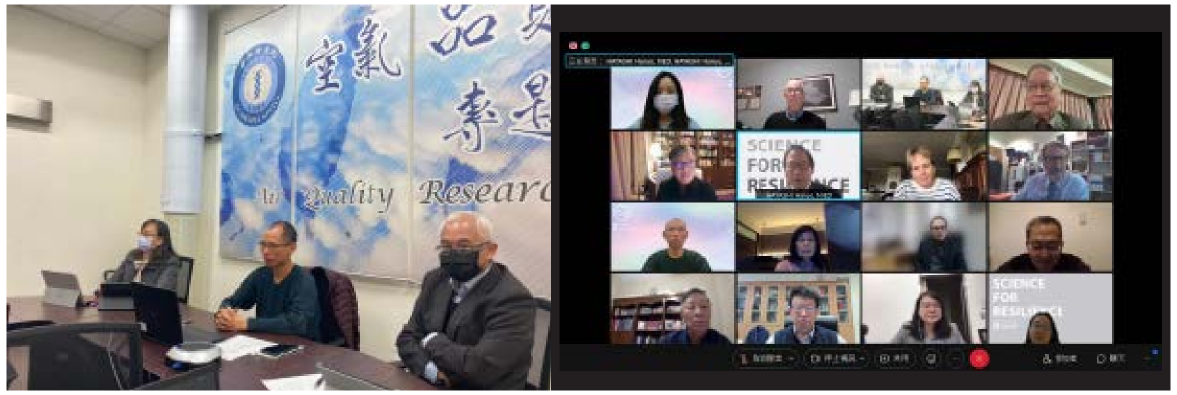
AI on Hi-ASAP 2021, Organizing training course: 2021 Advanced Institute on Health Investigation and Air Sensing for Asian Pollution

ICoE-Taipei has organized the AI on Hi-ASAP for several years. To conduct cross-country air pollution and health research, this series aims to train research groups from 13 different areas of the Asia-Pacific region.

November 25

SAB meeting, Organizing Annual Scientific Advisory Board Meeting

Owing to COVID-19, we held an online SAB meeting this year. As the most important core strategic development discussion for ICoE Taipei annually, board members reviewed the operation of ICoE-Taipei in 2020 and discussed a plan proposal for 2022. Not only did our SAB members Haruo Hayashi (Chair), James Terry, Kuo-Fong Ma, Shyh-Jiann Hwang, Tony Liu, and Wei-Sen Li join the meeting, but Chao-Han Liu (Academia Sinica), Gordon McBean, Heide Hackmann (ISC), Mathieu Denis (ISC), Qunli Han (IRDR IPO), and Ritsuko Yamazaki-Honda (NIED) as guest members also contributed their insightful opinions at the meeting. We elected Professor James Terry as our new chair and reappointed Professor Gordon McBean as our board. Several issues were covered, including ISC-ICoE Taipei agreement renewal, temporary budget management, the format of AI training courses taken in 2022, a new IRDR DRR research agenda, and an initiative of the JDR-ICoE Taipei special issue publication project.



INTERNATIONAL PROGRAM

Future Earth Taipei

Introduction

Future Earth is a global network for promoting sustainability science and driving social transformation under the auspices of the International Science Union. It is also a platform for international engagement to create opportunities to generate scientific knowledge through collaborations with society's stakeholders. Academia Sinica, representing Taiwanese academic communities, has been sending representatives to participate in the Future Earth visioning process since 2011.

In 2015, Academia Sinica supported the establishment of Future Earth Taipei as one of the National and Local Committees of Future Earth. The mission of Future Earth Taipei is: (1) to create a bridge between domestic and international scholars and stakeholders in promoting sustainability science for societal transformation, and (2) to stimulate and support domestic scholars and stakeholders in carrying out transdisciplinary, solution-oriented, and stakeholder-engaged sustainability science. The Center for Sustainability Science (CSS) has supported the operation of Future Earth Taipei since 2015.

The committee of Future Earth Taipei has 33 members (Table 1), including prominent scholars and representative stakeholders in Taiwan. By 2020, Future Earth Taipei has established 11 working groups (WGs, shown in Table 2) with currently more than 170 members. Ten WGs correspond to eight cross-disciplinary global research networks (GRNs), the emerging initiative on Sustainability in the Digital Age, and the Early-career Networks of Future Earth. The other is the Non-Governmental Organization (NGO) WG, which includes representatives from prominent NGOs promoting and engaging in sustainable development. The purpose of this WG is to further bridge the gap between scientists and NGOs. The CSS collaborates with these WGs for most domestic Future Earth Taipei events.

Moreover, in 2021 the CSS established one of the Future Earth distributed secretariats: Future Earth Global Secretariat Hub (GSH) Taipei (please see the details in Highlight in 2021 ***"Successfully Establishing Global Secretariat Hub-Taipei"***). The function of GSH Taipei is to support the operation of global Future Earth. The governance structure of Future Earth and the positions of Future Earth Taipei and Future Earth GSH Taipei are illustrated in Figure 1. Due to the establishment of GSH Taipei, all international activities held by Future Earth Taipei can now reach a wider international audience. The Governing Board of Future Earth GSH Taipei is shown in Table 3.

Table 1. The members of the 4th Future Earth Taipei Committee (November 2021- November 2023)

Ching-Cheng Chang	Wim Y.C. Chang	Yue-Gau Chen*
Chen-Tung Arthur Chen	Sophia Cheng	Ming-Dean Cheng
Yu-Chung Chiang	Eugene Chien	Chang-Hung Chou
Tyng-Ruey Chuang	Hsin-Huang Michael Hsiao	Shu-Li Huang
Ling-Ling Lee	Teng-Chiu Lin	Tze-Luen Lin
Hsing-Juh Lin	Jiun-Chuan Lin	Neng-Hui Lin
Yu-Pin Lin	Chao-Han Liu	Ching-Hua Lo
Shih-Chun Candice Lung§	Meng-Fan Luo	Wen-Harn Pan
Shao-Bo Peng	Daigee Shaw	Huey-Jen Jenny Su
Lin-Yi Tsai	Huei-Min Tsai	Jough-Tai Wang
Pao-Kuan Wang	Shin-Cheng Yeh	Po-Wen Yen

*: Chair; §: Executive Secretary

Table 2. Leadership of Future Earth Taipei working groups

Working Group	Coordinator	Advisor
Early-Career Researchers	Wan-Yu Shih	Jiun-Chuan Lin
Emergent Risks and Extreme Events	Jian-Hong Wu	Yue-Gau Chen
Finance & Economics	Ching-Cheng Chang	Daigee Shaw
Health	Shih-Chun Candice Lung	Huey-Jen Jenny Su
Natural Assets	Yu-Chung Chiang	Chang-Hung Chou
Non-Governmental Organizations	Young Ku	Eugene Chien
Ocean	Tung-Yuan Ho	Chen-Tung Arthur Chen
Systems of Sustainable Consumption and Production	Daigee Shaw	Eugene Chien
Sustainability in the Digital Age	Stephen J.H. Yang	Chao-Han Liu
Urban	Shu-Li Huang	Hsin-Huang Michael Hsiao
Water-Energy-Food Nexus	Yu-Ping Lin	Chao-Han Liu

Table 3. The Governing Board of Future Earth GSH Taipei *: Chair

Yue-Gau Chen*	Eugene Chien	Mohd Nordin Hasan
Fumiko Kasuga	Yuan-Tseh Lee	Minn-Tsong Lin
Chao-Han Liu	Antonia Loyazaga	Gordon McBean
Tzu-Ching Meng	Mark Stafford Smith	

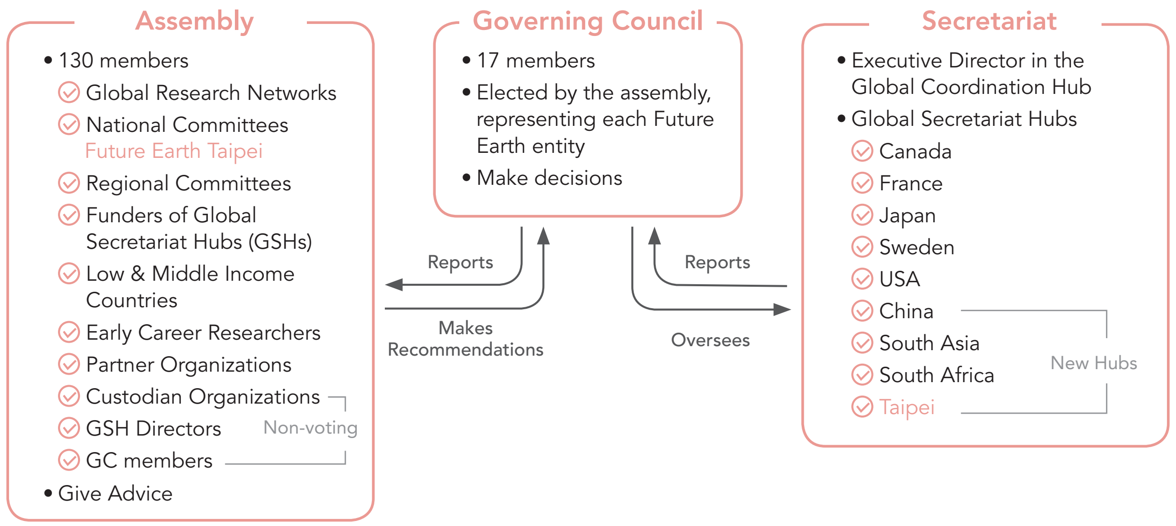


Figure 1. The governance structure of the global Future Earth organization.

Highlights in 2021

Most scientific events and meetings were held virtually in 2021 because of the COVID-19 pandemic. As shown in Figure 2, CSS organized 20 international events in collaboration with the aforementioned WGs to cover a variety of emerging issues. More than 1,400 participants from 25 countries participated in these events. The CSS also organized 54 domestic activities, reaching 1,500 scholars and stakeholders. Additionally, the CSS has connected with Taiwanese scientists and practitioners to participate in more than 43 Future Earth virtual events. This number is almost double that of 2020. The highlights of 2021 are briefly introduced in the following paragraphs:

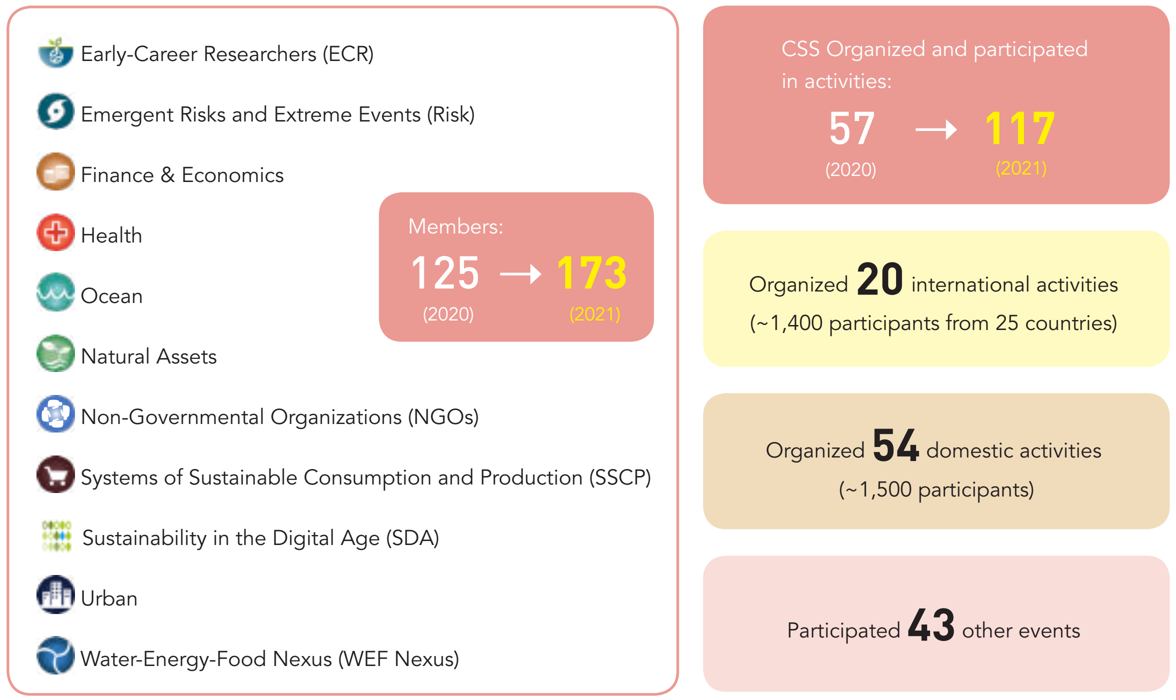


Fig. 2. Summary of the Future Earth activities which CSS organized or participated in, in 2021.

Successfully Establishing Global Secretariat Hub-Taipei

Future Earth initiated a discussion on restructuring in 2020. In 2021, Future Earth Secretariats were reorganized to include a Global Coordination Hub (GCH) and several distributed Global Secretariat Hubs (GSHs). Academia Sinica submitted a proposal to Future Earth and successfully established one of the GSHs. GSH Taipei is currently hosted by the CSS as one of the CSS's international programs. Since September 2021, GSH Taipei has supported four main functions of the secretariat: (1) strategy, advancement, and partnership; (2) research, synthesis, and policy; (3) national and regional networks and capacity building; and (4) communication. The CSS is not only contributing to Future Earth's restructuring process and is highly recognized by the international society but also has the opportunity, via GSH Taipei, to contribute more to Future Earth globally.

Launching New Event Brands to Promote Sustainability Science

Future Earth Taipei organized and participated in over 100 activities across a variety of sustainability issues in 2021. To increase the sense of ownership of Future Earth for members and to reach out to more people in the sustainability science network, we have established four event brands targeting different audiences: Master Forum in Sustainability Science, Webinar Series on Global Sustainability, Transdisciplinary Research (TDR) Training Courses, and Early-Career Researchers (ECRs) Friday Flash Talk. These events not only helped us attract attention in the international network, but also increased the credibility of Future Earth Taipei.

