Executive Summary

There are a wide range of social, economic, and environmental issues that need to be addressed. The progress of the world in recent years, however, has stagnated or regressed in several aspects due to the impact of some disastrous events such as the pandemic of COVID-19, climate change, natural disasters, and conflicts in various places. It is an urgent task for us to find the way we can move forward and realize the transition to a sustainable and prosperous society.

The central issue in recent years is climate change. Some governments around the world implementing economic stimulus packages for the recovery from negative impacts of COVID-19 establish green policies alongside measures against the infectious disease. Anthropogenic climate change is affecting the frequency and intensity of extreme heat, precipitation and droughts in all regions of the world, already causing severe loss and damage. Thus, climate change has become a high-priority issue for the governments in order to maintain the livelihoods of their citizens and the foundation of industries. An increasing number of countries are also aiming to achieve net zero emissions of greenhouse gases, so-called carbon neutrality (CN), towards the Paris Agreement. There are high expectations for science, technology and innovation (STI) on these issues. Since there is an aspect of the struggle for supremacy over technology and resources as well, the governments are also emphasized as their industrial policies. On the other hand, there is a growing movement to require companies to disclose financial information regarding their efforts to address climate change and its impact. In international discussions, comprehensive efforts that focus on the interconnection of multiple global issues, such as climate change and air pollution, or climate change and biodiversity, are becoming more prominent.

Russia's invasion upon Ukraine, began in February 2022, has had a major impact on the international energy market and has given many countries and regions an opportunity to reaffirm the importance of energy security. If it becomes difficult to stably supply necessary and sufficient energy at reasonable prices, it will immediately have a serious impact on people's lives and socioeconomic activities. How to balance energy security and CN is a new social concern.

This report has set 35 research and development (R&D) areas under the recognition of the social and economic trends surrounding the environment and energy fields, and provides an overview of R&D trends in each area.

<Energy field>

- **Zero emission and stabilization of electricity:** Expansion of renewable energy sources through expansion of installation locations, equipment size increase, cost reduction through efficiency improvement, and operation optimization, etc., reduction of CO_2 emissions from thermal power generation that contributes to electricity stability, transition of fossil fuels to CN fuels such as hydrogen and ammonia, expansion of energy storage, and the use of nuclear power generation on the premise of ensuring safety have been studied.
- **Zero emissions and carbon recycling in the industry and transportation sector:** Electrification of power and heat sources and transition to low-carbon emission fuels is promoted, as well

as energy efficiency improvement and carbon recycling technology development. R&D for higher capacity, longer life, safety, and cost reduction in the field of large-scale electric power storage batteries are being examined. Efficient and low-cost water electrolysis and hydrogen carrier technologies (liquified hydrogen, organic hydride and ammonia) are key targets in the field of hydrogen and ammonia. In terms of CO_2 utilization, advanced catalyst development, and methods for directly electrolytically reducing CO_2 without passing through hydrogen are being studied. Further technological development is required for heat control, such as high-temperature heat pumps and heat storage materials.

- **Zero emissions and low-temperature heat utilization in the commercial and residential sectors:** Shifting to ZEB (Net Zero Energy Building) and ZEH (Net Zero Energy House) is being promoted in order to reduce energy consumption in the residential sector.
- **Atmospheric CO_2 removal:** Technologies for capturing and storing CO_2 emitted from large-scale fixed sources are being developed through demonstration tests in Japan and overseas. As a technology that leads to negative emissions, not only an industrial method such as Direct Air Carbon Capture and Storage (DACCS), but also nature-based solutions including soil carbon sequestration, afforestation/reforestation and coastal blue carbon is being developed.

