Asian Journal of Innovation and Policy (2022) 11.1:001-029
DOI: http//dx.doi.org/10.7545/ajip.2022.11.1.001

A Study on Strategies of Public R&D to Achieve National Carbon Neutrality: Focusing on the Implications of the Republic of Korea

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Abstract Climate action is at the top of the agenda in the international community, as demonstrated at the 2021 G7 Summit and the 2021 UN Climate Summit. Major developed countries are scrambling to make a transition to a green economy and create a new growth momentum. Following the Paris Climate Agreement in 2016, they focus on "carbon neutrality" as an effective means of tackling climate change. The Republic of Korea, a high-carbon economy, submitted its second Nationally Determined Contribution and announced carbon neutrality as a top policy priority. Accordingly, the country increases government budget in research and development (R&D) and science and technology (S&T) policies. Against this backdrop, this study analyzed policies on carbon-neutral S&T and R&D in major advanced countries. The analysis was made by identifying globally pending issues in carbon-neutral policies and climate technology. In addition, focus group interviews were conducted six times with 10 experts to come up with three R&D strategies and action plans for government-funded research institutes to achieve carbon neutrality. To be specific, the following measures were suggested. First, creative and innovative R&D programs are required to solve the problem of carbon emissions. Second, it is necessary to establish carbon neutrality policies and infrastructure which are sustainable to run and manage. Third, it is crucial to promote cooperation in climate technology based on excellence. In conclusion, the strategies proposed in this study are expected to provide directions and implications for policymakers, researchers, and scholars in science and technology to develop effective strategies to achieve national carbon neutrality.

Keywords Carbon Neutrality (Net Zero), Nationally Determined Contribution (NDC), Long-term Low Greenhouse Gas Emission Development Strategies (LEDs), Research and Development (R&D) Strategies, Policy Research

Submitted, December 17, 2021; Accepted, February 17, 2022
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I. Background

1. Research Purpose and Justification

Climate change is getting more serious across the world as global warming causes weather extremes such as heatwaves, heavy snow, typhoons, and forest fire. Climate disasters indiscriminately and abruptly hit countries and continents. In response to the issue, major advanced countries have declared carbon neutrality to deal with climate change in a preemptive manner. "Carbon neutrality" has become a new and irreversible international order. To be specific, key emerging topics include restricting investment in non-eco-friendly businesses, reviewing the introduction of a carbon border tax, and upgrading vehicle emission control.

Each government is struggling to come up with measures against the peril of rapidly-changing global climate change and the subsequent socioeconomic impacts. That challenge can be addressed by building up the momentum for global agendas including air pollution, climate change, and the UN Sustainable Development Goals (SDGs), along with international mutual assistance based on openness, solidarity, and cooperation. For this reason, it is time to make joint efforts against the threat posed by climate change, going beyond simply paying international attention (Song, Yoo, Lim and Ko, 2020).

In the international community, it is scientifically proven that climate change is the result of human activities and the accumulation of greenhouse gas (GHG) emissions (IPCC, 2014). In that sense, an international regime on climate change has been established, including the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol, and the Paris Agreement. Each government has focused on policies and institutions to address the issue. Cases in point include the European Green Deal by the European Commission (EC), the Green New Deal by the U.S. Democratic Party, China's drive for ecological civilization, and the Green New Deal policy by the Korean government. All these cases demonstrate that "low carbon, green growth" is a national top priority policy across the world in the fight against climate change. That approach is based on a green economy, and the term "net zero" is recently gaining attention as a policy tool. Carbon neutrality is a new growth strategy to achieve environmental conservation (climate response, transition to a low-carbon society) and economic growth (renewable energy industry, job creation, etc.) at the same time.

Starting from Europe, 120 countries worldwide have declared net zero. As demonstrated in the past events including the 2021 G7 Summit and the 2021 Climate Summit, each country is fiercely competing for a socioeconomic paradigm shift to tackle the climate crisis and secure a new momentum for

economic growth. President Moon Jae-in of the Republic of Korea (South Korea) promised "an early transition to a low carbon economy" in the 2019 UN Climate Action Summit, and declared the goal of "Net Zero by 2050" in October 2021. In Northeast Asia, President Xi Jinping of China announced that the country will reach carbon neutrality by 2060 (Sep. 22, 2020), while Prime Minister Yoshihide Suga of Japan revealed a plan to achieve net-zero by 2050 (Oct. 26, 2020). Furthermore, following global companies, Korean businesses also announced ESG management and RE100, showing that net-zero is gaining huge global attention across fields and countermeasures are being developed.

In particular, countries such as South Korea and China are classified as net carbon exporters in carbon emissions embedded in trade. The carbon border tax heavily affects industries such as steel, petrochemical, transport, and electrical/electronic devices. South Korea is given the role and responsibility as an advanced country such as the so-called K-quarantine and a G7 reform. Nevertheless, the country is facing difficulties at home and abroad, as it is pointed out as a huge GHG emitter and a heavy energy consumer. Given that the existing global economy relies heavily on high-emitting industries, achieving carbon neutrality can be a challenging task, as it takes much time to hit the goal after GHG emissions reach the peak, and factors need to be considered such as industrial structures and the energy mix. Nevertheless, industries, in general, are hesitant to go carbon neutral as it incurs the cost, while governments say that it can have a negative impact on businesses and people in the process. However, it is essential to adapt to changing conditions such as international politics, economy, industry, and the environment, and given that net-zero is a mainstream global agenda, there is a growing need to establish a policy direction and action plans amid a great transition in the global economic order towards carbon neutrality.

2. Research Objectives and Scope

This study is designed to come up with research questions by examining pending issues in net-zero policies and climate science on a global level and analyzing science and technology (S&T) and R&D policies on carbon neutrality in advanced countries. Furthermore, focus group interviews (FGIs) were conducted six times based on the result of a literature review. Thereafter, this study suggested three R&D strategies and sub-strategies. In conclusion, it is expected that the strategies presented by this study will provide implications and a sense of direction in setting an effective strategy and action plans for policymakers, researchers, and scholars in the field of science and technology to achieve national carbon neutrality.

The content and scope of this study were set as follows. First, this study surveyed and analyzed a global carbon neutrality agenda and pending issues of policies on carbon neutrality and S&T innovation in major countries. With that, implications were produced on globally pending issues in carbon neutrality and key areas prioritized by each country. Second, six FGIs were carried out with 10 experts on relevant policies to develop a future strategy on S&T and innovation policy to reach carbon neutrality. Third, it proposed strategies to achieve national carbon neutrality through S&T innovation, R&D strategies, and action plans based on the literature review and the result from the FGIs.