Strengthen International and Domestic Sustainability Science Networks

Future Earth and the Belmont Forum co-organized the first Global Sustainability Science Congress, Sustainability Research and Innovation (SRI), in June 2021. Taiwanese researchers had opportunities to exchange information and engage with international researchers at this event. Future Earth Taipei also organized the first annual symposium in 2021. We hope that through these two events, more research ideas can be inspired and exchanged, and the sustainability science network can be expanded.

Fostering Early-Career Researchers (ECRs)

The ECRs Working Group of Future Earth Taipei launched an initiative to establish a local ECR network. The working group called for applications and selected 15 fellows as the 2022 members of the ECR network. To establish a platform for ECRs to become better acquainted and share research activities/outcomes, the working group organized a talk series, comprising a series of regular virtual events, for ECRs in sustainability. This series started in May 2021 with a total of 18 talks; it included ten male and eight female ECRs from various disciplines. The participant numbers grew from 20 to 70 across the seminars and engaged people from academia, government, NGOs, and industry. As a result, these meetings have facilitated networking between ECRs and senior researchers in Taiwan and six other countries. Regular talks from the ECR have successfully drawn attention of, and recognition from international/domestic scholars and stakeholders with an interest in sustainable development. The ECRs Working Group also promoted transdisciplinary research through capacity building in collaboration with other working groups.

Major Activities

January 19

2021 Annual Symposium of Future Earth Taipei

The 1st Annual Symposium of Future Earth Taipei was successfully held, with participation from all committee and working group members. The symposium was open to the science, industry, and non-governmental communities. Eleven Future Earth Taipei working groups presented their annual plans. Several working groups organized parallel sessions on a variety of topics. The symposium discussion was fruitful and highlighted the importance of fostering young scientists to contribute to sustainability science and societal transformation.

January 23

Taiwan Urban Sustainability Research Retrospective and Prospective Workshop

Future Earth Taipei's Urban Working Group organized this brainstorming workshop and divided the sessions into four major topics: (1) accelerating transition pathways, (2) ensuring equity and inclusivity, (3) negotiating complexity and interdependency, and (4) navigating global environmental change. In this workshop, 25 invited experts had intensive discussions and identified research priorities for each topic. The Urban Working Group committed to refining the results and engaging policymakers in Taiwan. The invited experts suggested running a regional event to promote knowledge about Taiwan's urban sustainability.

February 3-5

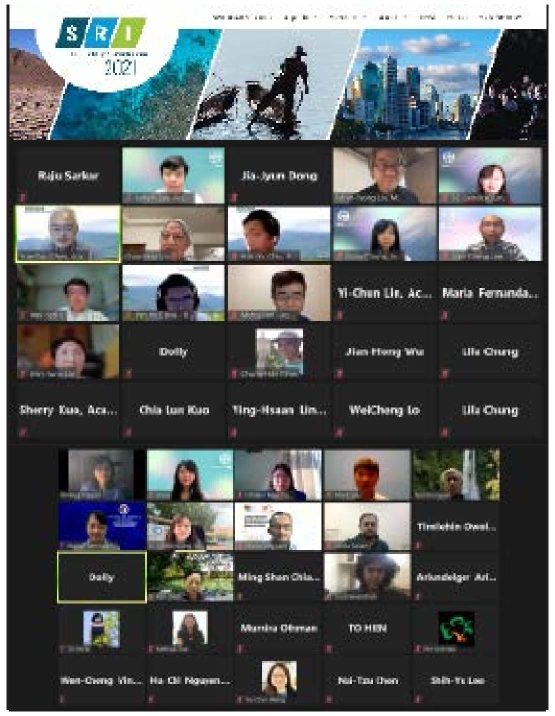
Workshop on Transdisciplinary Research on Health for ECRs

The Health and ECR Working Groups co-organized a workshop to provide participant-oriented, flexible, and interactive training courses for local young scientists interested in health-related transdisciplinary research. Approximately 25 young scientists learned and utilized the transdisciplinary (TDR) tools. The participants brainstormed to form several feasible research topics. Collaboration is likely to continue going forward. Based on this success, Future Earth Taipei planned to organize a series of transdisciplinary research workshops in various areas for either early or mid-career researchers and experts.

June 12-15

Sustainability Research & Innovation Congress (SRI) 2021

SRI 2021, held in Brisbane, was the first Future Earth-Belmont Forum co-branded global congress on sustainability science. This hybrid conference, with international sustainability leaders, experts, industry, and innovators, aimed to inspire action and promote sustainability transformation. Future Earth Taipei organized two sessions. 'Tackle Air Quality and Human Health with New Thinking and Technologies' attracted attendance from worldwide researchers, experts, and policymakers. 'Capacity and leadership in sustainability science of Taiwan – Development and Opportunities' presented Taiwan's strategies and experience in promoting sustainability science and opportunities for collaborations with international scientists.



September 29-30

1st Future Earth Assembly Meeting

Future Earth restructured its governance to form a more inclusive, accessible, transparent, and transformative organization. The first assembly meeting was held online. Representatives from all Future Earth communities attended the assembly. The most critical outcome was the new governing council elected by the assembly. Academician Chao-Han Liu and Dr. CH Jeffery Lee (representing Future Earth Taipei), Dr. Yue-Gau Chen and Dr. Tzu-Ching Meng (representing funders of Future Earth GSH Taipei), and Dr. SC Candice Lung (Ex Officio of Future Earth GSH Taipei) presented at the meeting and gave their strategic recommendations.

November 16-17

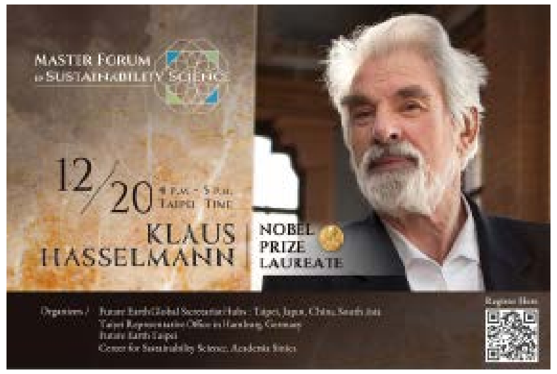
Future Earth Taipei Ocean Action Symposium

The Ocean Working Group, in partnership with Future Earth GSH Taipei, organized the 1st Future Earth Taipei Ocean Action Symposium. This hybrid event included three themed sessions on the ocean environment and climate change. The Executive Director of Future Earth Ocean Knowledge-Action Network, Dr. Linwood Pendleton, shared a pre-recorded film and interacted with local researchers, stakeholders, and policymakers to deliver the co-design concepts of ocean science. Twelve local speakers from universities, NGOs, fisheries, and government shared their insights into the future of ocean science. Future Earth Taipei called for regional collaborations to organize the next Ocean Action Symposium.

December 20

Master Forum in Sustainability Science – Klaus Hasselmann

Dr. Klaus Hasselmann, 2021 Physics Nobel laureate, is a pioneer in proving unequivocal human influence on the climate system. Over 40 years, Hasselmann's model for identifying natural phenomena related to human activity signals has greatly improved our understanding of climate variability in connection with changeable and chaotic weather. This was the first event of the series of Master Forum in Sustainability Science, co-organized by Future Earth GSH Taipei; Taipei Representative Office in Hamburg, Germany; Center for Sustainability Science, Academia Sinica; Future Earth Taipei; and Future Earth GSHs of Japan, China, and South Asia.



December 23

Webinar Series on Global Sustainability: Interdisciplinary Discussion on Risk Mitigation and Global Sustainability

Future Earth Taipei and Future Earth GSH Taipei designed a Webinar Series on Global Sustainability. The Risk Working Group organized the first event of the series on the topic 'Interdisciplinary Discussions on the Risk Mitigation and Global Sustainability'. The goal was to promote knowledge exchange and cooperation between experts and scholars from disaster-related disciplines across the world and to create the opportunity to interact with the three domestic and Canadian speakers.

Belmont Forum

Introduction

The Belmont Forum was established in 2009. In partnership with the funding organizations, the International Science Council, Science and Technology Alliance for Global Sustainability, and Future Earth, the Forum is dedicated to the advancement of transdisciplinary science. The Belmont Forum is operated through the collaboration of funders committed to understanding, mitigating, and adapting to global environmental change. The funding members, who are also members of the Forum, are authorized to mobilize resources to promote research on critical global change challenges.

The Belmont Forum aims to support multinational and transdisciplinary collaborative research, bringing together the natural sciences, social sciences, and humanities as well as stakeholders in co-creating knowledge and solutions for sustainable development that benefits society. These solution-oriented studies, called collaborative research actions (CRAs), have addressed a wide array of themes since 2012.

The Ministry of Science and Technology (MOST), Taiwan, became a Belmont Forum member in 2015. The MOST established two thematic program offices (TPO), namely the disaster risk reduction and resilience (DR^3) CRA in 2019 and systems of sustainable consumption and production (SSCP) CRA in 2021, to implement the review plan, host the review panel(s), support the participation of a neutral panel chair, and coordinate the funding of recommended projects. Currently, Taiwan participates in seven CRAs: food-water-energy nexus (Nexus); science-driven e-infrastructure innovation (SEI); climate, environment, and health (CEH); towards sustainability of soils and groundwater for society (Soils); transdisciplinary research for pathways to sustainability (Pathways); DR^3; and SSCP. Academia Sinica (AS) became a member of the Belmont Forum in 2021.

Highlights in 2021

1.Launching the SSCP CRA theme

Since 2019, MOST, Belmont Forum Program Office (BFPO), and Taiwan's SSCP-related research teams have made strong efforts to promote the SSCP CRA. In addition, MOST proactively sought support from the Belmont Forum to establish the SSCP CRA TPO in Taiwan. In 2021, the BFPO held several meetings with Belmont Forum members and funding agencies to discuss and finalize the SSCP CRA call text. The SSCP TPO was officially established in Taiwan and approved by the Belmont Forum Plenary Meeting on October 26, 2021. The four major themes of the SSCP call text are: (a) transdisciplinary research to help transition to green economies with sustainable systems of consumption and production; (b) sustainable and resilient industries and their governance systems; (c) social inequality and environmental justice; and (d) integrating new technologies, policies, and practices into everyday life.

2.Promoting collaborations between Taiwanese and international scholars

The Sustainability Research & Innovation Congress 2021 (SRI2021) is a global transdisciplinary gathering in sustainability. This annual event united global research leaders, experts, industry, and innovators to inspire action and promote sustainability transformation. The three sessions related to the Belmont Forum hosted by the BFPO on SRI2021 were as follows:

Workshop for the Belmont Forum DR^3 CRA

Five DR^3 project groups from the DR^3 CRA were invited into the workshop to report their research progress over the past year. In the Q&A session, the PIs shared the challenges they faced during research and solutions proposed with the participants.

AS-MOST event: Capacity and leadership in sustainability science of Taiwan-Development and opportunities

The AS-MOST event introduced the organizational structure of the Center for Sustainability Science of Academia Sinica, including IRDR ICoE-Taipei, Future Earth Taipei, and BFPO, and its social media (Facebook and Twitter). It also introduced the history of the MOST joining the Belmont Forum.

SSCP scoping event

The SSCP scoping event mainly discussed the contents of the SSCP CRA call draft text. The theme of the SSCP CRA involved interdisciplinary research, which increased the opportunities for collaboration between Taiwanese and international scholars.

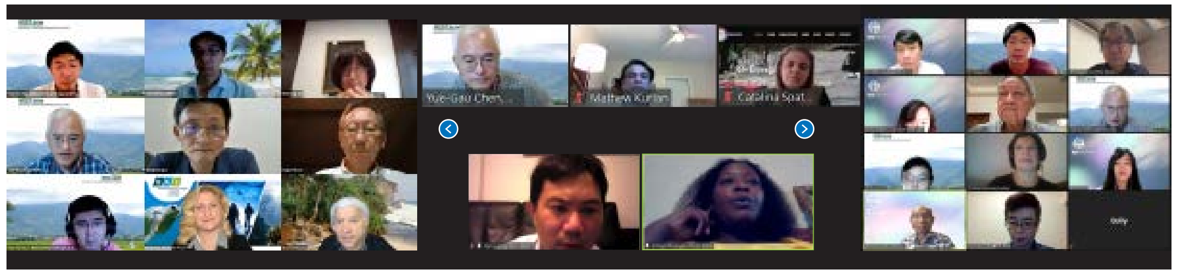


Figure 1. Three sessions hosted by Belmont Forum Program Office (BFPO) during Sustainability Research & Innovation Congress 2021 (SRI2021), June 14 – 15, 2021

2021 Activities

March 4

Belmont Forum SSCP Funders' Discussion Meeting

The participants in this meeting included 17 Belmont Forum members and 24 funding agencies. The progress of the SSCP CRA was discussed with the funders, and feedback opinions were collected.

May 11

Belmont Forum SSCP Experts Workshop

The BFPO invited Dr. Steven McGreevy from the Research Institute of Humanity and Nature (RIHN) as a represented speaker. Dr. McGreevy presented the SSCP CRA theme, outlining the development of consumer and production systems. In addition, experts' ideas and modified themes were added to the SSCP CRA call text.

June 14 – 15

The Sustainability Research & Innovation Congress 2021

At the SRI2021, the BFPO hosted three sessions related to the Belmont Forum:

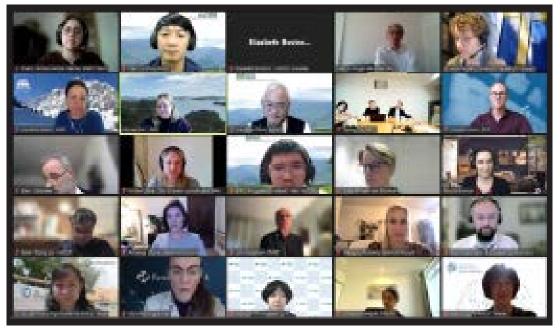
1. Workshop for the Belmont Forum DR^3 CRA
2. AS–MOST event: Capacity and leadership in sustainability science of Taiwan-Development and opportunities
3. SSCP scoping event

October 26 – 28

Belmont Forum 15th Plenary Meeting

The plenary meeting was organized by the Secretariat of the Belmont Forum. The meeting was held virtually, and more than 50 members of the Belmont Forum attended the closed session on the first day, whereas over 70 participants participated in the open session on the final day. The meeting mainly focused on the following:

1. Presentation of upcoming CRA timeline and activities
2. Discussion on any proposed CRA themes
3. Presentation of Belmont Forum portfolio analysis following 2021 reporting



November 29

Belmont Forum SSCP GPC Funders Meeting

This meeting focused on completing the preoperative procedures of the SSCP CRA. The four main discussion points were: (1) reconfirming the list of funders participating in the SSCP CRA, including members and partners; (2) re-examining the contents of the SSCP call text to see if any modification is needed; (3) checking with all funders from the SSCP TPO to ensure resources are available for the budget plan; and (4) discussing and developing a timeline for the SSCP CRA process.