<Environmental field>

- **Earth system observation and prediction:** Accurate and high-resolution understanding of greenhouse gases (GHGs) emissions with satellite-based, terrestrial, and oceanographic observations is in progress. In parallel with the advancement of various prediction models such as global climate models, earth system models, and global cloud resolving models, efforts are being made to expand the social use of prediction results. In the field of water circulation, pioneering research through multidisciplinary collaboration and even with society are found, centering on hydrology. In ecosystem and biodiversity observation, the use of satellite-based observation data, various observation methods and tools such as environmental DNA, 3D scanning and unmanned aerial vehicles (UAVs) are expanding. Data driven science is a common trend in this area.
- **Harmonious coexistence between human and nature:** Research on qualitative/quantitative evaluation of ecosystem services and analysis of linkages (nexus) between those is underway for an evaluation and prediction of socio-ecological systems. Scenario-based projection and evaluation are applied to the impact assessment of climate change on agriculture, forestry and fisheries. Along with the Ecosystem-based Adaptation (EbA) and the Ecosystem-based Disaster Risk Reduction (Eco-DRR), the concept of Nature-based Solutions (NbS) has been rapidly spreading. Analysis of precautions against extreme heat in urban areas is now at a resolution of the block level. Verification of the effectiveness of countermeasures to the COVID-19 pandemic from the perspective of risk research are being investigated. Wastewater surveillance and wastewater-based epidemiology are also being vigorously conducted.
- **Sustainable Resource Use:** Desalination of seawater and water reuse are still of great interest worldwide. Other important themes on water use include the issue of water supply infrastructure suffered by social changes and aging infrastructure, and contribution to CN.

Regarding air pollution, understanding the generation mechanism of tropospheric ozone and aerosols such as $PM_{2.5}$ is important issue of research. There is also interest in changes in air pollution problems accompanying the social transition toward the realization of CN. Sustainable remediation is a keyword in the field of soil pollution. R&D of chemical recycling technology that converts plastics into hydrocarbon raw materials is active. As for life cycle assessment, studies are underway on methods for evaluating the potential of technologies and systems in the future. Analysis using stable isotopes, simultaneous multi-component (wide-target) analysis, non-target analysis are still major R&D target in environmental analysis. Data-driven research, such as the use of deep learning for estimating unknown substances, is also being a trend. In bioassays and toxicity assessments, development of quantitative structure-activity relationships (QSAR) and methods for predicting toxicity from data of similar substances are active. Research related to nano/microplastics has focused on its dynamics in the environment, but research on the toxicity such as the effects of additives is also underway.

Looking at the R&D trends mentioned above, efforts to address climate change are becoming more active. This seems to be because carbon neutrality has been incorporated into the policies of each country and region, specific plans and strategies have begun to be formulated and implemented, and the impact of this has begun to be seen even in R&D trends. However, while efforts in R&D of various technologies and systems and their social implementation have been promoted, it has become clear that some R&D areas are difficult to progress. For example, the use of thermal energy in industrial activities is difficult to decarbonize due to its large scale and mature process. The cost of electrolysis is a bottleneck for "green hydrogen" produced using electricity derived from renewable energy. Thus, it is considered necessary to study a wide range of clean hydrogen, including “blue hydrogen” extracted from natural gas (with carbon capture and sequestration). Since distributed and autonomous energy systems are more complex than conventional large-scale centralized energy systems, new energy management technologies are required to maintain a balance between supply and demand. In addition to these individual R&D issues, the turmoil in the international energy market caused by Russia's invasion upon Ukraine has served as an opportunity to reaffirm the importance of energy security. Although it is temporary, people's attention has been focused on the short-term issue of securing energy resources for the time being, and it has caused a situation in which progress toward the realization of carbon neutrality may be stalled.

As we move forward with the transition of society over a long period of time toward the realization of carbon neutrality, various uncertainties such as the stagnation of social implementation of new technologies and systems and the occurrence of unforeseen circumstances will accompany us. It will be difficult to achieve ambitious goals unless we can move forward steadily while responding flexibly and dynamically to these changes. Therefore, how to deal with uncertainty will be important in the process of transition in the future. Currently, this trend is noticeable in efforts to respond to climate change, especially in mitigating climate change. It is considered to be a common theme in various aspects related to the transition to a sustainable society, such as an adaptation to climate change, disaster risk reduction, biodiversity, circular economy, chemical substance management, and urban environment.