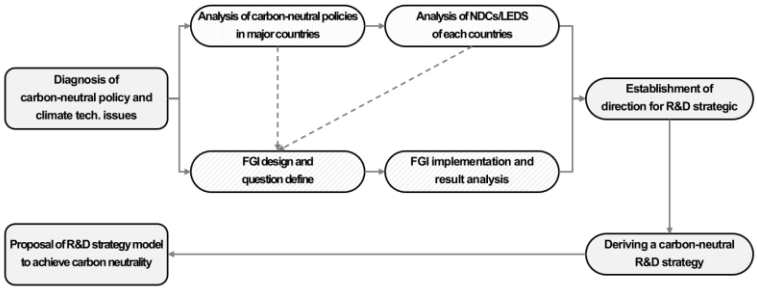

Figure 1 Research Process for R&D Strategies of National Carbon Neutrality

The composition of this study is as follows. The first chapter of introduction stipulated the necessity and goal of this study, briefly suggesting the content and scope of this study. The second chapter of reviewing literature intensively analyzed global trends in carbon neutrality policies and cases of S&T policies. The third chapter of Research Methodology described methods to analyze the policies and the FGIs, setting research questions. The fourth chapter of Result of the Study presented the result of the policy analysis upon the research questions with that of the FGIs. Last but not least, the fifth chapter of conclusion came up with R&D strategies for carbon neutrality and implications for government-funded research institutes (GRIs).

II. Theoretical Discussion

1. Paris Climate Agreement and related R&D

The first World Climate Conference in 1979 raised the possibility of human activities causing climate change. Thereafter, an Intergovernmental Panel on Climate Change (IPCC) was established in 1988, and its first report suggested

that climate change is a scientifically existing issue and it is the product of human activities. The Kyoto protocol, the conventional climate change regime, limited the responsibility of climate change to advanced nations. With the adoption of the Paris Agreement in 2015, however, it is stipulated that all countries including developing nations shall set their voluntary GHG emission reduction target. The Agreement underlines detailed principles on long-term goals, emission reduction, carbon markets, implementation monitoring, adaptation, financial resources, and technology. In accordance with the Paris Agreement (Article 2(1), Article 4(19)) and the 21st Conference of the Parties (COP21) Decision (Paragraph 35), all parties shall submit by 2020 their Long-term Low Greenhouse Gas Emission Development Strategies (LEDS) in reflection of their mid- to long-term energy and climate policies by 2050 (UNFCCC, 2016). Long-term objectives and implementation monitoring of the Paris Agreement have driven the advent of carbon neutrality as a means of tackling climate change.

In line with this trend, all governments across the world focus on industrial structure innovation and capacity building in science and technology (R&D) to effectively deal with unpredictable global warming. The White House announced, "American Innovation Effort to Create Jobs and Tackle the Climate Crisis in February 2021 (Biden-Harris Administration Launches American Innovation Effort to Create Jobs and Tackle the Climate Crisis) (Feb. 2021)." The announcement includes that it will form a national Climate Innovation Working Group as part of the National Climate Task Force, promote R&D in carbon neutrality via ARPA-C (Advanced Research Projects Agency-Climate), and provide a $100 million funding to support transformational low-carbon energy technologies through ARPA-E (Advanced Research Projects Agency-Energy). The Japanese government established a "Revolutionary Environment. Innovation Strategy" in January 2020, including 30 trillion yen for 10 years in R&D on public-private technology in the energy & environment sector. In addition, the strategy also specifies 39 themes that are expected to greatly cut GHG emissions and suggests detailed scenarios and implementation schemes including objectives by theme, technology development, elemental technology development, and development for practical use in 16 technologies in five sectors, with an aim at firmly establishing innovative technologies by 2050.

In addition to major advanced economies, carbon neutrality has become a top policy agenda in developing countries with a high reliance on carbon-emitting industries. Choe (2018) underlined the importance of an active policy response to find new opportunities under the new climate regime by promoting green technology and industry in his analysis result on the follow-up process of the Paris Agreement. As major advanced countries and developing nations with industrial capacities are expected to invest more in policies and R&D in science and technology for carbon neutrality, there will be growing discussions on

science and technology (R&D) strategies and action plans to reach the goal.

Aghion et al. (2009) forecast that the key to designing climate change policy is a market-based approach based on science and institutional support for low-carbon technology innovation. In addition, if the implementation of the climate change policy accelerates new low-carbon technology innovation and sustainable economic growth in the private sector, government support and market intervention for climate action will be gradually reduced. For its part, the Korean government has taken more responsibility for climate change and has engaged in leading climate action and international cooperation in climate technology, walking away from its developing country status since the Paris Agreement (Choi, Song and Lee, 2020). The government announced on December 30, 2020 that it will invest 150.1 billion won (KRW) in climate and the environment R&D to achieve carbon neutrality by 2050. Furthermore, the Korean Ministry of Science and ICT (MSIT) released a "Strategy for Technology Innovation for Carbon Neutrality" (Mar. 31, 2021). The policy presents goals and strategies to secure 10 key technologies for carbon neutrality by 2050 (MSIT, 2021). For this reason, R&D and innovation strategies for the GRIs are in desperate need.

2. Literature Review

In general terms, policies refer to whatever a government decides to do or not to do, an action chosen by the government (Dye, 1992), which can also be seen as a grand plan or a conventionally planned project of goals, values, and strategies (Lasswell and Kaplan, 1970; 71). In addition, a study by the European Commission defines a policy as "a series of activities to pursue a common and universal goal or purpose (Nagarajan and Vanheukelen, 1997)." For this reason, a policy can be understood as a basic goal and the subsequent plan and project made by the government to achieve the intended goal of the nation. Lee (2020) put a basic science and technology plan at the top of S&T policy research and analyzed the level of alignment in S&T policy tasks and national strategic technology investment.

Jo and Yoon (2021) discussed "the scope of S&T policy" and "the area of the policy" through a literature review on S&T policy. The scope of science technology policy was mainly divided into science and technology development, infrastructure, manpower nurturing, building a tool to facilitate seamless innovation, and the promotion and support of making ideas into businesses. The policy area includes science and technology R&D, infrastructure, talent nurturing and utilization, start-ups and commercialization support, and governance and support system. Their study, however, mainly analyzed what science and technology policy issues are being dealt with and how policy

responds to the issues. Nevertheless, the detailed areas that they suggested can be used as a key indicator to propose the R&D strategy that this study intends to proceed, so it is greatly noteworthy.

As discussed earlier, science and technology policy not only has an impact on diverse industries and areas on a national level, but also serves as a troubleshooter in some cases. The UNFCCC Decisions and the Paris Agreement underline that science, technology, and innovation can tackle climate change triggered by global warming. Nonetheless, what matters is not a mere policy contribution but why science and technology are imperative to achieve carbon neutrality and what role they should play. In this regard, the 1998 research paper by Richard Sclove provides significant implications. He criticized exclusively elite and insider approaches in science and technology policy. He also explained that citizens deserve better access to universal benefits of science as they experience its consequences and that public access to science needs to be expanded. Furthermore, he also argued that "it is time for science policy to welcome new voices and fresh ideas for addressing the social needs of the 21st century" (Sclove, 1998). As seen in the discussion, science and technology (R&D) of a new era needs to play its original role, implicate the spirit of the times, and encourage citizens to participate through policy efforts. This is why there is a growing need for an in-depth discussion on carbon neutrality policy and action plans in the fight against climate change which is an existential threat to humanity.