Sustainability Science Research Program

Introduction

In order to provide scientific solutions to various sustainability problems that threaten humans and many creature species, Academia Sinica has promoted Sustainability Science Research Program (SSRP) that is "problem-solving-oriented, trans-disciplinary, and encourages stakeholder participation." The current focal themes include the following six research orientations:

- Energy and Decarbonization Technologies
- Food, Air, and Water Security and Safety
- Transformation towards Sustainable Society
- Health and Environmental Changes
- Earth System under Global Changes
- Disaster Prevention, Reduction and Recovery

In 2021, a total of 12 projects were in the second or third year execution. We had called for 2021 SSRP projects for five main themes and received a total of 15 applications. Eight projects have been approved and granted.

2021 Annual main themes and granted projects

Main Theme	Granted Projects
Social and Economic Impacts of Climate Change	Study on Climate Change Risk Assessment of Business
Risk Investigation and Assessment for Human Health under Environmental Changes	Trans-disciplinary $PM_{2.5}$ Exposure Research in Urban Areas for Health oriented Preventive Strategies (II)
Science and Technology for Energy and Decarbonization	• Bio-electro Opto-controlled Conversion of CO_2 • Scalable GDE-Based Flow CO_2 Electrolyzer with High Energy Efficiency and High Product Selectivity • Reduce Power Plant CO_2 Emission by Catalytic Pyrolysis Technique
Biodiversity and Sustainable Agriculture	Integrative Studies of Species Vulnerability to Climate Change
Governance and Transformation toward a Sustainable Society	• Global Risks and Local Sustainability under Climate Change in Taiwan • Governance Transition toward a Sustainable Society: The analysis and practice of the governance transition toward Taiwan 2050 Net-Zero Society

Emissions of Reactive Nitrogen Species due to Fertilization and its Impacts on Air Quality

Project Duration	2019-2021
Project Director	**Charles C.-K. Chou**: Chief Executive Officer of Air Quality Research Center and Research Fellow of the Research Center for Environmental Changes, Academia Sinica. Dr. Charles Chou received his PhD degree at the Institute of Environmental Engineering, National Central University in 1996. His major research interests include tropospheric photochemistry, physico-chemical properties of atmospheric aerosols, and urban air quality management.
Hosting Institute	Research Center for Environmental Changes, Academia Sinica
Sub-Project PI, Co-PI	Pao-Kuan Wang, RCEC, AS Horng-Yuh Guo, TARI Chuan-Yao Lin, RCEC, AS Chia-Wei Lee, EHS, NKUST Chih-Chung Chang, RCEC, AS Yi-Ying Chen, RCEC, AS Yo-Jin Shiau, BE, NTU

Research Objectives

This study aims to resolve the paradox of air pollution in the agricultural areas of Taiwan. Given the extremely high density of N fertilizers applied to agricultural soils in Taiwan, this study hypothesizes that the emission of reactive nitrogen species from fertilized soils is substantial and responsible to a certain degree for the unusually high levels of nitrate aerosols and ozone over agricultural areas. In addition, the application of N fertilizers is known to be one of the main anthropogenic sources of nitrous oxide (N_2O), the third most abundant greenhouse gas, and the quantity of N_2O emissions is still highly uncertain. Therefore, the main objectives of this project are as follows:

1. To improve understanding of the emission processes of reactive nitrogen oxides (NO, HNO_2, and HNO_3) and N_2O from N-fertilized croplands,
2. To evaluate the effect of the application of N fertilizers on air quality, and
3. To assess N_2O emissions from N-fertilized croplands in Taiwan.

Main Results to Date

To test our research hypothesis, we set up research facilities at the experimental farm of the Taiwan Agricultural Research Institute (TARI) in Wufong in 2019. This was the first investigation platform for reactive nitrogen flux in the agricultural ecosystem in Taiwan. As data analysis is ongoing, we present two major findings retrieved from the preliminary results. The first concerns the emission of N_2O from N-fertilized soils, and the other relates to the relationship between nitrous acid (HONO) flux and the concentrations of ozone (O_3) and fine particulate matter ($PM_{2.5}$) around the source area.

Over the last two decades, the human population and anthropogenic activity-induced climate change have dramatically increased. Among the climate forcing contributions accounted to respective greenhouse gases, N_2O is considered the third highest species in terms of global warming potential. In addition, N_2O plays a crucial role in stratospheric O_3 depletion. Recent findings have suggested that the amount of N_2O in the atmosphere has increased by 10% (31.0±0.5 ppb) between 1980 and 2019. In 2019, the abundance of N_2O in the troposphere (332.1±0.4 ppb) was 23% higher than pre-industrial levels (270.1±6.0 ppb). Agricultural soil is one of the main sources of N_2O, and microbial nitrification and denitrification processes are key contributors. Approximately 80% of global anthropogenic N_2O is attributed to the agricultural sector, especially to the application of N fertilizers. Therefore, controlling N_2O emissions from agricultural soil is considered a top priority for mitigating global warming.

During the 2019–2020 period, two field experiments were conducted to investigate the emissions of N species from fertilized soils in a Chinese cabbage *(Brassica rapa chinensis)* farm. The average N_2O emission fluxes for the two crop campaigns were 6.5±15.4 and 3.6±12.4 $nmolm^{-2}s^{-1}$, respectively. The coefficients of variation for the 2019 and 2020 campaigns were 237.7% and 351.7%, respectively, indicating the high variability of N_2O flux during the crop season. Our results demonstrate that N fertilization triggered N_2O flux, with emission peaks consistently occurring within 3–4 days after fertilizer application. As shown in Figure 1, the dynamics of N_2O flux were determined by two episodes. The first box plot represents the fertilization episode of intense agricultural practices comprising basal N fertilizer, tillage, and topdress application. Conversely, post-fertilization episodes did not involve any agricultural practices. The mean N_2O fluxes for the fertilization periods were 7.9±15.6 and 4.7±15.3 $nmolm^{-2}s^{-1}$, respectively, whereas those for the post-fertilization periods were 1.8 and 2.8 times lower for the 2019 and 2020 campaigns, respectively. Significant variations

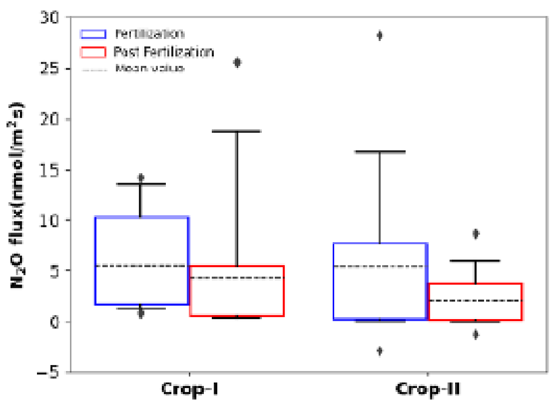


Figure 1. Variations in the daily means of N_2O flux during the fertilization and post-fertilization periods of two Chinese cabbage cropping experiments, Crop-I and Crop-II, conducted in this study. The lower and upper bounds of each box indicate 25th and 75th percentile. Whiskers are drawn at 5th and 95th percentile, and the symbols denote outliers.

in N_2O flux were found to be closely related to soil temperature and moisture. It was revealed that N_2O emissions was triggered at ~28 °C, with an optimum zone between 40% and 60% water-filled pore space (WFPS).

Soil nitrifier and denitrifier abundance was investigated during the 2020 cropping season. During the cropping season, more soil nitrifying microbes than denitrifying microbes were observed. However, it was found that fertilizer application increased the abundance of denitrifiers. This change can be attributed to the development of favorable conditions through fertilization and irrigation and/or rain that provides organic carbon and nutrients to soils and minimizes the oxygen availability favoring the growth of denitrifiers, the anaerobic or facultative anaerobic chemoheterotrophs. These processes may also depend on the composition of denitrifiers. Figure 2 illustrates that *Massilia sp.*, *Bradyrhizobium sp.*, and *Luteimonas sp.* were the three most abundant denitrifiers during vegetable cultivation. Most *Bradyrhizobium sp.* are denitrifiers; however, many of them have incomplete denitrification pathways with N_2O end products. Similar studies have shown that *Luteimonas sp.* can only reduce nitrite to N_2O, but not N_2. As the N_2O fluxes seemed to correlate with the denitrifying abundance, both *Bradyrhizobium sp.* and *Luteimonas sp.* may be responsible for the N_2O emissions observed at the site.

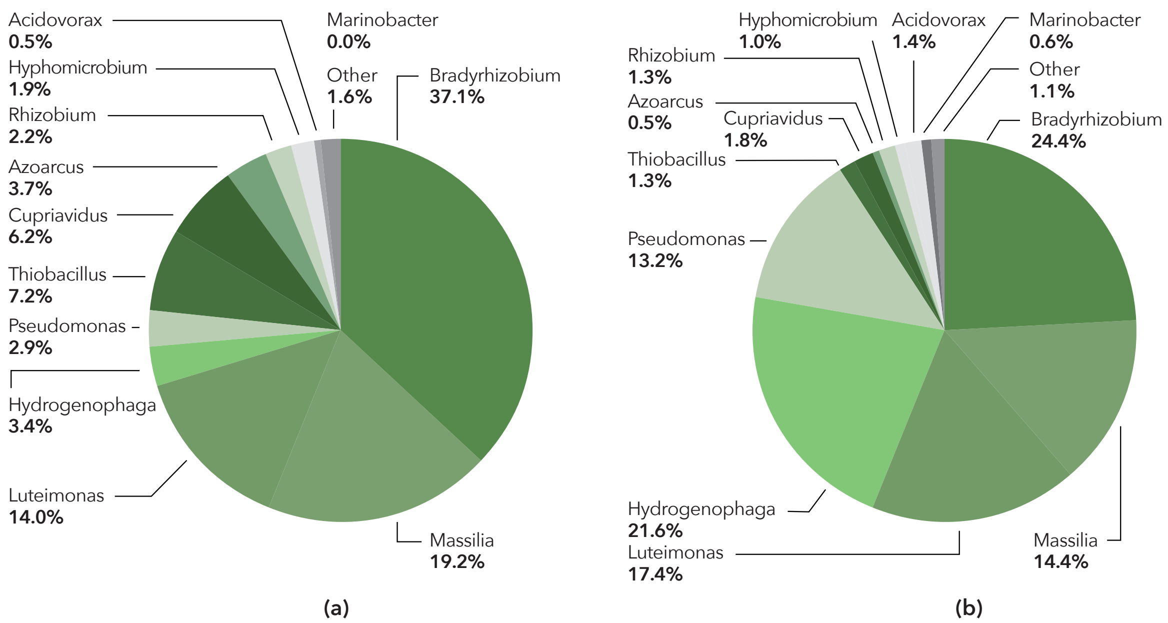


Figure 2. Composition of denitrifiers in the cropping soils of a Chinese cabbage farm for fertilization (a) and post-fertilization (b) periods.

Figure 3 shows the cumulative fluxes for the 2019 (2.64 kg·ha^{-1}) and 2020 (2.87 kg·ha^{-1}) campaigns, which were estimated by integrating the daily mean flux over each cultivation period. Compared to the amount of N fertilizer applied to the soils, the N_2O emission factor values derived from N fertilizers were 2.5% and 2.3%, respectively, for the two cases. Although the N_2O emission factors derived from our experimental results are higher than the IPCC Tier 1 default value of 1%, they are still within the range, with uncertainty bounds of 0.3%–3% for agricultural fields. The uncertainty in N_2O emissions can be attributed to several factors, including measurement techniques, fertilization type, crop diversity, tillage, and environmental conditions. Despite being a significant contributor to global warming, the large variations in N_2O flux derived from agricultural practices have not yet been clearly elucidated, making it difficult to determine countermeasures for different areas and propose suitable strategies for alleviating N_2O emissions. The results of this study demonstrate that the influence of N_2O emitted from agroecosystems can be significantly stronger than that reflected in the current emission inventory.

In addition to N_2O emissions, we investigated HONO emission and its potential influence on ambient air quality. In the 2019 cropping season, we demonstrated that HONO and NO emissions occurred with the application of N fertilizers. Subsequently, a detailed experimental study was conducted in 2020. Along with the HONO flux from the soils, ambient concentrations of nitrogen oxides (NO_x, i.e., NO and N_2O), O_3, and $PM_{2.5}$, were measured at a mobile station located ~100 m downwind of the cropping field. During the study period, the air quality was generally good, which was consistent with previous reports of air quality in summer.

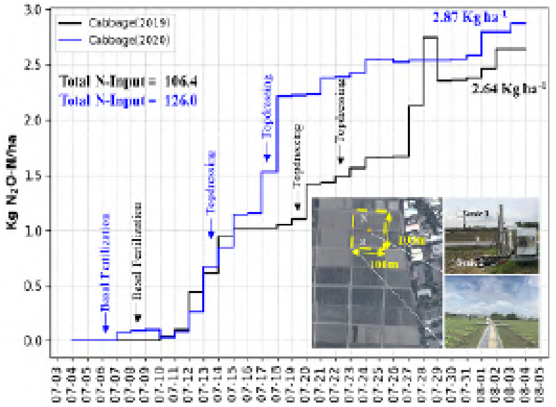


Figure 3. The cumulative N_2O flux for Chinese cabbage crop experiments in 2019 and 2020. The cumulative fluxes were estimated by integrating the daily mean flux over cultivation periods.

