MARINE CLIMATE TECHNOLOGY RESEARCH TREND ANALYSIS AND TECHNOLOGY LEVEL EVALUATION FOR FIVE MAJOR COUNTRIES

Kyung-Ran Choi[1], Seungseob Euh[2]*

[1]Seoul National University of Seoul & Technology, Graduate School of Convergence Science, Department of Energy Policy, 232 Gongreung-Ro, Nowon-Gu, Seoul, 01811, Republic of Korea

[2]Seoul National University of Seoul & Technology, Research Center for Energy Convergence, 232 Gongreung-Ro, Nowon-Gu, Seoul, 01811, Republic of Korea

*Corresponding Author: livelab21@nate.com

ABSTRACT

Rapid increases in greenhouse gases due to climate change have led to a surge in extreme weather events. Marine climate technologies offer solutions focusing on observation, reduction, absorption and the prevention of weather-related damages. This study establishes a classification system for marine climate technology, analyzes research trends, and evaluates the technological levels of five major countries: South Korea, the United States, China, Japan, and the European Union (EU). Marine climate technology is categorized into four major groups: monitoring and observation, reduction, absorption, and adaptation. As a result of analyzing 23,221 research papers published from 2013 to 2022, the monitoring and observation field was the most common with 9,314 papers, followed by reduction with 7,269, adaptation with 3,756, and absorption with 2,882. The Technology Strength index revealed that the EU and US have the highest technological capabilities, scoring 767.9 and 637.2 respectively, indicating a strong correlation between research output and technological leadership. The analysis revealed South Korea is 5.7 to 6.7 years behind the US in most areas, except for marine renewable energy and greenhouse gas reduction efficiency. The Delphi survey indicated the main factors for South Korea's gaps are lack of basic research support, insufficient research and development funding, and inadequate government policies. Securing a leading position in marine climate technology is crucial for greenhouse gas reduction and climate change response.

NOMENCLATURE

CPP	Cites Per Paper
PII	Paper Impact Index
TS	Technology Strength
EU	European Union
WOS	Web of Science
R&D	Research and Development
KIOST	Korea Institute of Ocean Science and Technology

1 INTRODUCTION

As climate change continues, the rapid increase in greenhouse gases in the atmosphere is leading to a rise in extreme weather events worldwide (Halpern *et al*., 2015; Poloczanska *et al*., 2016; Trégarot *et al*., 2024). This trend is attributed to various aspects of modern lifestyles, such as excessive coastal development and environmental pollution, which are identified as major contributors to climate change through the increased emission of greenhouse gases (Abel *et al*., 2011; Choi *et al*., 2020). Covering approximately 70% of the Earth's surface, the ocean plays a crucial role in mitigating climate change

https://doi.org/10.52202/077185-0153

by absorbing the heat and greenhouse gases generated by global warming (Abraham *et al*., 2022). From this perspective, marine climate technology, focusing on climate change observation, greenhouse gas reduction, absorption and storage, and prevention of weather-related damages in the marine sector, is considered a promising alternative to address environmental challenges and respond to climate change (Gattuso *et al*., 2018; Hoegh-Guldberg *et al*., 2019).

However, to achieve the international consensus on reducing greenhouse gases and addressing climate change, particularly the goals set by the Paris Agreement adopted in 2015, there are still many deficiencies in the current field of marine climate technology. Specifically, recent research calls for urgent development of innovative technologies for the absorption and storage of greenhouse gases and the protection of marine ecosystems (Gattuso *et al*., 2018; Hoegh-Guldberg *et al*., 2019). Although the overall technological capability of marine climate technology has shown considerable progress over the last decade, this pace of development is still not sufficient when considering the severity of climate change. For instance, current carbon dioxide absorption technologies can only process a very small fraction of the annual emissions. Moreover, future core technologies for addressing marine climate change, such as blue carbon development or other innovative technologies, will require a leading technological edge. Therefore, it is crucial first to understand how marine climate change-related technologies have evolved from the past to the present and to identify the demand for technology development needed by future societies and humanity. Analyzing research trends and the current level of technology, based on this understanding, to establish strategic decisions for the development of marine climate technology will be highly significant.