III. Methodology

1. Methodology Overview

This study is designed to set the direction and develop strategies for science and technology innovation policies to achieve carbon neutrality which is a globally significant issue. To this end, this study aims to figure out whether science and technology policy is implemented in major advanced economies on a global level and develop innovative strategies to reach national carbon neutrality by carrying out a qualitative analysis of the FGIs. To this end, this study first analyzed representative carbon neutrality policies and sub-science and technology (R&D) policies in the EU, the U.S., Japan, China, and South Korea. It also analyzed what difference lies between the policies and their NDCs (Nationally Determined Contributions) and LEDS (Low Emission Development Strategies). The analysis will provide implications by identifying the gap between the goal of carbon-neutral technology & innovation policies by country and their target areas to foster. Second, the FGIs with 10 experts were carried

out regarding the policy direction of science and technology, response strategy, and detailed action plans to reach carbon neutrality. To be specific, it clarified the role and difference by the level of analysis in science and technology (R&D) policy-making and gathered opinions on the policy direction and detailed action plans. As described earlier, the following research questions were set to produce results.

Research Question 1. What are representative policies to achieve net zero in major economies (The EU, the U.S., Japan, China, and South Korea), and how are they different?

Research Question 2. How do major countries set their NDC and LEDS, and what is different in their target areas to nurture science and technology?

Research Question 3. How do experts forecast the direction and goal of carbon-neutral science and technology policy on a national and institutional level?

Research Question 4. What specific measures do experts suggest to support R&D in carbon neutrality, infrastructure, and collaboration?

2. Analysis Methods

A policy analysis enables a critical assessment based on policy knowledge, systematizes complicated policy issues, and suggests proper measures to address the issues (Dunn, 2018). This study intends to utilize diverse policy documents to analyze carbon neutrality and technological innovation policies in major countries. They include carbon neutrality declaration by each country, carbon neutrality policies of government departments, and the subsequent technology/innovation policies and relevant laws. To be specific, it analyzed S&T innovation policies prescribed in NDCs and LEDS, which were officially submitted to the UNFCCC, the leading international organization on climate change to fairly compare the carbon neutrality innovation policies between countries. The policy documents herein refer to those released after each Head of State declared carbon neutrality in 2020, but this study also analyzed cases and documents before 2020 in the case of the EU that announced the goal at an early stage. As secondary sources, it reviewed analysis reports from major institutions as well as research papers as carbon neutrality is the latest topic and came up with implications.

A study on science and technology policy can be carried out in a quantitative way by running a survey of experts and analyzing the result statistically, and in

a qualitative manner by interviewing sampled experts. This study focuses on the role of science and technology to go net-zero and develops R&D strategies. To date, some studies on S&T policy have been carried out based on climate and the environment (Arrow, 2007; Baker, 2011; Kim et al., 2014), but studies on such policies or response strategies on carbon neutrality, the new global agenda, have been insufficient. The reason lies in that the carbon neutrality agenda is recently discussed on a global level. Strategy development and suggestion of action plans to achieve carbon neutrality for the future require a process to collect opinions and perspectives of experts to explore conditions at home and abroad, in addition to the policy analysis. Putting it differently, this study carried out the FGIs, the qualitative method, to listen to the real voices of people in the field and compensate for the limitations of the policy analysis. This method has been widely used in studies on culture or ethnography, which are hard to prove in a quantitative manner (Kim and Lee, 2013). Lederman (1990) said that even though a group participating in the FGI cannot represent a specific group for a certain issue, more focused discussions on a topic can be made when an in-depth group interview is carried out with participants for a clear purpose. As the FGI generates more data in a shorter period of time, it can be used as a pilot study for a quantitative study in the future. To gather rich data and have interview participants focus on discussions in the FGI, it is essential to form a group sharing similar experiences (Casey and Krueger 1994). For this reason, as a group of experts in S&T and climate change can provide data for an in-depth analysis on the S&T strategy and policy for carbon neutrality, this study carried out the FGIs with the group.

The interviews were conducted with 10 experts at home and abroad from the Korean government, the GRIs on science and technology, organizations nurturing and supporting the GRIs, and including professors of national and public universities in the U.S. and Europe. Six FGIs were carried out from April 5 to June 16, 2021 for three months (90 minutes per session biweekly) via Zoom. Written interviews were conducted when an additional opinion was necessary. For the FGI analysis, it was recorded upon the consent of the participants, and transcripts were written six times. The transcripts were checked against stenographic records made during the interviews for the analysis, while each key point was rearranged according to the research questions to identify the underlying meaning. After that, implications were derived from common and key responses of all interviews, and they were also used to shape the R&D strategies to achieve carbon neutrality.

Table 1 List of Focus Group Interview Attendees

	Affiliation	Country of Affiliation	Area	Age	Years of Experience
Expert A	Presidential Committee	Korea	Technology Policy for International Cooperation	40s	over 10 years
Expert B	Presidential Committee	Korea	Science and Technology Policy	40s	within 20 years
Expert C	Government-funded Research Institutes	Korea	ICT Commercialization	60s	over 30 years
Expert D	Government-funded Research Institutes	Korea	Green Technology Policy	30s	within 10 years
Expert E	Government-funded Research Institutes	Korea	Machine R&D Policy	30s	within 10 years
Expert F	R&D Education Agency	Korea	Human Resource Development	50s	within 20 years
Expert G	R&D Support Agency	Korea	R&D Strategy	30s	within 10 years
Expert H	R&D Support Agency	Korea	R&D Strategy	40s	over 10 years
Expert I	University	USA	Climate and Environmental Economy	40s	over 15 years
Expert J	University	France	Environmental Engineering	40s	over 15 years

IV. Findings

1. Analysis of Carbon-neutral Policies in Major Countries

1.1 European Union (EU)

The EU declared a climate emergency and revealed its green deal policy in November 2019. After that, Ursula von der Leyen, the President of the European Commission, drew a consensus among member countries and reached the Green Deal Agreement (Dec. 2019, EU Summit), announcing a green deal investment plan and passing the European Climate Law (Jan. 2020). The law stipulates that a trillion euros shall be injected into “building a carbon-neutral economy by 2050” and the “promotion of renewable energy to reduce greenhouse gas emissions by 50 to 55% by 2030” alongside the introduction of the carbon border tax (Jang et al., 2020; Moon et al., 2020).