However, elevated levels of O_3 and $PM_{2.5}$ were observed during the daytime. Figure 4(a) shows the correlation between the ambient mixing ratio of O_3 and the HONO flux over the farmland during the daytime (09:00–16:00). A significant linear correlation was observed (R^2=0.40). Accordingly, it was inferred that the photolysis of HONO emitted from farmland released OH radicals into the atmosphere and, in turn, increased local O_3 production. Moreover, our investigation found that O_3 production was dominated by volatile organic compounds (VOCs). Given this, it was deduced that the increase in OH radicals could have enhanced the formation of organic peroxy radicals and, in turn, O_3 production. The elevated abundance of O_3 in the air provides feedback on higher levels of OH radicals through photolysis and reaction with water molecules, particularly in humid environments. Both O_3 and OH are precursors of secondary aerosols (a major portion of $PM_{2.5}$), which are mostly products of the photooxidation or ozonolysis of NO_x, SO_2, and VOCs. This inference is evidenced by the linear correlation (R^2=0.57) between $PM_{2.5}$ and O_3 during the daytime (09:00–16:00), as shown in Figure 4(b). The results showed that all the major particulate species,

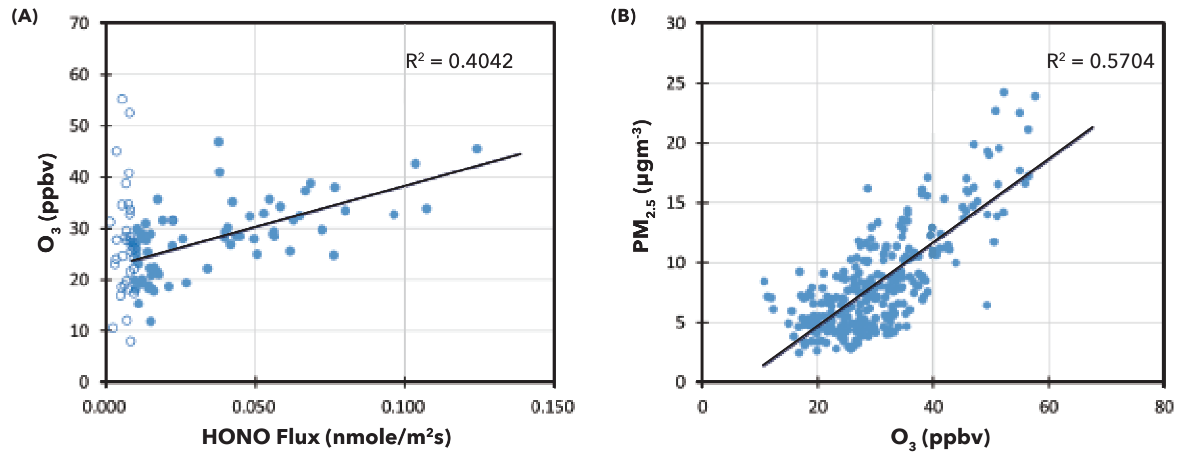


Figure 4. The response of ambient O_3 mixing ratio to the HONO flux over the farm (a) and the correlation between the ambient levels of $PM_{2.5}$ and O_3 (b) during the daytime (09:00–16:00 LT). The data with HONO flux < 0.01 nmol/m^{2}s are excluded from the regression due to high uncertainties.

including organic matter, sulfate, nitrate, and ammonium, exhibited a positive linear correlation with O_3.

In summary, the results of this study show substantial N_2O and HONO emissions from fertilized vegetable farmlands. We revealed that the N_2O emission factor of N fertilization was higher than the IPCC default parameter by a factor of 2.5, which highlights the role of agriculture in mitigating climate change. In addition, it was inferred that the OH radicals released from HONO photolysis were responsible for the increased O_3 production and, in turn, increased O_3 and $PM_{2.5}$ in the ambient air. Accordingly, we argue that further studies should be designed and conducted to optimize N fertilizer application, which should be considered one of the essential components in the sustainable development of agriculture.

Future Research Plan

This project is now in the data analysis phase. However, our preliminary results have demonstrated that the application of N fertilizers can play a major role in climate change and local air pollution. Thus, a plan for the reasonable usage of N fertilizers is needed to achieve sustainable agriculture. Therefore, in the next phase of this study, experiments should be designed to test various agricultural practices and, accordingly, to determine the best practices in terms of balance between food production and environmental sustainability.

Publications

1. Jhang S. R., Chen, Y. Y., Shiau, Y. J., Lee, C. W., Chen, W. N., Chang, C. C., Chiang, C. F., Guo, H. Y., Wang, P. K., & **Chou, C. C. K.** (2022). Denitrifiers and nitrous oxide emissions from a subtropical vegetable cropland. *ACS Earth and Space Chemistry*, Article ASAP, https://doi.org/10.1021/acsearthspacechem.2c00106

2. Jhang, S. R., Chen, Y. Y., & **Chou, C. C. K.** (2021, December 13-17). *Measurement of nitrous oxide emissions from a typical vegetable cropland* [Conference presentation]. The American Geophysical Union (AGU) Fall Meeting, New Orleans, USA.

High Efficiency Solar Fuels: from Material Development to Device Integration

Project Duration	2019-2021
Project Director	**Yu-Tai Tao** Yu-Tai Tao is a Distinguished Research Fellow of IoC. His research centers around organic materials chemistry and surface chemistry, including electroluminescent materials and devices, organic field effect transistor materials and devices, organic memory devices, and solar cells.
Hosting Institute	Institute of Chemistry
Sub-Project PI, Co-PI	Ming-Hsi Chiang, Chun-Hong Kuo, IoC, AS; Shi-Sheng Sun, Kuo-Chuan Ho, DCE, NTU. Yu-Tai Tao, IoC, AS; Yian Tai, NTUST; Chen-Hsiung Hung, IoC, AS; Wen-Feng Liaw, DC, NTHU.

Research Objectives

The search for sustainable energy sources is a global and particularly urgent issue for Taiwan. Solar energy is an everlasting and free energy source that can be harvested efficiently. Hydrogen is also a good and clean energy source that can be generated from water via water splitting reactions. The objective of this project is to develop a pioneering technology for high-efficiency solar-energy-driven hydrogen generation. This project has two parts: 1) hydrogen generation systems, particularly water splitting, and 2) solar cell development. Solar energy is used to directly drive the photocatalytic water splitting process or is stored in a solar cell and used later to drive the electrocatalytic water splitting system for hydrogen generation. Therefore, four sub-projects are involved: (i) optimization of materials for total water splitting, (ii) light-harvesting antenna and solar cell units, (iii) electrode material development and interface engineering, and (iv) device assembly and optimization.

Main Results to Date

A target of the hydrogen generation system is the development of a platform that carries multiple catalytic sites for total water splitting. $FeCo_2S_4$ nanospheres were successfully deposited onto Ni foam as an electrode material for the water oxidation reaction. Thus, under alkaline conditions, a Tafel slope of 180 mV dec^{-1} and an overpotential of 418 mV at a current density of 100 mA/cm^2 were observed for $FeCo_2S_4$. The electrical conductivity of the electrode material was improved to 0.379 Ω compared to 1.176 Ω of the Ni foam. The electrocatalytic performance of $FeCo_2S_4$ remains steady for up to 12 h. Another system is the Fe2 catalyst, which is capable of performing the hydrogen evolution reaction (HER) under illumination. A turn-over-frequency (TOF) of 20 h^{-1} was achieved at λ=560 nm, while no HER activity was observed in the absence of illumination. The photocatalytic efficiency of this Fe2 catalyst surpasses the best result reported in the literature, which utilized an Rh2 catalyst. The mechanisms of hydrogen formation and cleavage reactions in this system are well understood via various spectroscopic methods and isotope labeling experiments. Based on the hard–soft chemistry engineering concept, our team also developed another system of $FeCoNi_2Al_{0.2}$/Ni/NF bifunctional catalysts by incorporating a p-block Al dopant into $FeCoNi_2$ nanoparticles grown on a Ni-nanopolyhedral array architecture of Ni foam (Figure 1) for neutral/alkaline water splitting reactions. Various tools, including CV, XPS, HRTEM, SEM, pXRD, EXAFS, XANES, L-edge XAS, UPS, and AEM, were used to delineate the working mechanism. The electrical conductivity and electronic structure of $FeCoNi_2Al_{0.2}$/Ni/NF were optimized for electrocatalytic water dissociation and HER/OER kinetics. As an alkaline electrolyzer, $FeCoNi_2Al_{0.2}$/Ni/NF electrode-pair device requires a voltage of 1.73 V and 1.97 V to achieve the current density of 100 and 500 mA/cm^2 in 1 M NaOH aqueous solution at 25 °C, respectively. The bifunctional $FeCoNi_2Al_{0.2}$/Ni/NF electrodes applied as the cathode and anode in an anion exchange membrane (AEM) device achieved a current density of 2.0 A/cm^2 at a cell voltage of 1.82 V in a 1 M KOH aqueous solution at 80 °C. The possible reasons for the very high HER/OER activity of the $FeCoNi_2Al_{0.2}$/Ni/NF electrode were elucidated via material and kinetic studies. For large-scale AEM devices, the zero-gap single-cell $FeCoNi_2Al_{0.2}$/Ni/NF//$FeCoNi_2Al_{0.2}$/Ni/NF AEM device (5×5 cm^2) in a 1 M KOH aqueous solution at 60 °C achieved a current density of 1 A/cm^2 at a cell voltage of 2.04 V with an energy efficiency 74.9% and hydrogen generation rate of 12.74 L/h, which is more superior compared to the current density of 1.004 A/cm^2 at a cell voltage of 10.09 V (energy efficiency 75.73% and hydrogen generation rate 63.93 L/h) for the stack-cell AEM device ((5×5 cm^2)×5).

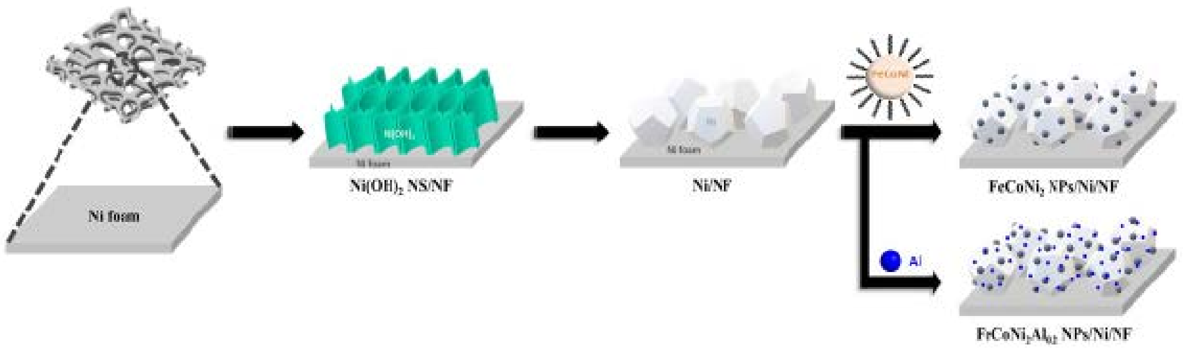


Figure 1. Preparation of aluminum-doped bifunctional $FeCoNi_2Al_{0.2}$/Ni/NF electrode

In terms of solar cell preparation, high-performance and durable organic solar cells, including dye-sensitized solar cells (DSSCs) and perovskite solar cells (PSCs), required a major effort, and integration of the solar cell system with the H_2-generation system discussed above was the ultimate goal. In this study, novel organic light-harvesting dyes with a D-A-π-A framework integrated with a fluorenyl moiety were designed and synthesized for use in DSSCs. The champion device displayed an efficiency of 8.68% under one sun and 26.81% under indoor 6000 lux illumination. The device efficiency remained nearly constant after continuous light soaking (100 mW/cm^2) for 600 h. Additionally, double-anchored triphenylamine (TPA)-tethered phenothiazine-based dyes have been synthesized as metal-free organic sensitizers for DSSCs. The insertion of TPA as an N-substituent successfully provided a good cascade charge-transfer channel, fast dye regeneration, and suppression of dye aggregation. The optimal DSSC exhibited a good conversion efficiency of up to 10.47% under one sun. Under indoor light illumination, DSSCs achieved cell efficiencies of 21.2%, 19.5%, and 16.8% at 1000, 600, and 300 lux, respectively. With respect to PSCs, novel HTMs based on carbohelicene and cyclopentadithiophene cores with low synthetic material costs were developed and used to fabricate efficient and stable PSCs. The champion devices delivered excellent device efficiencies of more than 19%, outperforming the control device fabricated with the benchmark spiro-OMeTAD material. Furthermore, PSCs exhibited good ambient stability by retaining 80–90% of the initial performance after aging with 50–60% relative humidity over 500 h at 25 °C. Finally, a novel polymer ionic liquid system (POEI-TEMPO) in conjunction with a Pt counter electrode (PtCE) with a silver mirror coating (PtCE/SMC) was applied in a quasi-solid-state DSSC. With N719 as the light-harvesting dye, the system exhibited a high efficiency of 9.83% under one sun irradiation and 25.99% under indoor conditions at 6000 lux. Overall, an excellent long-term stability of up to 90% of the initial efficiency was achieved after over 2000 h of testing.

To integrate the solar cells with the catalytic water splitting system for effective OER and HER reactions, several challenges should be overcome. First, for the water splitting reaction, a minimum theoretical potential value of 1.23 V, or in practice, a potential >1.8 V was generally needed. However, a single solar cell can usually only provide a V_{oc} of ~1.0 V. To provide the driving voltage needed for water splitting, a tandem cell with two or more single cells stacked together is a plausible solution. For a tandem solar cell, a key factor in the performance of the device is the characteristics of the interconnecting layer (ICL), which acts as a separator between the top and bottom cells and simultaneously acts as a recombination layer for electron/hole charges from the top/bottom cells to recombine there. A proper ICL should be thin, transparent, easy to fabricate, and could simultaneously attract both the electron/hole to its top/bottom surfaces. With these criteria in mind, our team focused on the design and fabrication of a solution-processed ICL using ZnO with Janus surfaces. A thin ZnO layer passivated on the top and bottom surfaces with two self-assembled monolayers with opposite electrical properties was prepared. This ZnO ICL has the advantages of high transparency, simplicity, and cost-effectiveness. A multi-tandem organic solar cell with four single devices using this ICL (Figure 2) provided a high open-circuit voltage of 2.3 V, which is sufficient for the water splitting reaction. A unique fabrication process involving doping the ZnO precursor solution with water and self-assembled monolayer passivation on the ZnO surface was developed for using as an ICL in perovskite solar cells.