Meanwhile, the Delphi survey method, based on the consensus of expert groups, has been utilized to analyze research trends and current levels of technological development (Kanama, 2013; Keller and Gracht, 2014; Haleem *et al*., 2019; Flostrand *et al*., 2020). The Delphi survey employs the intuitive judgments of experts, proceeding through a consensus-building process among a specified group of experts on the given topic (Crisp *et al*., 1997). However, with the acceleration of technological advancement in recent times, the production of technological trend information such as research papers, patents, and research reports has also increased exponentially. Therefore, in the process of formulating strategies for scientific and technological development, relying solely on expert-based opinion gathering methods presents challenges in conducting objective comparisons of rapidly evolving technologies. In response, some researchers have endeavored to understand the development levels and trends within specific scientific and technological fields through the investigation and analysis of quantitative items such as research papers and patents (Vargas *et al*., 2017; Li *et al*., 2020; Pace *et al*., 2023). Particularly in the field of marine climate technology, analyses of research trends and technology levels have been conducted using methods such as patent mapping (Lin and Chen, 2016; Zhang *et al*., 2018), citation network analysis of papers (Pauna *et al*., 2019), and text mining to compare research papers and patents (Kuzminov *et al*., 2018).

Building upon this framework, this study aims to analyze the research and development (R&D) trends of major countries in marine climate technology, classified into major groups and subcategories based on research paper outputs, and to provide the results of technology level analysis based on expert Delphi surveys. The remainder of this paper is organized into four sections. The classification system for marine climate technology is described in Section 2. The analysis of research trends and the Delphi survey method are presented in Section 3. Section 4 discusses the research findings, and the final section concludes the study.

2 CLASSIFICATION SYSTEM FOR MARINE CLIMATE TECHNOLOGY

In this study, the marine climate technology classification system was established utilizing the National Institute of Green Technology's national climate technology classification system and the Korea Institute of Ocean Science and Technology's (KIOST) proposed marine climate technology classification system. KIOST's classification system comprises four major groups: monitoring and observation, reduction, absorption, and Adaptation; 12 subcategories; and 82 specific technological areas. This study focuses on conducting a research study on the technology levels in the marine climate sector, covering the four major groups, as well as the 12 subcategories.

https://doi.org/10.52202/077185-0153

The monitoring and observation sector is defined as 'technologies for observing and measuring changes in the marine environment to assess the impacts of climate change,' and is differentiated into two areas: 'marine climate change phenomena and impact observation technology,' 'marine atmospheric pollution observation technology.' The Reduction sector is defined as 'technologies aimed at reducing the total amount of greenhouse gases or controlling their emissions,' and is divided into four areas: 'port sector emission reduction technology,' 'marine climate sector energy potential estimation technology,' 'marine renewable energy generation technology,' and 'greenhouse gas reduction efficiency and process improvement technology.' The Absorption sector is defined as 'technologies for absorbing, storing, or removing greenhouse gases from the marine atmosphere,' and is bifurcated into three areas: 'marine greenhouse gas capture and storage technology' and 'marine-based carbon removal technology,' and 'blue carbon development and management technology.' The Adaptation sector is defined as 'technologies for adjusting to and preventing damage from the actual or anticipated impacts due to climate change in the marine sector,' and is divided into three areas: 'Infrastructure adaptation technology (for responding to marine climate change),' 'fisheries and ecological sector impact adaptation technology,' and 'adaptation technology for managing marine warming.' The definitions for the subcategories of marine climate technologies are presented in Table 1.

Table 1: Subcategories of marine climate technology and definitions

Code	Subcategories	Definitions
M1	Marine climate change phenomena and impact observation technology	Technology for observing marine climate change to identify vulnerable regions, develop national climate change scenarios, and provide information services for early warning and response through atmospheric environmental modeling
M2	Marine atmospheric pollution observation technology	Technology used to identify atmospheric pollution originating from the marine sector, utilizing marine-atmospheric greenhouse gas/carbon observations and port atmospheric pollutant monitoring, in order to develop mitigation strategies
R1	Port sector emission reduction technology	Technologies for reducing carbon emissions in the port sector, including low-carbon/no-carbon ship technologies
R2	Marine climate sector energy potential estimation technology	Technologies for estimating the potential of offshore wind, tidal, and wave energy, as well as for generating renewable energy (such as offshore wind, tidal, and wave energy) from the ocean
R3	Marine renewable energy generation technology	Technologies for generating renewable energy from the ocean, including offshore wind power, tidal energy, and wave energy
R4	Greenhouse gas reduction efficiency and process improvement technology	Technologies for improving ship energy efficiency, developing low-carbon processes through the utilization of marine waste resources, constructing zero-carbon fuel supply infrastructure, and commercializing marine energy
Ab1	Marine greenhouse gas capture and storage technology	Technologies for capturing large amounts of CO2 generated in the ocean, followed by compression, transportation, and safe storage within the marine subsoil, or direct utilization and conversion into useful substances
Ab2	Marine-based carbon removal technology	Technologies for nutrient fertilization, artificial upwelling and downwelling, seaweed cultivation, restoration of marine and coastal ecosystems, and enhancement of ocean alkalinity and phytoplankton absorption capacity
Ab3	Blue carbon development and management technology.	Technologies that include the restoration of mudflats and salt marshes, coastal formation using mangrove forests, protection of seaweed and marine benthic organisms to explore blue carbon, and isolation carbon measurement, detection, mapping