Table 2 Analysis Result of Principal Carbon-neutral Policies in Major Countries

		South Korea	EU	Japan	China	USA
Representative Policy		2050 Carbon Neutrality Plan	Green Deal	Decarbonization Plan	Zero Carbon China	Clean Energy Revolution
Main Goals		Carbon Neutrality in 2050 and GHG 24.4% Reduction by 2030 (compared to 2017)	GHG 50% Reduction by 2030 (Compared to 2019)	GHG 85 billion tons Reduction by 2050 (Compared to 2019)	Carbon Neutrality by 2060 and 67% of Total Energy Demand by Electricity and 12% Hydrogen in 2050	Carbon Neutrality in 2050 and Zero Carbon Power Generation by 2035
Key Items	**Renewable Energy**	·Wind & Solar Power ·Distributed Energy ·ESS	·Offshore Wind & Tidal Power	·Wind, Solar & Geothermal Power ·Nuclear Power ·Hydrogen Supply Chain ·Biofuels	·Wind& Solar Power ·Zero carbon power ·ESS	·Wind & Solar Power ·Nuclear power ·ESS ·Power Transmission Network for Renewable Energy ·Zero-carbon Power
	Green Mobility	·Hydrogen/Electric Vehicle ·Secondary Battery ·Fuel Cell ·Hydrogen Charging Station ·High-speed Railway ·Eco-friendly Ship	·Autonomous Vehicle ·Electric Vehicle ·Secondary Battery	·Hydrogen/Electric Vehicle ·Secondary Battery ·Biofuel Aircraft	·Hydrogen/Electric Vehicle ·Secondary Battery	·Hydrogen/Electric Vehicle ·Electric Vehicle Charging Station ·Clean LRT & Bus ·High-speed Railway ·Eco-friendly Ship & Port
	Energy Efficiency	·Energy Reduction Building ·Recycling Waste ·Big data & AI-based energy efficiency	·Energy Reduction Building ·Recycling Waste ·Digitalization of Carbon Information	·Energy Reduction Building ·Blue Carbon. ·Shared Economy ·Big data, AI-based Energy Efficiency	·Digitalization of Energy Supply ·Recycling Waste	·Energy Reduction Building
	New Green Industry	·Green Hydrogen ·CCUS ·White Bio ·Low Power Semiconductor	·Green Hydrogen	·CO2 Cement. ·CO2 Absorbed Concrete ·Smart Agricultural & Fishery Industry	·Green Hydrogen ·Zero-carbon Steel	·Expansion of Clean Energy Infrastructure

The EU is adopting technologies for climate change adaptation such as new technology, disruptive innovation, a suggestion of sustainable solutions,

development of a "green deal mission" program, climate, maritime, urban areas, and land. The block is also promoting data-driven science technologies such as hydrogen, circular economy, renewable energy, and battery, further innovating disaster management. Furthermore, as it also considers education and training a key tool, the EU aims to build the capacity of schools, universities, and training institutions for sustainable education, develop training materials, and share the best practices. Lee (2020) regards R&D promotion and innovation as a major tool to achieve the EU Green Deal. The EU's NDC was first submitted in October 2016, followed by an update in December 2020, with its LEDS submitted in March 2020. Each submitted document, however, only presents typical emission reduction targets, and there is no specific goal or strategy regarding R&D (EU, 2020).

1.2 United States (U.S.)

The Obama administration of the United States set climate change on a national agenda and exercised its leadership in signing the Paris Agreement. The Trump administration, however, halted all international discussions on climate and the environment and announced the country's withdrawal from the Paris Agreement. The current Biden administration proposes national goals on turning climate change into a mainstream agenda in the world and a green new deal (Commits to invest $1.7 trillion in reaching net zero by 2050) by upholding the policy of the Obama administration, so it is highly expected to put carbon neutrality in connection with climate change as a major national policy (Yang and Cho, 2021). The basic direction of the Biden administration encompasses aggressive R&D investment in future industries, clean energy development, and climate change. Therefore, it is expected that R&D is actively carried out in new growth industries including artificial intelligence, semiconductors, and autonomous vehicles, and in eco-friendly/clean energy fields. Furthermore, as part of the action plan, it plans to newly establish ARPA-C (Advanced Research Projects Agency on Climate) dedicated to R&D in climate action.

After submitting its first NDC in September 2016, the U.S. officially withdrew from the Paris Agreement in September 2020 and officially rejoined it in February 2021. Two months later in April 2021, the country submitted an update on the NDC, presenting numerous strategies on climate technology R&D along with its GHG emission reduction target. The suggestion encompasses the transition to pollution-free electricity to decarbonize all energy sources including energy conservation, the electrification and efficient operation of automobiles, buildings, and industrial parts, and the expansion of storage/modes of transport of new carbon-free energy sources such as hydrogen (U.S. Government, 2021).

In the LEDS submitted in 2016, the country set a macroscopic direction of climate technology R&D (House, 2016), mapping out the following strategies:

further support for public and private RDD&D (Research, Development, Demonstration and Deployment), carbon capture and storage, and as for specific technologies at an early stage of commercial deployments such as the second generation biofuels and cutting-edge nuclear energy, the release of an initial facility for commercialization into the market to reduce the cost by learning lessons and creating economic effects, and broader support to promote technology given that the direction of technological development is unpredictable, thereby reducing the cost of decarbonization.

1.3 Japan

The Japanese government recently set three key areas and 14 growth sectors in an "Overview of Japan's Green Growth Strategy Through Achieving Carbon Neutrality in 2050" (METI, 2021). In the energy sector, it underlines offshore wind power generation, fuel ammonia, hydrogen, and nuclear power generation. In the transport/manufacturing sector, it underscores mobility/battery, semiconductor/ICT, maritime, logistics/ transport/infrastructure, foods/agriculture, forestry and fisheries, aviation, and carbon recycling. The home/office sector includes housing/building, resource circulation, and lifestyle-related industry. It also highlights the necessity of alternative measures including hydrogen import, bioenergy use, and electricity grid connection, underscoring technology innovation in the decarbonization sector of heavy industries.

Japan submitted its first NDC in November 2016, followed by an updated NDC in March 2020. The country's R&D strategy in climate technology is more clearly stated in the LEDS submitted in June 2019, rather than NDC with declaratory goals. The government encourages disruptive innovation as much as possible to achieve carbon neutrality, sets a target cost so that technology is adopted in the society, provides the maximum resources in private and public sectors, explores and creates potential technology in Japan and abroad, makes efforts into developing necessary infrastructure, and promotes the relevant initiative in this regard (Government of Japan, 2019). To this end, the country set the direction of climate technology R&D, which prioritizes promising technology with the aim of applying it in practice. In addition, it was announced that the country would keep reviewing the widespread use and possibility of technology in reflection of social needs to adopt decarbonization technology in the society on a large scale, visualize the needs of the user and bottlenecks to be addressed, and objectively present the possible feasibility and limitation of technology under development.

As detailed measures, the country mapped out a strategy to keep building an R&D platform for excellent technology, proceed with long-term R&D to make the best of brilliant ideas by individuals, and aggressively implement technology demonstration in the appropriate place (such as the market or production sites)

including overseas countries once the technology is established on a certain level. In particular, the Ministry of Economy, Trade and Industry (METI) of Japan launched an Unprecedented Challenge 2050, while the Ministry of Education, Culture, Sports, Science and Technology (MEXT) commenced a JST-Mirai program, implying that collaboration is being made to connect academic problems arising from research to the academia and serve as an intermediary on academic research topics related to what is used in the real world.