Another challenge is the fabrication of large-area solar cells to provide adequate current for practical applications. The conventional spin-coating process involving an anti-solvent for fabricating PSCs is not applicable to large-area production. Our team used the solution-shearing (SS) process and successfully prepared 10×10 cm^2 multilayer films required in fabricating PSC devices (Figure 3). All layers were sheared by using greener solvents at relatively lower temperatures (~35 °C – 100 °C). These films, which were of similar quality to those obtained from spin-coating, achieved similar or better efficiency (PCE 20.30%) than spin-coated films (PCE 17.60%). This protocol offers a simple and cost-effective method for large-scale preparation and module fabrication.

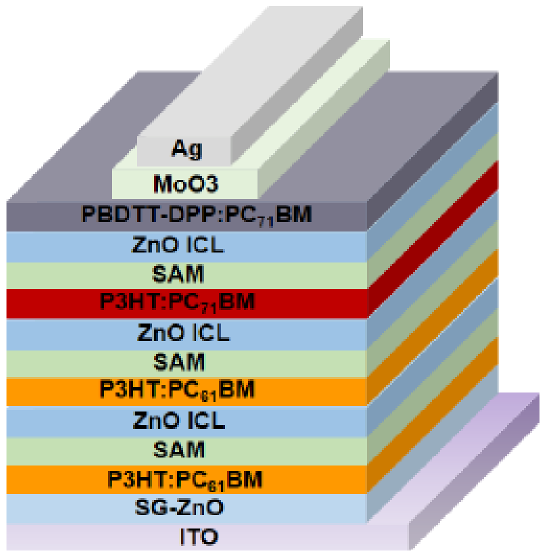


Figure 2. Tandem organic solar cell with four single devices

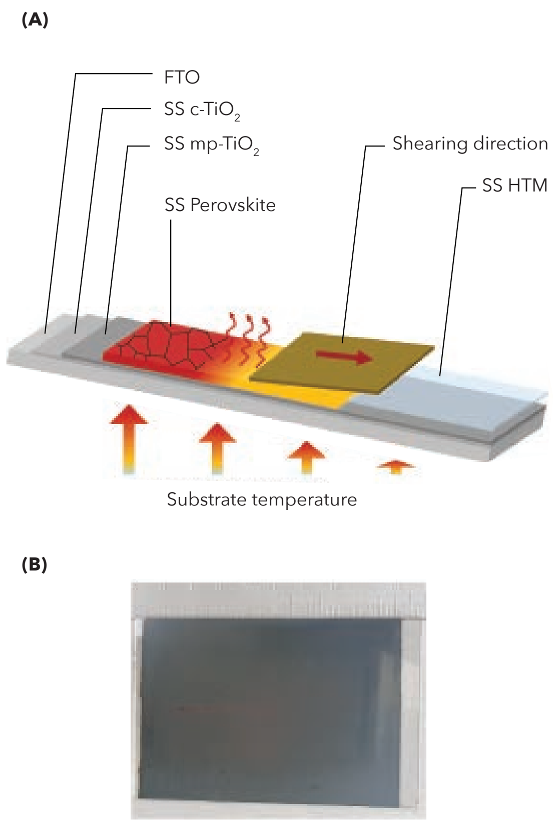


Figure 3. (a) SS scheme of all layers used in perovskite solar cells; (b) perovskite film prepared in a 10 ×10 cm^2 area.

Future Research Plan

In the next phase, the results of this project will be integrated to produce a high-efficiency solar-energy-driven hydrogen generation system. Additionally, sensitizers will be used to harvest light and initiate photocatalytic water splitting reactions for hydrogen generation. These efforts will include the optimization of materials for total water splitting, development of light-harvesting antennas and solar cell units, electrode materials and interface engineering, and device assembly and optimization. Therefore, we will continue the development of sensitizers and hole-transporting materials to increase the efficiency of DSSCs and the stability of perovskite solar cells.

Large-area perovskite tandem cells fabricated by solution shearing will be used to provide the voltage and current required for practical water splitting. An important challenge is to extend the lifetime of materials used in oxygen evolution anodes. Currently, the connection of the entire cell to a 3 V solar panel is sufficient to drive the water splitting reaction. Furthermore, the efficiency of scaled-up devices is being pursued.

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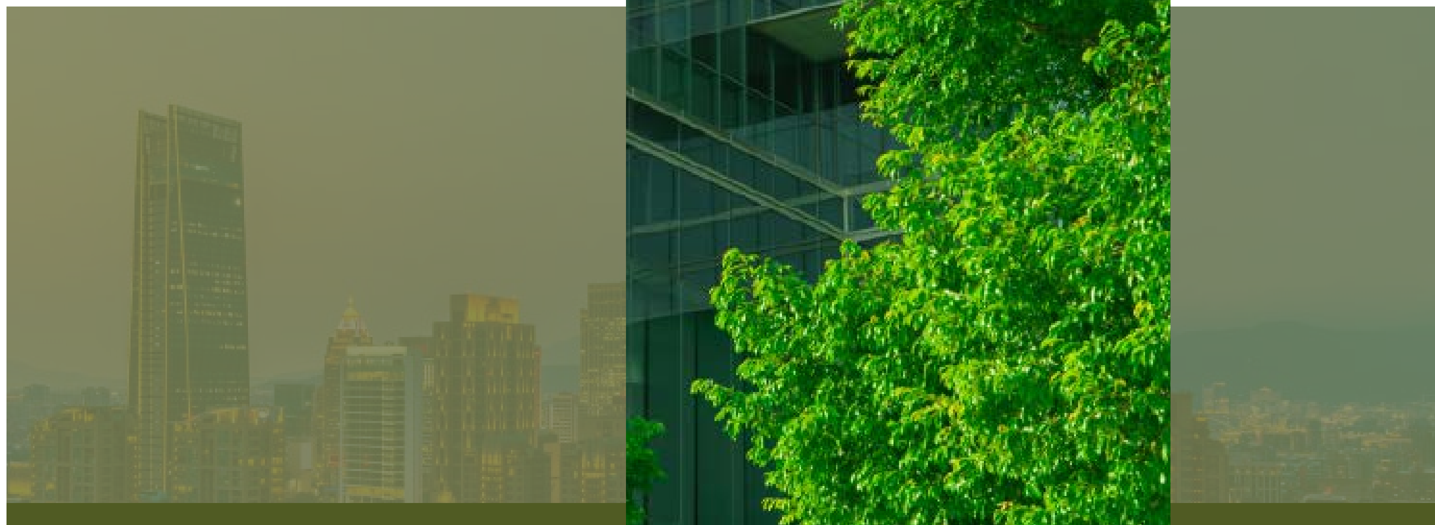
A Research Roadmap for Transitioning to Systems of Sustainable Consumption and Production

Project Duration	2019-2020
Project Director	**Daigee Shaw**, Research Fellow at the Institute of Economics, Academia Sinica in Taipei, specialized in economic analysis and policy analysis related to natural resources, environmental quality, and sustainability issues.
Hosting Institute	Institute of Economics, Academia Sinica
Sub-Project PI, Co-PI	Ming-Feng Hung, Tamkang University Chiung-Ting Chang, National Sun Yat-sen University Thung-Hong Lin, Academia Sinica

Research Objectives

The objectives of the project were twofold. First, by applying participatory methods, we identified research issues in the interdisciplinary research field of systems of sustainable consumption and production (SSCP) in Taiwan. We evaluated the importance of further research and practice issues and formulated a five-year research roadmap for the SSCP using a systemic approach, for Taiwan's scientific community. The roadmap for this research further implies policy preferences. Second, we reviewed and evaluated the research capacity of SSCP in Taiwan.



Main Results to Date

I. An SSCP Research Roadmap for Taiwan

Research on sustainable systems of consumption and production is imperative to meet the current and critical societal needs to ensure the survival of human beings facing sustainability disasters, such as climate change, biodiversity loss, extinction, and atmospheric aerosol loading (Rockström et al., 2009; Steffen et al., 2015). The transdisciplinary approach that comprehensively engages natural, engineering, and social scientists with various stakeholders to inform of SSCP policies and practices is required for SSCP research. We organized this research roadmap around three key themes. Figure 1 shows a schematic of the roadmap.

1. Political-Economic Systems

Markets and democracy—the two major social systems derived from liberalism—and continued innovations in science and technology, have created a growth focused society and helped engender sustainability disasters. First, future generations are unable to participate in today's markets and express their willingness to preserve current resources. Second, democracy dominated by the current population is not concerned with future sustainability disasters.

1.1 Sustainable Politics

Recently, SSCP scholars formulated a new research agenda for facilitating social change beyond consumerism. However, political obstacles have limited its diffusion. In current dominant political ideology, increases in consumption and investment share are celebrated as important societal goals. The public sector was accused of paying 'lip service' to the SSCP policy agenda. Why do politicians govern in the short term, rather than prudently invest in society's long-term welfare? Researchers in sustainable development have been encouraged to introduce alternative institutional options on ways to resolve the deficit in our representative democracy, to establish institutional arrangements for intergenerational justice to achieve sustainability.

1.1.1 What are the current best practices, and how can they be more widely diffused and promoted?

1.1.2 How to improve the representation of future interests? Electoral law reform and future-oriented institutions.

1.2 Sustainable Economics

Since the market is one of the two major social systems that have helped cause sustainability disasters, we need to ask what structural challenges and changes in the current economic system could create opportunities to advance sustainability in general, and sustainable consumption and production. First, we need to develop alternative macroeconomic models for economy-wide policies and alternative welfare assessment metrics for society and the economy to advance sustainability. What economy-wide policies exist that work to shift the economy toward more sustainable forms? What policies have worked in these specific contexts? Second, we need to study existing policy tools and business models, such as green public procurement, labeling, green taxation, and the sharing economy, which can encourage sustainable lifestyles. Simultaneously, new policy tools and business models can be developed.

1.2.1 Sustainable Macroeconomics: development of alternative macroeconomic models

1.2.2 Sustainable Microeconomics:
- Policy tools (e.g., green public procurement, labeling, and taxation)
- Sharing economy, access economy, and other new business models; their advantages and disadvantages; and their governance systems
- Behavioral sciences, including psychology, social neuroscience, ethology, cognitive science, sociology, economics, public health, anthropology, demography,and political science
- Rebound effects and unintended consequences of behavioral changes

2. Consumer Culture, Lifestyles, and Social Equality

2.1 Developing normative concepts for transitioning toward sustainability

Deepened understanding of people's motivations and diversity of values, and access to sustainable lifestyle choices are required to change behavior. We suggest further study on a specific behavior, the context in which the behavior occurs, the intended target of the intervention, and barriers (and benefits) associated with the behavior. Thus, basic science research for SSCP needs to reflect and compare different value-based concepts and paradigms concerning societal transformation toward

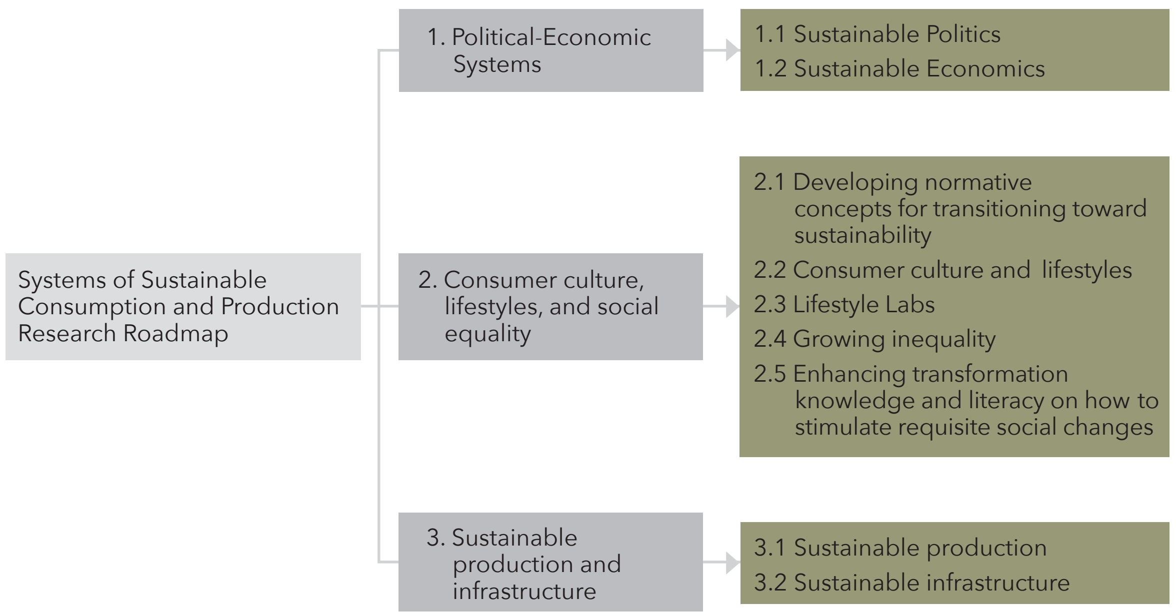


Figure 1. Diagram of the SSCP research roadmap

individual and societal well-being in different sociocultural and economic contexts.

2.1.1 Interventions to stimulate change in the collective mind-set

2.1.2 Deepening understanding of people's motives and values

2.2 Consumer culture and lifestyles

Sustainable consumer behavior attempts to satisfy present needs while simultaneously limiting social and environmental impacts. Moreover, understanding sustainable consumer behavior is central to any paradigm shift in how society approaches environmental problems. Understanding sustainable consumer behavior facilitators should be of interest to policymakers and academics for many reasons. Hence, it is necessary to develop a transdisciplinary understanding of the spectrum of social change processes (both structural and strategic) that undermines prevailing consumerist lifestyles and contributes to sustainable transformations. Deployment of this understanding provides a basis for generating practical knowledge for policymakers, social entrepreneurs, change agents, and others engaged in transformative social change. Since SSCP is a commonly shared objective in humanity's interests, it highlights the need for a just transition to sustainable living as equitable as possible.