https://doi.org/10.52202/077185-0153

Ad1	Infrastructure adaptation technology (for responding to marine climate change)	Technologies for maintaining and strengthening infrastructure in response to disasters or environmental changes caused by marine climate change
Ad2	Fisheries and ecological sector impact adaptation technology	Technologies for fisheries resource management, minimizing the impact on marine ecosystems (such as harm from harmful organisms, damage due to ocean acidification) to secure future fisheries resources and a green environment
Ad3	Adaptation technology for managing marine warming	Technologies to mitigate and address the impacts of marine warming, including measures for marine warming, increasing marine cloud reflectivity, and enhancing sea surface albedo

3 METHOD

This study analyzes trends and technological levels in the field of marine climate technology, utilizing both quantitative and qualitative measurement methods. Quantitative measurements involved the analysis of research paper trends, whereas qualitative measurements were conducted through expert Delphi surveys. This analysis encompassed five key countries: South Korea, the United States, China, Japan, and the European Union (EU).

3.1 Analysis of Research Paper Trends

In the analysis of research paper trends, this study targeted papers associated with marine climate technology, utilizing keywords relevant to this field for the search. The Web of Science (WOS) information platform was employed to search for these paper details. The WOS, a database provided by Clarivate Analytics, enables the simultaneous search of over 60 million records listed in the Science Citation Index Expanded and the Social Sciences Citation Index, among others. The search keywords for the four major technology groups related to this field are as follows:

· ts=(("marine" or "ocean") and ("climate change") and (monitor* or observ*))
· ts=(("marine" or "ocean") and ("climate change") and (reduc* or mitigat*))
· ts=(("marine" or "ocean") and ("climate change") and (capture* or separat* or absorpt* or storage* or adsorpt*))
· ts=(("marine" or "ocean") and ("climate change") and (adapt*))

The search strategy for research paper information was designed to emphasize three primary criteria: the titles, abstracts, and author keywords of the documents. For subcategory technologies, the classification was further refined using subcategory keywords from the major group data, followed by analysis. The analytical scope encompassed a comprehensive review of documents, including articles, letters, reprints, and reviews, published within the timeframe from January 2013 to December 2022, totaling 23,221 papers. Subsequently, the papers considered for analysis were limited to those published by institutions affiliated with the five key countries associated with marine climate technology: South Korea, the United States, China, Japan, and the EU.

For the analysis of research trends, the study examined the number of papers published, the number of authors, research activity, and research influence as the fundamental metrics from 2013 to 2022. Research activity is defined as the ratio of the number of papers published (A) to the number of authors (B), while research influence is determined by the ratio of citation index (C) to the number of papers published (A). As indicators of the technological level in the analysis of research paper trends, the study utilized Cites Per Paper (CPP), Paper Impact Index (PII), and Technology Strength (TS). CPP serves as an indicator of the extent to which papers from the target countries have influenced subsequent publications, with higher values suggesting a higher qualitative level of the papers. This can be represented by formula (1), where n_t represents the number of papers published in year t, and C_i denotes the citation count of the paper.

$$CPP = \frac{\sum_{i=1}^{n_t} C_i}{n_t} \quad (1)$$

https://doi.org/10.52202/077185-0153

The PII is an indicator used to measure the impact of papers based on the citation ratio, where a higher value indicates a higher qualitative level of the paper. This can be represented as formula (2), where C_a denotes the citation count of papers from a specific country, N_a represents the number of papers from that specific country, C_t is the total citation count of all papers, and N_t indicates the total number of all papers.