1.4 China

President Xi Jinping of China declared that the country will set the year of 2030 as the peak of carbon emissions and achieve carbon neutrality by 2060 in his address to the 75th UN General Assembly (Sep. 22, 2020). China upgraded its NDC to go carbon neutral while establishing effective policy and measures to reinforce scientific/technological support such as nurturing basic science research, research on and application of low-carbon technology, and international science cooperation in climate change to actively deal with climate change (Ministry of Ecology and Environment of the People's Republic of China, 2019). That move demonstrates that the largest emitter of GHG in the last century declared carbon neutrality by 2060 to ensure policy effectiveness for a new ecological civilization, with an aim to become a game-changer to exercise leadership in tackling the climate crisis in the international community.

The Chinese government set out the following three goals by stage to achieve carbon neutrality by 2060. The first stage (2020 to 2030) is to curb coal consumption and nurture the clean energy industry on a massive scale. The second stage (2030 to 2045) focuses on renewable energy, nurturing electric vehicles (EVs) and carbon dioxide capture technology. The third stage (2045 to 2060) is to introduce clean carbon emission technology, CCUS (Carbon Capture, Utilization, and Storage) and BECCS (Bioenergy with Carbon Capture and Storage) technologies in industries, power plants, transportation, and housing. In this regard, the central government underlines the role of science and technology (R&D) and innovation in tackling climate change and achieving net-zero (Busch et al., 2021). Since the first NDC was submitted in September 2016, China has not submitted an official updated document yet. Its climate technology R&D strategy described in the initial NDC shows that the country will improve basic research on climate change, conduct studies on the monitoring and forecast of climate change, and promote research on the impact and risk mechanism of climate change and assessment methodology (NDRC, 2015).

To be specific, it is suggested that the country will promote R&D and commercial demonstration on energy conservation, renewable energy, advanced nuclear power technology, and low-carbon technologies including CCUS, build up R&D on oil recovery, coal bed methane recovery, and an early warning

system on weather extremes. In addition, it will develop technologies on biological nitrogen fixation and the prevention and control of harmful insects and diseases, with the one related to green agriculture, while promoting R&D in technologies to save and desalinate seawater. Furthermore, it is proposed that the country will improve a technology support system for climate response to nurture manpower and fulfill the role of the government, set a mechanism to effectively integrate the cooperation between industry, university, research, and the government, and foster the talented specializing in the climate response.

1.5 South Korea

President Moon Jae-in of South Korea unveiled the goal of carbon neutrality by 2050 in an attempt to actively deal with climate change with the international community in his address at the National Assembly (Oct. 28, 2020). To this end, it was announced that the country will submit its LEDS with the goal of carbon neutrality by 2050 within the year, come up with roadmaps and implementation strategies for major tasks such as energy transition, industrial innovation, future cars, building an ecosystem conducive to innovation, the realization of circular economy, and fair transition. Furthermore, the country will launch a "Presidential Committee on Carbon Neutrality" and newly appointed the 2nd Vice Minister for Energy of the Ministry of Trade, Industry and Energy. Thereafter, on the occasion of the G20 Summit (Nov. 22, 2020), the government said that "carbon neutrality by 2050 is a bold challenge to transform the structure of industry and energy, which can be addressed only through international cooperation," and "South Korea is joining the international community towards carbon neutrality," demonstrating its commitment to achieving the goal.

Thereafter, South Korea came up with the 2050 Carbon Neutral Strategy (Dec. 7, 2020), which sets three policy directions of building a low-carbon economic structure, creating an ecosystem for low-carbon industry, and a fair transition to a carbon-neutral society, and a strategy of reinforcing the institutional foundation for carbon neutrality, with an aim to achieve carbon neutrality, economic growth, and a better quality of life all at the same time. And in its final LEDS submitted to the UN (Dec. 2020), under the "Carbon Neutral Strategy of the Republic of Korea towards a Sustainable and Green Society," South Korea proposed five basic directions for carbon neutrality: expanding the use of clean power and hydrogen, improving energy efficiency significantly in connection with digital technology, the development and commercialization of future decarbonization technology, stimulating a sustainable industry innovation towards a circular economy, and enhancing nature-based carbon sinks such as forests, mudflats, and wetlands.

Particularly regarding carbon neutrality R&D, the government established a "Strategy for Technology Innovation for Carbon Neutrality" (Mar. 31, 2021, Ministry of Science and ICT), presenting 10 key carbon-neutral technologies

and goals by 2050 and achievement strategies by technology based on the LEDS. South Korea submitted its first NDC in November 2016 and updated it in December 2020. The NDC presented its GHG emission reduction target and a plan to significantly increase R&D investment in core mitigation technologies (renewable energy, pollution-free cars, hydrogen technology, etc.) by implementing a KRW 73.4 trillion green new deal starting from 2020 (Government of the Republic of Korea (ROK), 2020).

South Korea clarified the following seven directions in the LEDS in December 2020. First, it will expand R&D for mitigation technology convergence and establish a life cycle, integrated R&D system first. In addition, to commercialize basic source technology, the country will actively reflect the voice of the user at an early stage of technology development and build a system in which businesses who need the technology participate in the R&D at the demonstration stage. Second, it will set the strategy and direction of national climate technology R&D, make the legal basis for it, and develop measures to support leading global standards and technology specifications beforehand to take the lead in the global market. Third, in carrying out a national R&D project, it will predict and reflect the expected GHG reduction of a technology to develop at a planning stage, evaluate the potential reduction amount of the technology under development in a systematic way in the project implementation stage to check the direction of technology development and use as the basis of policy-making. To this end, it will establish and standardize a methodology to calculate the reduction amount to set up relevant systems and secure an observation-based GHG emission verification system such as satellites. The purpose lies in building a system to objectively evaluate whether mitigation technology development is well underway and effective. Fourth, it will devise an analysis system to identify the effect of climate change adaptation technology such as the establishment of green infrastructure and an urban ecosystem, and use the system to come up with the best response route in a carbon-neutral society for synergy. Fifth, it will consider diverse environmental impacts including GHG reduction in a comprehensive manner when carrying out R&D to secure sustainable technology. Sixth, it will build a common assessment platform using an LCA (Life Cycle Assessment) method for R&D synergy from the technological combination in addition to unit technology, and fully use the platform to establish R&D strategy and implement policy, thereby promoting technology. Seventh, it will create a roadmap for innovative/breakthrough source technology on GHG reduction to implement R&D under the strategy and to expand investment at the same time.

1.6 Sub-conclusion

It is analyzed that major countries adopt or reinforce policies to nurture the green industry and establish new regulations to actively deal with climate

change and carbon neutrality. To be specific, they tend to announce the carbon neutrality goal together with plans to nurture and invest in the green industry. The EU announced a 1 trillion euro-package in the green industry for 10 years, with a $1.7 trillion investment by the U.S. for 10 years and South Korea's 73 trillion won-package by 2025. Furthermore, the EU and the U.S. accelerate discussions on the introduction of the carbon border tax. The EU, in particular, is tightening global environment regulations such as an upgraded car emission regulation and a new plastic tax. In this regard, the European Commission is discussing details of applying the carbon border tax, how to connect with the ETS (Emissions Trading System), and whether it is consistent with WTO rules. More recently, the commission announced its "Fit for 55" package to give shape to the discussion (Jang, 2021). In line with the policy trend in major countries, international financial organizations (IMF, BIS, etc.) also recommend a preemptive response against climate change on a national level such as raising the carbon tax and building a financial supervisory management system.