2.2.1 Describing the current state of lifestyles and consumerism, including sustainable consumption, sufficiency, yuppie, hipster, and consumer capitalism

2.2.2 Novel lifestyle practices and new systems of sustainable consumption and production

2.2.3 What role might growth stimulation of public goods, services, and amenities play in improving the well-being of underserved populations by means other than increased consumerism

2.3 Lifestyle Labs

Sustainable consumption is closely related to daily lifestyle patterns. Given that culture-driven processes cannot be studied and observed if removed from the real-life environment, an appropriate methodology to study the impact of culture on sustainable development is essential. Therefore, based on models and experiences in the EU, particularly Germany, this research aims to develop a sustainable living lab as a methodological approach that will help integrate sustainability into daily lifestyle patterns by analyzing household behavior and devising specific recommendations and policy tools for change.

2.3.1 Analysis of why policies on sustainable lifestyles are lacking

2.3.2 The potential of open (social) innovation processes

2.3.3 Learning from stakeholder involvement initiatives

2.3.4 Integrating new technologies, policies, and practices into everyday life

2.3.5 Income, changing work-life balance, and environmental impact

2.3.6 Segmentation research to customize policy tools and packages

2.4 Growing inequality

Social inequality and environmental injustice are not new phenomena, including those between urban and rural regions and the global North and South, which have not been adequately addressed in SSCP research. This working group investigates the main determinants of growing inequality in sustainability transitions toward SSCP. Consumption and production patterns, and unequal distribution of benefits and burdens through basic services provision (including unequal access to services such as public healthcare and education) is a growing concern.

2.4.1 Reducing social inequality and environmental injustice in consumption-production systems

2.5 Enhancing transformation knowledge and literacy on how to stimulate requisite social changes

Education and communication are crucial for sustainable living. The integration of SSCP courses at all education levels is an essential tool for understanding and developing strategies for sustainable lifestyles. Curricula on existing educational programs (from primary schools to universities) should integrate sustainability knowledge. Governments must facilitate sustainable living courses in all informal learning institutions. Community-based learning is vital for sustainable development and active citizenship. It enables people to take direct, practical actions to fight all forms of environmental challenges in a rapidly changing world.

2.5.1 Education and communication

2.5.2 Knowledge about the framing of sustainable actions

2.5.3 Exploration of bridging social capital within communities

3. Sustainable Production and Infrastructure

3.1 Sustainable production

The combination of extracting exhaustible and renewable natural resources and manufacturing industries has enormous environmental impact and has created mountains of low-quality and disposable products. Transdisciplinary research can help identify critical problems in industries and redesign industries' governance systems and various provisioning systems to be more sustainable and resilient, and with enhanced adaptive capacities. Value chain management is a crucial provisioning system. Although many studies and practices in sustainable value chain management exist, more in-depth and innovative policies and practices, such as extending producer responsibility to upstream natural resource extraction and depletion, and downstream manufacturing pollution emissions and wastes after consumption, are needed.

3.1.1 How can industries' governance systems, such as food and agriculture, information and communication technology (ICT), and petrochemicals, be improved to be sustainable and resilient?

3.1.2 Sustainable global value chains

Transboundary policies that help make global value chains sustainable (reduce environmental and social impacts)

- Extended producer responsibility from upstream natural resource extraction and depletion to downstream manufacturing pollution emissions and waste after consumption
- Right to Repair

3.2 Sustainable infrastructure

It is essential to know how to make infrastructures such as transportation and build stocks for SSCP. This requires the spatial planning and management of regions, cities, and natural resources, utilizing new technologies such as ICT to make regions and cities smart, resilient, and sustainable.

3.2.1 Spatial planning and management

3.2.2 Smart cities

3.2.3 Resilient cities

3.2.4 Daily transportation patterns of individuals, households, and industries

3.2.5 Sustainable building stock (housing and business)

II. Research Capacity of SSCP in Taiwan

To review and evaluate the research capacity of SSCPs in Taiwan, we established a database of SSCP researchers and practitioners. This database is an Excel file that provides a facility to search for SSCPs experts by name, institution, industry sector, and field of expertise. The database contained 262 records. Academics, policymakers, stakeholders, and the public can find researchers and practitioners in different fields working on several subjects related to SSCP. All materials were obtained using Google Scholar, Network of Asian Social Science Data Archives (NASSDA), Ministry of Science and Technology Statistics Database, and Airiti Library via 12 keywords: circular economy, consumerism, sustainable production, sustainable consumption, global value chain, sustainable city, sustainable agriculture, share economy, green economy, lock-in effect, green supply chain, and sustainable value chain management.

We then analyzed the network of 262 individuals, as shown in Figure 2. Using Figure 2, we depicted the relationships among those persons and analyzed the social structures, scales of those research topics, and the structural holes that needed further attention.

We found Taiwan's SSCP research capacity can contribute objective, independent, and high-quality research and practices on SSCP issues.

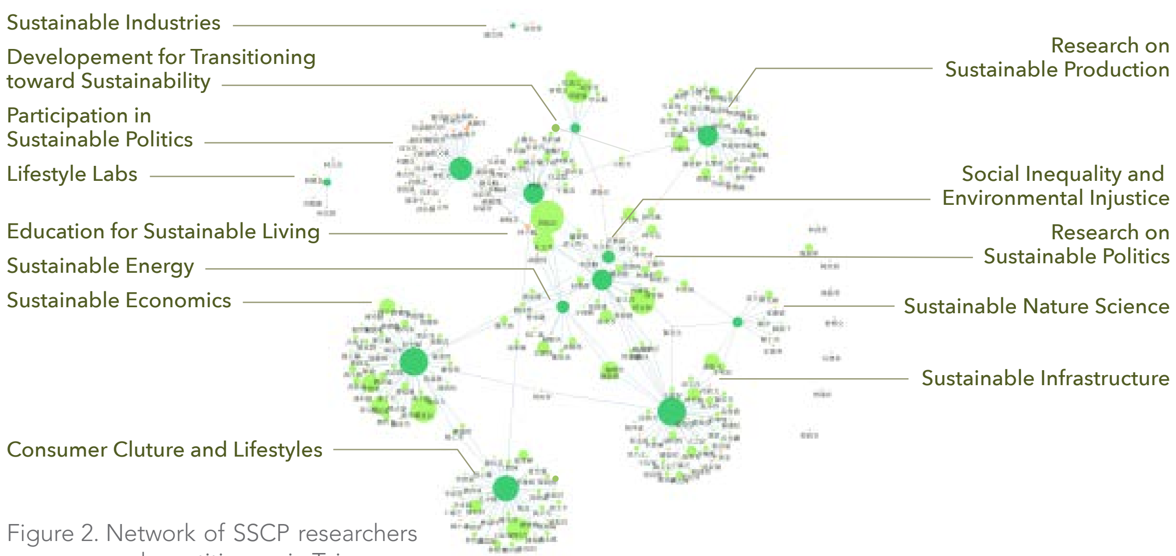


Figure 2. Network of SSCP researchers and practitioners in Taiwan

Future Research Plan

This roadmap for research can be used by funding agencies such as Academia Sinica and the Ministry of Science and Technology, to allocate national research and development budgets. Researchers and practitioners can use this roadmap to choose a research agenda that can meet the needs of society and contribute to the sustainability of humanity. This roadmap further indicates preferences for sustainable development policies.

Publications

蕭代基、張瓊婷、陳蓉怡、林宗弘、洪鳴丰，2021，「達成永續發展目標所需的消費與生產系統轉型」，台灣經濟論衡，19（3），頁 66-72。

Development of New-Generation Photovoltaics for Indoor and Healthcare Applications

Research Objectives

Develop new-generation sustainable photovoltaics for indoor and healthcare applications

Project Duration	2020
Project Director	**Juen-Kai Wang**, Research Fellow Dr. Wang received his Ph.D. in Applied Physics from Harvard University in 1992. Dr. Wang joined Center for Condensed Matter Sciences, National Taiwan University in 1994 and was jointly appointed by Institute of Atomic and Molecular Sciences, Academia Sinica in 2003. His current research interests are surface-enhanced Raman spectroscopy, nanometer-scale optical spectroscopy, and steady-state and time-resolved optical spectroscopy. Dr. Wang was granted Executive Yuan Award for Outstanding Contributions in Science and Technology in 2009 and Nano-Tech Award bestowed by Ministry of Economic Affairs in 2010. **Chin-Ti Chen**, Research Fellow Dr. Chen received his Ph.D. in Chemistry from University of Illinois at Urbana-Champaign in 1992. Dr. Chen worked as postdoctoral research fellow at California Institute of Technology from 1992 to 1995. In year 1995, Dr. Chen joined the Institute of Chemistry, Academia Sinica as an assistant research fellow, was promoted to associate research fellow in 2000, and research fellow in 2003. His research interests include organic materials for optoelectronics applications, including perovskite solar cells (PVSCs), organic photovoltaics (OPVs), and organic light-emitting diodes (OLEDs). He has served Journal of the Chinese Chemical Society as associate editor since 2014, and Sustainable Chemical Science and Technology Program of TIGP, Academia Sinica as coordinator since 2013.
Hosting Institute	Institute of Atomic and Molecular Sciences
Sub-Project PI, Co-PI	**Subproject 1:** Chin-Ti Chen, IC-AS (PI); Leeyih Wang, CCMS-NTU (Co-PI); Ping-Tsung Huang, CH-FJU (Co-PI) **Subproject 2:** Ken-Tsung Wong, CH-NTU (PI); Chih-Wei Chu, RCAS-AS (Co-PI); Hao-Wu Lin, MSE-NTHU (Co-PI) **Subproject 3:** Li-Chyong Lin, CCMS-NTU (PI); Cheng-Ying Chen, ME-MCUT (Co-PI) **Subproject 4:** Juen-Kai Wang, CCMS-NTU/IAMS-AS (PI); Chun-Wei Pao, RCAS-AS (Co-PI) **Subproject 5:** Cheng-Si Tsao, INER (PI); Yu-Ching Huang, MSE-MCUT (Co-PI); Hou-Chin Cha, INER (Co-PI)

Main Results to Date

The project in 2020 aimed to demonstrate the operation of indoor and healthcare applications powered by photovoltaic cells. The five main accomplishments are summarized as follows:

1. Development of high-performance flexible all-polymer solar cells with long-term device stability for potential energy-autonomous electronics

A new newly synthesized low-bandgap donor polymer, pBCN, was exploited in a pBCN/PCBM-based photovoltaic device with sol-gel ZnO-nanoparticle layer as the electron-transport layer, to generate sufficient power to drive the chosen biosensor (AMS Biosensor AS7000).

2. Development of dry-processed organic and perovskite photovoltaics for indoor applications

A D-A-A-configured donor, DTDCPB, combined with C_{70} as the active layer in an organic photovoltaic device. The device with a size of 3 cm^2 delivered a maximum voltage of 3.43 V and a maximum output power of 146 μW under 1000 lux. Additionally, this vacuum-processed device had an output efficiency sufficient to drive a temperature/humidity sensor (BLE Sensor Beacon, CYALKIT-E03, Cypress). A perovskite-based photovoltaic device with $CsPbI_2Br$ as the active-layer material, C_{60} as the electron-transport material, and TAPC as the hole-transport material achieved an output power density of 77.6 mW/cm^2 at 1000 lux. The operation of CYALKIT-E03, driven by the aforementioned photovoltaic device under ambient light, is shown in Figure 1.

Figure 1. Perovskite photovoltaic cell powers a temperature/humidity sensor (BLE Sensor Beacon, CYALKIT-E03, Cypress) under ambient light.

3. Exploration of the next-generation non-toxic/earth-abundant metal chalcogenides based thin-film solar cells for application in household energy-autonomous electronics

Ag-alloyed CZTSSe was used in fabricated photovoltaic cells to suppress the open-circuit voltage deficit and defect-induced band tails. Its best power conversion efficiency of 9.10% (0.3×0.35 cm^2 under 1 Sun) was demonstrated. Furthermore, CZTSSe was grown on a Mo foil for flexible thin-film photovoltaics. The obtained power conversion efficiency was approximately 6.1% (Figure 2).

4. Fundamental studies of new-generation photovoltaic materials and devices

The energetics and microstructures of the $MA_yFA_{1-y}Pb(Br_xI_{1-x})_3$ mixed-ion perovskite were mapped over the entire composition space by extensive atomistic Monte Carlo sampling of approximately one million structures (1728 atoms in each structure) (Figure 3). The evaluation of such a large ensemble of structures was facilitated by a machine learning-enabled potential energy model

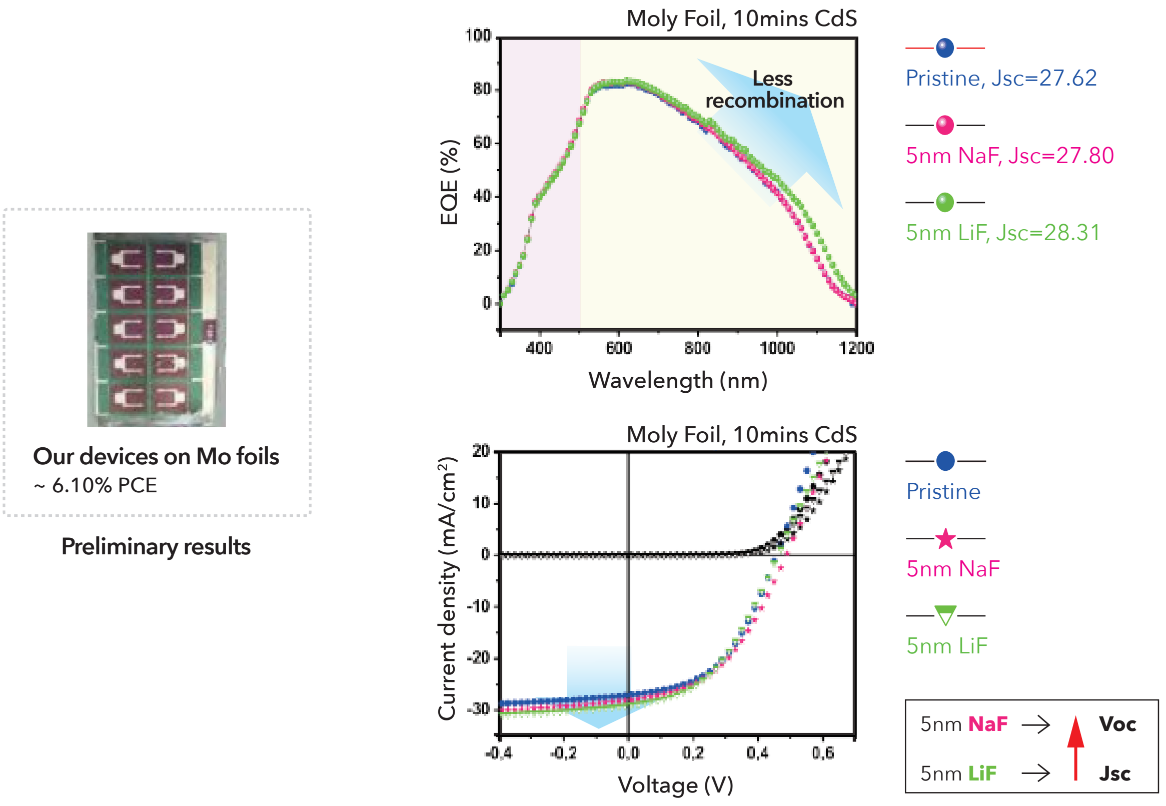


Figure 2. Current density–voltage and external quantum efficiency curves of flexible CZTSSe photovoltaic devices.