Based on the above, an important keyword for the future direction of R&D in the environment and energy fields is "transition and uncertainty management." In the future, we need to deepen our thinking about how STI can contribute to this.

From a R&D perspective, "transition and uncertainty management" can be organized into three pillars. That is, (1) facilitation of transition, (2) monitoring, forecasting, and evaluating progress of transition, and (3) preparation for stagnation and negative aspects of transition. The first one is the development of technology and system to promote transition. It is necessary to promote R&D of new technologies and solving problems, system design, and acceleration of social implementation. The second one is monitoring, forecasting, and evaluating the progress of the transition. This requires improvement in resolution and accuracy of technologies for monitoring, forecasting/predicting, and evaluation. The target of evaluation is not always clear, and it is necessary to develop methods for comprehensive evaluation and integration of multifaceted evaluations. The third one is to prepare for the stagnation and negative aspects of the transition that will become apparent as the transition progresses. Stagnation in social implementation of new technology or system due to unexpected and/or fundamental problems. New oppositions (including ethical, legal, and social issues) in the process of social implementation. Aggravation of serious problems overlooked due to focusing on certain issue. It is necessary to respond flexibly to these situations. R&D is needed on alternative technologies, system stabilization, strengthening resilience, and integrated promotion methods.

From a perspective of R&D support system, in the energy field, accelerating social implementation for achieving carbon neutrality is an important issue now. It is necessary to be aware of how to transform the energy system as a whole, not just the sophistication of individual devices and technologies. It is also necessary to set R&D targets based on investigation on what kind of energy balance is better to achieve both "S+3E" (safety, energy security, economic efficiency, reduction of environmental impact) and carbon neutrality, and what kind of role and at what scale individual technology can play within that. Industry plays a critical role. Universities and public research institutions are expected to contribute through, for example, identifying issues that need to be examined going back to basic research and exploring future technologies that could replace current candidate technologies. Strengthening cooperation between industry and academia is essential. Within academia, not only traditional science and engineering research, but also a wide range of research fields such as economics, society, politics, culture, and ethics should be involved. Scenario analysis and life cycle assessment (LCA) is also essential. Efforts to foster an atmosphere that encourages multidisciplinary collaboration among them is important.

In the environmental field, not only the realization of carbon neutrality, but also adaptation to climate change, disaster prevention and risk reduction, safe and affordable water supply, conservation and decontamination of air, water, and soil, sustainable and resilient urban development, sustainable production and consumption, etc are social wishes. In recent years, the problems to be targeted have become more complicated than before, and it is necessary to promote R&D through multidisciplinary approach, including collaborations with society. Here, "multidisciplinary" has two meanings, one of which is cooperation with decision-making bodies such as the government and cooperation with stakeholders. The other means strengthening cross-sectional connections that transcend the boundaries of specialized fields from the perspective of strengthening academic foundations. There are many public systems and services in the environmental field, and it is necessary for the national and local governments to take the lead in maintaining and strengthening domestic R&D infrastructure. Maintaining and managing large-scale research infrastructure requires a long-term perspective, planning, and strategy. The same applies to data/analysis infrastructure and computer facilities. Training and securing engineering human resources to support these activities has become an urgent issue.

International collaboration and international cooperation are important items common to the energy and environment fields. Although there are some fields in the energy field in which domestic industries are not active, from the perspective of energy security as well, it is necessary to maintain critical technologies and human resources through international cooperation. In the environmental field, global-scale research areas, such as earth observation and climate change prediction, should be deeply connected to international frameworks, and active participation in international research projects and research communities is essential.

R&D in the environment and energy fields is extremely wide-ranging. Along with the development of the current society, we are responsible for passing on a better society and global environment to future generations. It is necessary to strongly promote R&D as a pillar for overcoming these difficulties and developing future society.