Regarding carbon-neutral technology, the analysis shows that all the countries plan to nurture renewable energy, energy efficiency, and CCUS. Among them, the U.S. and Japan try to include nuclear power in carbon-neutral technology to nurture, while South Korea focuses on technologies covering the life-cycle of hydrogen from production to storage and to utilization. The EU and Japan imply that they will provide further support in creating carbon sinks. In line with the policy trend, the market is rapidly changing as well. As carbon neutrality has become a key agenda to reorganize the global economic order by going beyond corporate social responsibility, the green market is exponentially growing accordingly. In particular, it is encouraging that business management considering climate change and the environment is spreading, as private and financial companies join RE100, invest more in the ESG, and limit their investment in a non-eco-friendly company. In that sense, the U.S.-based BlackRock, the world's largest asset manager, announced that it would not invest in a company that undermines the sustainability of the environment by carbon emissions, etc. (BlackRock, 2021), which demonstrates that carbon neutrality is reshaping the market. In addition, as each country pursues a greener energy production and utilization, the renewable energy industry such as photovoltaics (PV) and wind power is growing, and hydrogen is gaining momentum, along with rapid growth in the secondary cell market thanks to the wider use of EVs.

Under the analysis result of carbon-neutral policies in major countries, the following sub-conclusion can be produced with regard to S&T innovation policy for carbon neutrality in South Korea. The key to designing a carbon neutrality policy is that it is necessary to provide institutional support for carbon-neutral technology innovation (assessment system, support for technology introduction, etc.) in consideration of the needs of the market/industry and how to apply the

policy based on science, rather than a mere injection of budget. If new low-carbon technology innovation and sustainable economic growth are accelerated in the market/industry in the direction of carbon-neutral policy implementation in the future, government support and market intervention for carbon neutrality will be gradually reduced. The government, however, needs to keep paying keen attention to industries, workers, and communities which can be left behind politically and technologically in the process of achieving carbon neutrality. In addition, it is necessary to reduce backlash from industries that can be hit by carbon-neutral activities such as the ETS and the use of green fuels and provide support for a soft landing.

Table 3 Results of NDCs/LEDS analyses in major countries

Country	S&T Policies Presence		Key Policies for Science, Technology and Innovation within NDCs/LEDS
	NDCs	LEDS	
USA	O	O	(NDCs) - R&D and commercialization for low-cost power generation - R&D and commercialization of advanced transportation utilizing ultra-low carbon renewable fuels - Expansion of new technologies and investments for low-carbon construction - Encouragement of new hydrogen sources produced from carbon capture, renewable energy, nuclear power or waste (LEDS) - Expansion of public and private RDD&D support policies - Commercialization of CCUS, the 2nd generation biofuels and cutting-edge nuclear energy - Broader support to promote technologies to reducing the cost of decarbonization
Japan	-	O	(LEDS) - Building and continuing platforms for excellent technology and R&D - Supporting Long-term R&D for individual outstanding ideas - Promoting aggressive demonstration of climate technology including domestic & overseas countries - Supporting policies that connect the government's academic research and the market with special programs (activating climate technology R&D and fostering manpower) at the pan-ministerial level
China	O	-	(NDCs) - Reinforcement of the demonstration of low-carbon R&D and commercialization of renewable energy, advanced nuclear power, and CCUS - Reinforcement of R&D against oil recovery, coal layer methane recovery, and early warning systems in extreme weather - Development of agricultural-related technologies such as fixing biological nitrogen, preventing green pests, and diseases - Reinforcement of R&D on seawater-saving and desalination technologies - Development of the technology support system for responding to climate change - Establishment of a mechanism to effectively integrate industry-university-research institutions - Cultivating and strengthening professionals in response to climate change
South Korea	O	O	(NDCs) - Implementation for Green New Deal worth 73.4 trillion KRW from 2020 - Significant expansion of R&D investment in core reduction technologies such as renewable energy, eco-friendly automobiles, and hydrogen technologies (LEDS) - Expansion of convergence R&D of GHG reduction technologies and establishment of a whole cycle integrated R&D system - Establishment of an R&D system to strengthen the commercialization of basic research - Development of R&D strategies and legal basis for climate technology - Development of international standardization and technological standardization of climate technology - Comprehensive consideration of various environmental impacts, including GHG reduction effects, when planning & conducting R&D - Establishment of a methodology for calculating GHG reduction and preparing related systems such as standardization - Establishment of an objective evaluation system for observation-based GHG emission verification system and reduction technology such as satellites - Establishment of an analysis system for the effects of climate change adaptation technologies such as green infrastructure and urban ecosystem construction - Establishment of a common evaluation platform utilizing R&D and whole process evaluation related to synergy effects of technology convergence - Establishment of a roadmap for innovation/breakthrough basic technology related to GHG reduction

2. Analysis of Carbon-neutral Policies in Major Countries

2.1 Core Value of Carbon Neutral R&D Policy

The previous analysis result shows that major advanced countries have put in place diverse innovation policies and effective cases to achieve carbon neutrality. These policies and cases are expected to provide significant implications for the Korean government and the R&D field of the GRIs. Nevertheless, the policies of advanced countries may not exactly fit the reality and situation in South Korea. For this reason, this study conducted the FGIs on the global agenda of carbon neutrality and to which direction the GRIs respond, with 10 experts in the research field, technology and innovation policy, and academia, in addition to the policy analysis.

Table 4 Summary of remarks by experts participating in FGI

	Summary of remarks
Expert A	Developing and applying an 'R&D-Carbon Emission Reduction Forecast Scenario Program' model on how technology can cut carbon emissions in a pre-stage of R&D at the GRIs are necessary
Expert B	The establishment of a carbon-neutral R&D public procurement policy is necessary
Expert C	ICT-based carbon neutral response using AI and blockchain is necessary
Expert D	R&D innovation policy for national carbon neutrality needs to contribute to humanity and develop technology in reflection of a change in the innovation system across the society
Expert E	In reflecting ESG to assess the GRIs, a higher-level institution needs to deliberate on how to design guidelines and how the GRIs need to respond
Expert F	Carbon neutrality is a longer-term goal than the aforementioned policies; it is essential to come up with a long-term goal and a "Plan to Nurture Manpower in Carbon Neutral R&D
Expert G	A scenario that even considers changes in the industrial structure due to carbon neutrality is needed. Building and expanding a test bed facility to demonstrate after R&D is necessary.
Expert H	The current carbon-neutral R&D policy mainly focuses on cooperation with industries, but a long-term perspective and thorough pre-planning are in need to come up with detailed cooperation measures.
Expert I	Applying a macroscopic assessment model such as a new economic assessment model and the extension of time & space in carbon-neutral policy is important
Expert J	Considering measures to connect technology development by stage to other stage and technology one another and consider an additional reduction from the connection by building a system is necessary