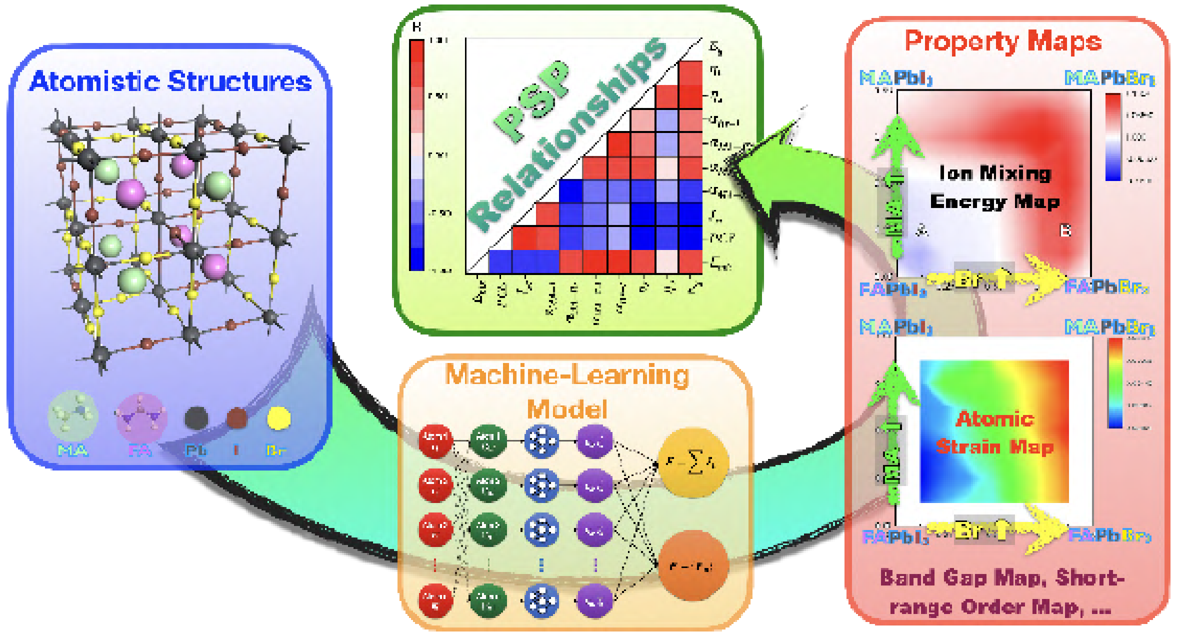


Figure 3. Simulated atomistic structures and properties of $MA_yFA_{1-y}Pb(Br_xI_{1-x})_3$ mixed-ion perovskites and their correlation with device performance

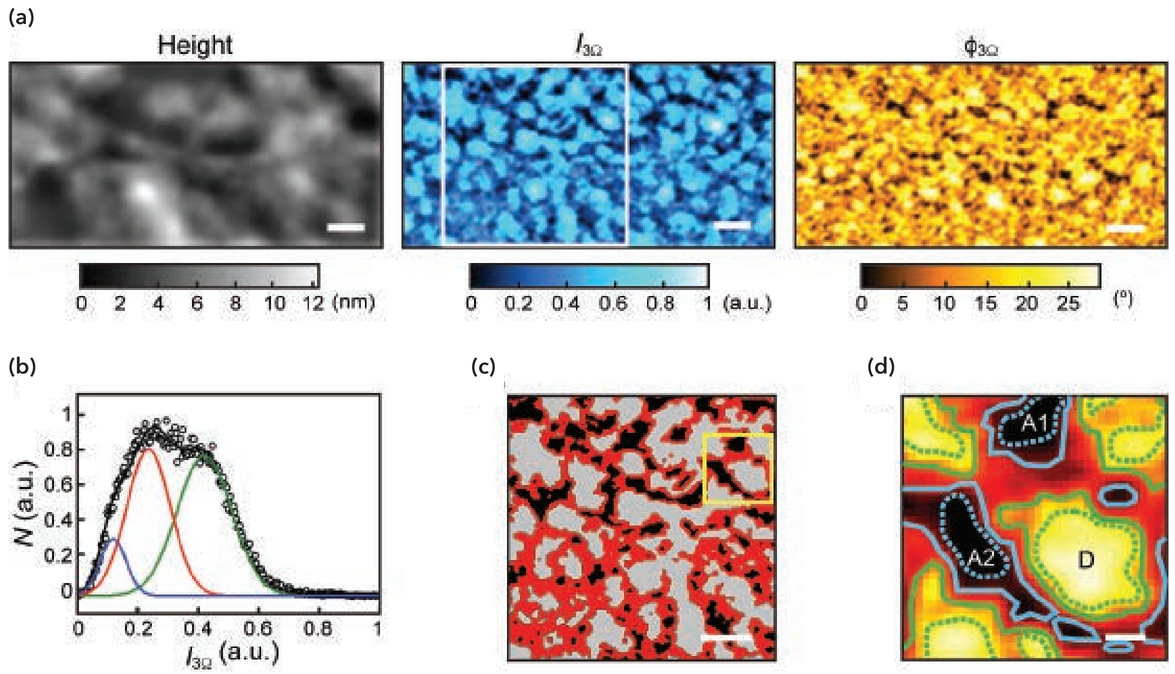


Figure 4. (a) *s*-SNOM amplitude and phase images ($I_{3\Omega}$ and $\Phi_{3\Omega}$) and topographic image (height) of P3HT:PCBM film; (b) intensity histogram of the $I_{3\Omega}$ image containing the contributions of P3HT, the intermixed phase, and PCBM; (c) $I_{3\Omega}$ image, selected from (a), highlighted with P3HT (grey area) and PCBM (black area) and intermixed-phase region (red area); (d) $I_{3\Omega}$ image, selected from (c), highlighted with pure P3HT regions (encircled by green dotted curves), P3HT-rich layers (between green solid and dotted curves), pure PCBM regions (encircled by blue dotted curves), and PCBM-rich layers (between blue solid and dotted curves). The scale bars in (a) and (c) are 100 nm while that in (d) is 20 nm.

with 10^5 times computational speedup and high fidelity to density functional theory calculations. The results predicted a stable phase diagram for mixed-ion perovskites.

Scattering-type scanning near-field optical microscopy operating with a visible light source was deployed to disclose the nanomorphology of P3HT:PCBM and pBCN:PCBM blends. Donor and acceptor domain as well as intermixed phase were identified and their intertwined distributions were mapped (Figure 4). This study shows that visible *s*-SNOM is capable of profiling the morphological backdrop pertaining to the operation of high-performance bulk-heterojunction organic solar cells.

5. Development of mass-produced fabrication of flexible large-area organic solar cell modules for integration with energy-autonomous electronics

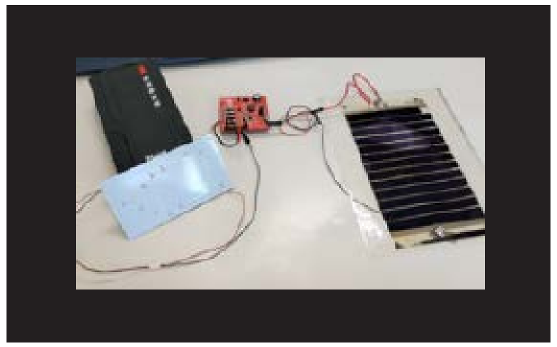


Figure 5. Light-emitting diodes (left) powered by the combination of a management circuit, supercapacitor, and PV module (right).

Flexible slot-die-coated modules were fabricated with PV2000:$PC_{71}BM$ as the thickness-optimized active layer. The prepared flexible module, comprising 13 series connected cells, had a total active area of 83.2 cm^2. This module produced an open-circuit voltage, short-circuit current, fill factor, and power conversion efficiency of 7.01 V, 4.22 μA/cm^2, 57.28%, and 11.66%, respectively, under 500 lux illumination. The corresponding power density and voltage outputs were 16.81 μW/cm^2 and 4.09 V, respectively. The entire module was able to power light-emitting diodes (Figure 5).

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Bio-electro Opto-controlled Conversion of CO_2

Project Duration	2021
Project Director	**Mitch Ming-Hsi Chiang:** Research Fellow of the Institute of Chemistry. His major research interest includes the development of transition metal catalysts for chemical transformation, energy conversion and storage. **James C. Liao:** Distinguished Research Fellow of the Institute of Biological Chemistry. President of Academia Sinica. A pioneer in metabolic engineering, synthetic biology, and systems biology. A leading role in development of proteins and genetically engineered microbes for biorefining and biofuel production, and development of a complete carbon conservation pathway for fermentation processes.
Hosting Institute	Institute of Chemistry (MHC), Institute of Biological Chemistry (JCL)
Sub-Project PI, Co-PI	Chi Chen, RCAS, AS Steve Sheng-Fa Yu, IOC, AS

Research Objectives

Developing technologies for carbon fixation, storage, and utilization to achieve net zero carbon emissions by 2050 is an urgent issue that needs to be addressed. To date, biological CO_2 fixation is the most effective means for scaling down CO_2 levels and accounts for most of the CO_2 that is fixed on earth. In this process, carbon is fixed as biomass and in cellular components during organismal growth. However, the biological CO_2 fixation rate is regulated cellularly such that CO_2 fixation is balanced with cell physiology and organismal growth; it is typically limited by oxygen sensitivity and carboxylase activity. Since this rate can be manipulated independently, cell-free CO_2 fixation systems are an alternative to uncouple CO_2 fixation from growth and cellular regulation. In this study, we have constructed a cell-free *in vitro* oxygen-tolerant CO_2 fixation system that exceeds the typical CO_2 fixation rates of model photosynthetic and lithoautotrophic organisms. This system maintains an optimal rate of the fixation cycle, as it is equipped with real-time opto-sensing modules. Notably, intermediate species formed during the cycle were isolated and used as feedstocks for further chemical processes. Thus, this designed *in vitro* system can facilitate the realization of a carbon-negative process.

Main Results to Date

A few challenges need to be overcome when developing an *in vitro* enzymatic system because the *in vitro* environment is unlike the protective environment within a cell. These challenges include exacerbated enzyme instability, metabolite instability, and cofactor regeneration. Additionally, the lack of cellular regulation in *in vitro* cell-free systems makes it challenging to balance the rates of cofactor consumption and regeneration under dynamic conditions. We overcame these difficulties by employing a modular approach and designed a highly efficient, oxygen-insensitive, and self-replenishing CO_2 fixing cycle. Our cycle started with the oxygen-insensitive phosphoenolpyruvate carboxylase (Ppc) that has a superior affinity towards HCO_3^-, a CO_2 equivalent in aqueous media. In this regard, Ppc catalyzed the carboxylation of phosphoenolpyruvate (PEP), a C3 compound, to form oxaloacetate (OAA), a C4 compound. Since the conversion of OAA to pyruvate (a C3 compound) or acetyl-CoA (a C2 compound) is always accompanied with carbon loss in most cells, we mitigated this loss by using the reductive glyoxylate synthesis (rGS) pathway. The rGS pathway was designed to replace the native CO_2 fixation pathway and convert one molecule of the C3 compound pyruvate to the two C2 metabolites acetyl-CoA and glyoxylate with one bicarbonate molecule getting fixed. Upon reverse conversion of glyoxylate to acetyl-CoA via glycerate, a net reaction fixing one carbon molecule to pyruvate by producing two acetyl-CoA molecules was established. At this point, we combined the rGS and glycerate pathways to formulate the malyl-CoA-glycerate (MCG) pathway, which is displayed in the upper part of the complete cycle presented in Figure 1.

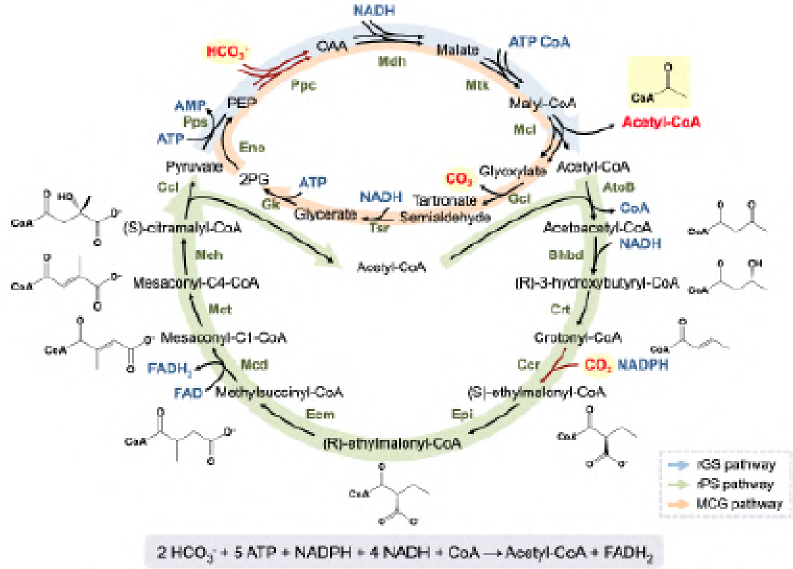

Figure 1. **The rGPS-MCG cycle has acetyl-CoA as the end product.** The rGPS cycle consists of the reductive glyoxylate synthesis (rGS) pathway (blue) and the reductive pyruvate synthesis (rPS) pathway (green). The MCG pathway (orange) consists of the rGS pathway and the glycerate pathway. The red arrows indicate the carboxylation reactions.