It is also crucial to clearly figure out international discussions on carbon neutrality. The expert D said that "the European Green Deal and the Green New Deal of the U.S. and South Korea are different in policy implications and from the sociocultural context, as the Green Deal discusses philosophy and structural transformation across the society, while the Green New Deal is more about creating green jobs." It indicates that R&D innovation policy for national carbon neutrality needs to contribute to humanity and develop technology in reflection of a change in the innovation system across the society. In this regard, the expert I highlighted that "it is important to apply a macroscopic assessment model such as a new economic assessment model and the extension of time and space in carbon neutral policy." The reason lies in that technology development to go carbon neutral can only contribute to the national economy when economic feasibility is sufficiently reviewed. To be sure, a partial economic feasibility assessment cannot be the center of the R&D field, but it is necessary to review in advance the level of the carbon economy.

International carbon-neutral policies are likely to encompass the entire society. In this sense, expert B pointed out the importance of a Mission-Oriented Innovation Policy (MOIP) of OECD. He said that "measures to link the global, standardized MOIP framework with carbon-neutral innovation policy can be reviewed. In addition, as discussions on ESG are actively underway in the U.S. and Europe, it is necessary to review whether it can be applied to the GRIs." In this regard, the expert I underlined that "it is necessary to define the carbon-neutral sector in terms of demand and supply and design ESG in consideration of conditions in South Korea to adopt it in the country." The expert D emphasized that when applying the ESG concept in the public sector, "it is crucial to see it from the R&R of public organizations and take a long-term approach, not a short-term one," while the expert E pointed out that "in reflecting ESG to assess the GRIs, a higher-level institution needs to deliberate on how to design guidelines and how the GRIs need to respond."

In order for the GRIs to make effective progress in carbon-neutral R&D, organizations that support and nurture the GRIs or the government need to set a proper direction. The expert H argued that "comprehensive planning to achieve national carbon neutrality led by the GRIs is important, but the effort by the GRIs alone is not enough to hit the goal, so it is crucial to consider allocating roles and working with players of relevant industries, universities, and research institutes." The current carbon-neutral R&D policy mainly focuses on cooperation with industries, but a long-term perspective and thorough pre-planning are in need to come up with detailed cooperation measures. For this reason, a follow-up, detailed action plan requires in-depth discussions between players. Expert F said that "as carbon neutrality aims to cut GHG emissions by nature, a life-cycle strategy is in need so that the technology of the GRIs is applied to a 'test bed' of industries." Given that each research institute considers

mitigation technology development and measures by phase under the national carbon-neutral R&D policy, an organization is needed to arrange and manage them in a comprehensive way. In addition, the expert J stressed that "it is essential to consider measures in which each stage of technology development is connected to one another and to other technologies while building a system which considers an additional reduction from that connection."

2.2 Policy Recommendations for the GRIs

As carbon-neutral R&D policy on a national level encompasses industries and academia, policy planning and implementation need to be led by the GRIs. Expert A underlined that it is necessary to "develop and apply an 'R&D-Carbon Emission Reduction Forecast Scenario Program' model on how a technology can cut carbon emissions in a pre-stage of R&D at the GRIs." That comment was to mention the importance of designing scenarios and action plans in detailed areas in government policy to support carbon neutrality. Expert G said that "it is time to come up with a scenario in consideration of the GRIs and even an industrial structure change from carbon neutrality." In this regard, expert E argued that "currently, it is hard for individual research institutes to measure the carbon emission reduction or contribution of R&D that they are working on." For this reason, it is effective for the higher-level institution or the government to design and apply the development of the program model.

As R&R is set by GRI, a strategy is necessary to make the best of it. Expert A explained that "the Green Technology Center (GTC) has a competitive edge in designing the policy framework for carbon-neutral technology and the promotion of international collaboration, while the Korea Institute of Energy Research (KIER) is competent in energy production and efficiency. The Korea Electrotechnology Research Institute (KERI) has the upper hand in transmission and distribution alongside the EMS (Energy Management System), while the Korea Institute of Civil Engineering and Building Technology (KICT) deals with BEMS (Building Energy Management System). The Korea Institute of Industrial Technology (KITECH) is competent in mitigation technology and production process, while the Electronics and Telecommunications Research Institute (ETRI) has an advantage in applying green ICT and digitalization for carbon neutrality." Furthermore, the expert H mentioned the Act on the Promotion of Technology Development and additionally explained that "it is supposed to select an institution dedicated to climate change technology development, so it is necessary for the GRIs to pay attention and play their role."

"Digitalization" is one of the 10 carbon-neutral technologies. In the Fourth Industrial Revolution and the Green New Deal, the so-called DNA (Data, Network, and AI) was highlighted. It is also necessary to develop a strategy to apply ICT, the nation's strength, in the right place at the right time, put in place the DNA technologies, and adopt them in industry. Expert C underscored an

ICT-based carbon neutral response using the AI and blockchain. He said that it is important to build a system to "apply digital twin technology in urban design and industrial process management as in the case of the 'Industrial IoT Business' by GE in the U.S." Expert G discussed the necessity of building and expanding a testbed facility to demonstrate after R&D. He mentioned that "even though the GRIs carry out national R&D, it is crucial to think of a 'town-based' testbed rather than a massive application which takes much time and cost." That suggestion can be a great initiative to link the demonstration and R&D of carbon neutrality and develop and commercialize relevant technology. In addition, expert F highlighted the educational aspect. He emphasized that "as in the Fourth Industrial Revolution, the Green New Deal, and ESG, diverse policies have been devised on a national level, and discussions have been made subsequently on manpower nurturing." Given that carbon neutrality is a longer-term goal than the aforementioned policies, it is essential to come up with a long-term goal and a "Plan to Nurture Manpower in Carbon Neutral R&D." Last but not least, it is expected that the discussion result of the 10 experts will present a tailored carbon neutral strategy or the best practices applicable to the GRIs as below.

Table 5 Public R&D strategies for carbon neutrality based on the FGI results

	Strategies and alternative policies
Expert A	System and policy of the international joint research innovation platform to cope with climate change
Expert B	Policies for public procurement of R&D to achieve carbon neutrality and a net economy
Expert C	Development of a new green financial platform that connects carbon neutrality and Data-Network-AI (DNA)
Expert D	Development of a strategy to link the national research institute's technological innovation policy with the carbon market (analysis of the effect of linking carbon tax or carbon border tax)
Expert E	Carbon-neutral NEXUS strategy to strengthen basic research
Expert F	Development of commercialization strategy linking carbon-neutral R&D and carbon market
Expert G	Establishment of a carbon-neutral innovation policy and R&D roadmap centered on contributions (annual)
Expert H	Re-establishment of roles and missions according to the 2050 carbon neutrality goal
Expert I	Regional industry-academic cooperation and establishment of a model for suggesting bottom-up policy alternatives
Expert J	International joint research with the International Research Institute and the Association of Korean Scientists abroad

V. Conclusion

1. Carbon Neutral R&D Strategy for the GRIs

Around 120 countries declared or are preparing to declare carbon neutrality. In this regard, advanced economies such as Europe, the U.S., and Japan place high expectations on the role of science and technology in achieving the goal. In addition, the result of R&D in those countries is expected to contribute to innovative national growth considerably. As a result, implementing a carbon-neutral S&T policy requires R&D strategies fit for the situation in South Korea, which intends to use the policy as a new momentum, along with effective goals and vision. Above all, to achieve the implementation target encompassing all government departments and social areas, in addition to the R&D field, preliminary and thorough action plans need to be established together.

To date, the GRIs have contributed to the national economic growth and leading innovation. Carbon neutrality has become an inevitable challenge to the world, and it requires a solution. The GRIs are asked to take on carbon neutrality which is the calling of the times and address the issue institute-wide. To this end, it is necessary to review the support for basic/source research, applied/industrial research, ICT utilization, transfer, and commercialization in consideration of impacts on the market and industry in a comprehensive manner. Given that a low-carbon technology available tomorrow is determined by how much we invest in technological innovation today, the government and higher-level institutions need to provide institutional support for technological innovation led by the private sector, along with carbon tax policy (Park et al., 2021).

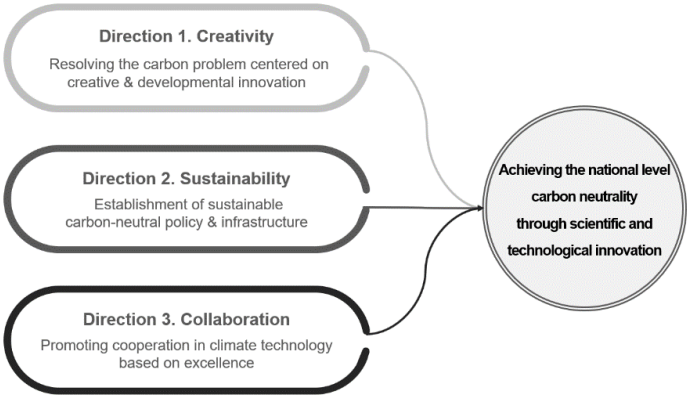

Figure 2 Science, Technology and Innovation Strategies to Achieve National Carbon Neutrality

This study analyzed science technology (R&D) innovation policies in each country upon carbon neutrality and carried out the FGIs with a group of experts. Depending on the result of the study, the following "R&D strategies to achieve carbon neutrality" can be suggested, and they are expected to contribute to "reaching national carbon neutrality through science technology innovation." The first strategy is "creativity" that is to address climate change based on emergent innovation. As it is time to hit the goal of carbon neutrality by going beyond a low-carbon society, it is crucial to make more creative and innovative progress in R&D activities. The second strategy is "sustainability" that is to build and apply a sustainable carbon-neutral policy and infrastructure. To be specific, in-depth discussions are required on laws and institutions alongside matters such as human resources development, facilities, equipment, and sub-programs in the policy. The third one is "collaboration" that is to facilitate cooperation in climate technology based on excellence. Cooperation can be divided into domestic and international, or central and local levels.

Jung (2000) argued that international cooperation in science and technology to tackle environmental issues on the planet is not an option but an obligation to be fulfilled as a member of the international community. In this sense, it is necessary to encourage practical and reciprocal cooperation between global leading institutions and researchers, not based on reputation or performance in international cooperation.

As for each strategy, the following goals and sub-implementation strategies are expected to be achieved. First, in addressing carbon issues based on emergent innovation, it is possible to set the target of the promotion of basic/source research and the development of applied/industrial technology. The goal can also suggest detailed implementation strategies, including the promotion and support of basic/source research on climate, the environment, and energy, encouraging technology development that connects the carbon industry to the market, and boosting R&D activities linking carbon neutrality to the 4th Industrial Revolution (e.g., Data, Network, AI). Second, in order to establish a sustainable R&D policy and infrastructure for carbon neutrality, it is imperative to set a goal of building them across the life cycle. To this end, it is necessary to establish innovation policy and R&D roadmaps for carbon neutrality, support R&D systems, equipment, facility, assessment systems, and newly launch a "Committee on innovation for carbon neutrality (tentative)" under the MSIT and research councils. Third, promoting climate technology cooperation based on excellence requires models of bilateral/multilateral cooperation and bottom-up support for community-based programs. Detailed implementation strategies include bilateral research support using joint committees on science and technology and S&T associations for overseas Koreans, promoting multilateral cooperation and networking with international research institutes and organizations, and setting a bottom-up model and

program support for community-based cooperation between industries, universities, and research institutes.

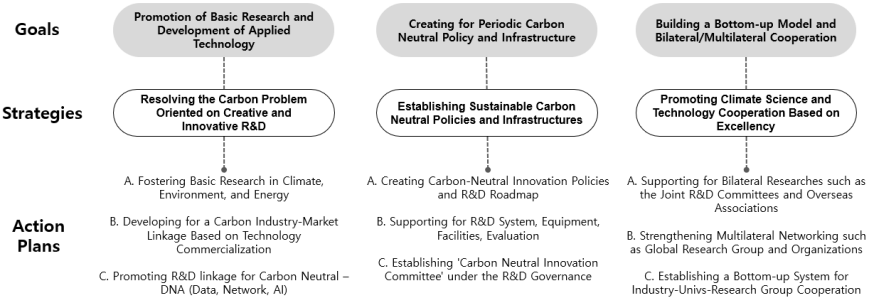

Figure 3 A Model of public R&D implementation for National Carbon Neutrality

2. Implications and Limitations

It is more appropriate to use the aforementioned strategies and detailed action plans to develop an integrated strategy on a national level or by GRIs under research councils, rather than individual GRI implementing them. In addition, as described in the policy analysis of major advanced countries, diverse stakeholders engage in joint research and cooperation across the society to contribute to achieving national carbon neutrality. Furthermore, it is necessary to provide support so that the innovation strategy of the GRIs is included in the goal and scenario to reach carbon neutrality by 2050 on a national level, making efforts to keep consistency with the existing policies on climate & the environment and R&D. Moreover, it is needed to raise awareness that climate response is a national agenda, and develop detailed tasks of carbon-neutral policy in connection with international cooperation and overseas expansion by referring to the policies of the EU and Japan which focus on "international relations."

This study interviewed a group of some experts, which is not a quantitative study on researchers of the GRIs. For this reason, it analyzed policies and cases of major advanced countries, rather than reviewing the R&D status of all GRIs, and suggested strategies that can be reviewed by government departments working on science and technology or strategy department of research councils. If a follow-up study is carried out, strategies will be designed with practical data on carbon-neutral R&D from the quantitative research on experts from the government, the GRIs, and relevant institutions.

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