To complete the CO_2 fixation cycle, another carboxylation reaction was needed to convert the C2 product to the C3 compound pyruvate. However, we bypassed the use of the oxygen-sensitive pyruvate-ferredoxin oxidoreductase, which is an enzyme that fixes one CO_2 molecule to acetyl-CoA and produces pyruvate using reduced ferredoxin as a redox cofactor. Rather, we designed a reductive pyruvate synthesis (rPS) pathway involving a crotonyl-CoA carboxylase/reductase. This enzyme catalyzed the reductive carboxylation of crotonyl-CoA to (S)-ethylmalonyl-CoA using NADPH as the reducing equivalent. Remarkably, the enzyme catalyzed the carboxylation reaction with substantial activity under aerobic conditions. Notably, the rPS pathway comprised 10 enzymes, and was efficient and oxygen-insensitive. Two acetyl-CoA molecules were converted to the C5 intermediate mesaconyl-C1-CoA by fixing a CO_2 molecule, following the splitting of the C5 compound into acetyl-CoA and pyruvate.

While the rPS pathway converted one acetyl-CoA to pyruvate and fixed one CO_2 molecule, the rGS pathway converted one pyruvate to glyoxylate (a C2 compound) and acetyl-CoA and fixed one bicarbonate molecule. Thus, we obtained a CO_2 fixation cycle that produced glyoxylate. This CO_2 fixation pathway was termed the reductive glyoxylate/pyruvate synthesis (rGPS) cycle. Therefore, combining the rGPS cycle with the MCG pathway yielded a self-replenishing CO_2 fixation cycle. Similar to the Calvin-Benson-Bassham (CBB) cycle that outputs a C3, C4, C5, C6, or C7 compound as the end product, the rGPS-MCG cycle produced C2 (i.e., acetyl-CoA), C3 (i.e., pyruvate, PEP, and glycerate), C4 (i.e., malate, OAA), and C5 (i.e., Me-succinate) products, provided that the rate of product utilized did not exceed the rate of replenishment.

To sustain this operation, the metabolite concentration and enzyme stability also needed to be sustained. Thus, we performed real-time monitoring of the concentration and regulated the regeneration of NAD(P)H, ferrocenium (Fc^+), and ATP using a fiber-optic system (Figure 2). Evaluating the concentration of Fc^+ was essential, as Fc^+ was crucial in the regeneration of FAD by (2S)-methylsuccinyl-CoA dehydrogenase. It inhibited the conversion of methylsuccinyl-CoA to methylsuccinate, which terminated the rPS pathway. In the protein soup, Fc^+ was regenerated by horseradish peroxidase (HRP) and H_2O_2. In fact, we discovered that H_2O_2 was capable of oxidizing NADH and NADPH in the presence of HRP. Moreover, free CoA was rapidly oxidized to CoA disulfide in the presence of a high concentration of H_2O_2. In addition, *Escherichia coli* acetyl-CoA acetyltransferase (AtoB), β-ketothiolase (PhaA), PEP carboxylase (Ppc), malate thiokinase (Mtk), and malyl-CoA lyase (Mcl) are sensitive to H_2O_2. Thus, precise regulation of H_2O_2 concentration for FAD regeneration was required to increase the CO_2 fixation efficiency and sustain the designed cycle.

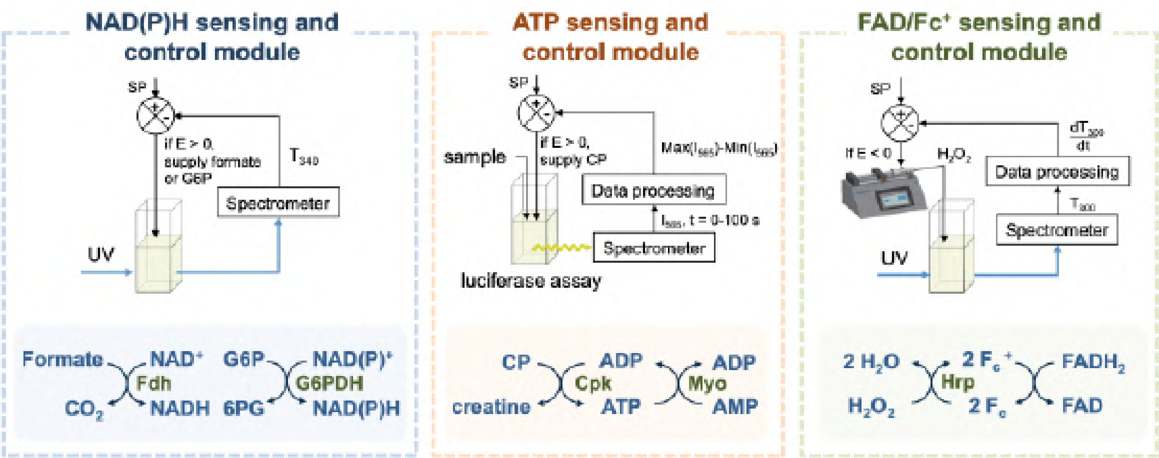

Figure 2. **Real-time monitoring and regulation of cofactor regeneration in the rGPS-MCG cycle.** The cofactor opto-sensing and control modules for [NAD(P)H], [ATP] and [Fc^+] are monitored by T_{340} (transmission at 340 nm), the luciferase assay, and T_{300}, respectively.

ATP regulates enzyme activity through substrate inhibition or allosteric regulation. Here, we identified that high concentrations of ATP inhibited the activity of PEP synthase (Pps), Mtk, and glycerate kinase (Gk). We regulated the concentrations of Fc^+, NAD(P)H, and ATP based on the optical signals analyzed and accordingly added H_2O_2, formate, G6P, and creatine phosphate, respectively, to maintain the optimal activity of the cycle.

This rGPS-MCG cycle achieved the highest steady-state CO_2 fixation rate (0.55 mM h^{-1}) among the pathways completely established *in vitro*. Indeed, based on the levels of the core proteins (pathway enzymes excluding those in the NAD(P)H, ATP, and FAD regeneration systems), this cycle had the highest protein efficiency to date for CO_2 fixation (28.5 nmol min^{-1} mg^{-1} core cycle protein at quasi-steady state; 100 nmol min^{-1} mg^{-1} core cycle protein within the initial 1.5 h; Table 1). Comparing our rGPS-MCG cycle with autotrophic and heterotrophic CO_2-fixing microbes based on dry weight revealed that the specific CO_2-fixation rate

Table 1. Comparison of the *in vitro* carbon fixation capacity of the rGPS-MCG cycle and CETCH 5.4.

Name	CETCH 5.4[a]	rGPS-MCG
Final product conc. (mM)	0.54 mM glyoxylate	0.7 mM acetyl-CoA 0.4 mM glycerate and 1 mM malate[c]
Starting substrate (mM)	0.2 mM propionyl-CoA	0.4 mM crotonyl-CoA 0.4 mM PEP
Reaction volume (mL)	0.52	20
Core enzyme amounts (μg)[b]	1196	9744[d]
Reaction time (hour)	1.5	6
Specific CO_2 fixation rate (nmol/min/mg core enzyme)	5	100 (from 0-1.5 h) 28.5 (from 0-6 h)

[a] Schwander, T., Schada von Borzyskowski, L., Burgener, S., Cortina, N. S. & Erb, T. J. (2016). A synthetic pathway for the fixation of carbon dioxide *in vitro*. *Science*, *354*, 900-904.
[b] Pathway enzymes excluding those involved in the NAD(P)H, ATP, and FAD regeneration systems
[c] Only the major products of the rGPS-MCG cycle are listed.
[d] Initially, 5456 μg of the core enzymes were added. 4288 μg was the total amount of unstable enzymes that were evenly distributed and added to the reaction every 30 min.

(28.5 nmol min^{-1} mg^{-1} core protein or 2 mmol h^{-1} g^{-1} core protein) of our cycle was at least threefold higher than that reported in the literature. In fact, it was comparable to the maximum CO_2 specific uptake rate of *Synechocystis* PCC 6803 during the log phase. Assuming that 50% of dry cell weight was protein, the maximum specific CO_2-fixation rate of *Synechocystis* PCC 6803 was approximately 4 mmol h^{-1} g^{-1} total protein. Furthermore, comparing the specific CO_2-fixation rate between the rGPS-MCG cycle and the CBB cycle revealed that approximately 3% of the dry cell weight amounted to the CBB cycle in *Synechocystis* PCC 6803. Based on these data, the maximum specific CO_2-fixation rate of the CBB cycle was approximately 65 mmol h^{-1} g^{-1} of the CBB protein. Thus, the CBB cycle and rPS pathway were predicted to function in the same order of magnitude through the enzyme cost minimization algorithm.

In summary, we successfully designed and operated a cell-free, self-replenishing, oxygen-tolerant, *in vitro* CO_2 fixation system. Indeed, its CO_2 fixation rate exceeds the typical CO_2 fixation rates of model photosynthetic and lithoautotrophic organisms. Apart from cellular growth and biomass, this cycle produces C2–C4 compounds derived from CO_2 that can be used for further chemical conversion processes. This *in vitro* system consists of two engineered metabolic pathways: the rGPS cycle and the MCG pathway, wherein each individual enzyme exhibits a high specific activity and can be easily purified and is oxygen tolerant. The equipped real-time opto-sensing modules regulate the output activity of the intermediate compounds and regenerate cofactors required for CO_2 fixation such that the cycle is maintained at an optimal rate. Thus, this *in vitro* CO_2 fixation system paves the way for a carbon-neutral economy.

Future Research Plan

The self-replenishing rGPS-MCG cycle designed in this study produces key metabolites, such as acetyl-CoA, pyruvate, and malate, and enables their further conversion to almost all chemicals in the biosphere. This cell-free CO_2 fixation system can be practical if the involved enzymes are further stabilized and if the cofactors are regenerated by renewable energy at a deployable scale and at a sufficiently low cost. Although enzyme stability remains an issue, it can, in principle, be addressed by bioprospecting more stable enzymes or by coupling directed evolution with a rational design. Furthermore, the rGPS-MCG cycle needs to be implemented in organisms and evolved *in vivo*. Thus, the rGPS-MCG cycle performs core reactions that can help establish *in vitro* and *in vivo* CO_2 conversion systems.

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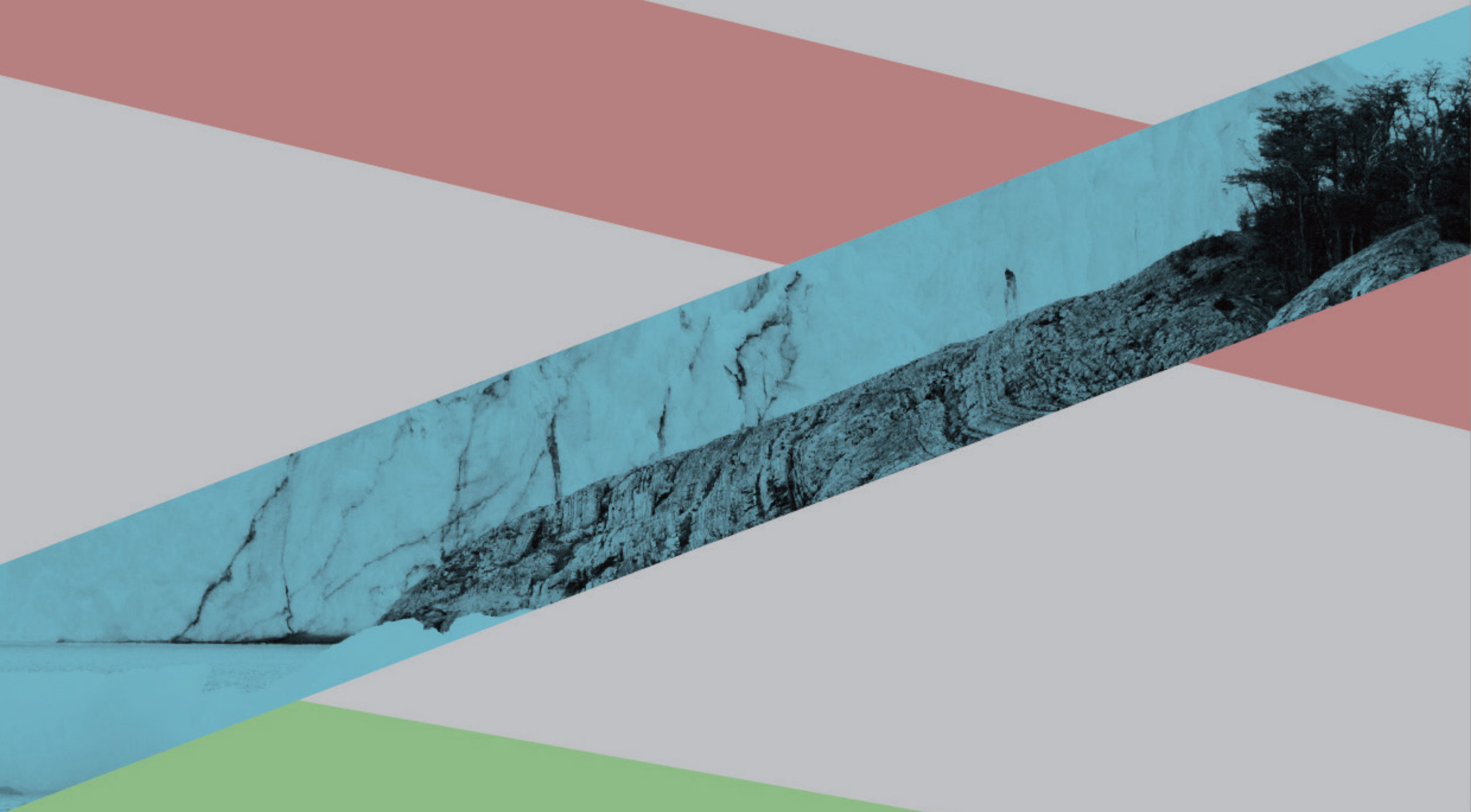

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