$$PII_a = \frac{CPP_a}{CPP_t} = \frac{C_a}{N_a} / \frac{C_t}{N_t} \tag{2}$$

The PII greater than 1 implies that the papers from a certain country are cited more frequently than the global average, indicating a greater impact of those country's papers. CPP signifies the simple average citation count, whereas PII can be interpreted as a measure of a paper's relative impact. TS evaluates both the qualitative and quantitative levels of papers by incorporating the PII, which represents the qualitative level, with the number of papers as an indicator of quantitative productivity. This can be depicted as formula (3), where PII_i is the PII value for the given year i, and N_i is the number of papers in that year. As an indicator that complements PII, which emphasized qualitative aspects, TS allows for an assessment of comprehensive capabilities.

$$TS_i = PII_i \times N_i \tag{3}$$

3.2 Analysis of Delphi surveys

The technological level and technology gap in the field of marine climate technology of the major five countries were evaluated through expert Delphi surveys in this study. This Delphi survey was conducted from November to December 2023, targeting 20 experts in the field of marine climate technology over two rounds. In the first round of Delphi, each expert evaluated the technological level, technology level groups, technology gap, and the reasons and contributions to the gap between South Korea's technological level and that of the top technology-holding country. The second round of Delphi was conducted by presenting the results of the first round for experts to revise their responses. Specifically, the technological level was evaluated by first investigating the top technology-holding country among the major five countries, then converting the technological level of the top country to 100% as a benchmark to assess the technological levels of other countries relative to it. The technology gap was assessed by considering the gap of the top technology-holding country as zero years and estimating the time required for other countries to reach the current technological level of the top country. Subsequently, the technology level groups of countries were divided into Top, Leading, Chasing, Following, and Lagging groups based on expert evaluation response rates for comparative analysis.

The Top group possesses technology and development capabilities that are close to or equivalent to the top technology-holding country, the Leading group is leading in the technology field, the Chasing group is capable of imitating and improving advanced technologies, the Following group is capable of adopting advanced technologies, and the Lagging group has weak R&D capabilities. Moreover, to comprehensively analyze the technology level groups of countries based on expert responses, results were judged as Top for response rates from 81% to 99%, Leading for 61% to 80%, Chasing for 41% to 60%, Following for 21% to 40%, and Lagging for 1% to 20%. Lastly, the stages of technological development were comparatively evaluated using a six-point Likert scale consisting of Development, Introduction, Growth, Expansion, Maturity, and Decline.

4 RESULTS

4.1 Analysis of Research Paper Trends by Major Groups

The number of valid papers related to marine climate technology published from January 2013 to December 2022, along with the distribution of these papers by country, is presented in Table 2. The valid papers mentioned refer to those selected for actual data analysis after reviewing necessary items and fields within the dataset obtained using specified search keywords for paper information. Based on the analysis of marine climate technology-related papers (9,314 in monitoring and observation, 7,269

https://doi.org/10.52202/077185-0153

in reduction, 2,882 in absorption, and 3,756 in adaptation), EU emerges as the country with the highest number of published papers, indicating a strong research focus and capacity.

The annual publication trends for papers analyzed across the four major groups are depicted in Figure 1. The EU leads in marine climate technology research across all categories, with the United States following closely as the second most active in research activities. China has shown a steady increase in research activities, particularly from 2018 to 2022, especially in the monitoring and observation, and absorption sectors, indicating rapid growth in marine climate technology research. South Korea has demonstrated a gradual increase in the number of research papers from 2013 to 2022, yet the overall volume of publications remains lower compared to the major countries such as the United States, EU, and China. Japan has maintained consistent and stable research activities overall, with a slight decrease in reduction research post-2020, while showing an increase in adaptation research. These publication trends highlight the EU and the United States as technological leaders in marine climate technology, as evidenced by their high volume of research outputs. The significant number of publications from these regions not only reflects their advanced research capabilities but also their leadership in technological development. The steady increase in China's publications suggests its growing capabilities and ambitions to close the technological gap with the leading countries.

Table 2: The results of effective papers researched about marine climate technology

Country	**Number of Papers**					**Period**
	Total	**Monitoring& Observation**	**Reduction**	**Absorption**	**Adaptation**	
South Korea	406	196	127	45	38	2013.01. ~ 2022.12.
China	2,543	1,059	826	343	315	
Japan	898	372	275	124	127	
United States	8,127	3,245	2,505	1,048	1,329	
EU	11,247	4,442	3,536	1,322	1,947	
Total	23,221	9,314	7,269	2,882	3,756	

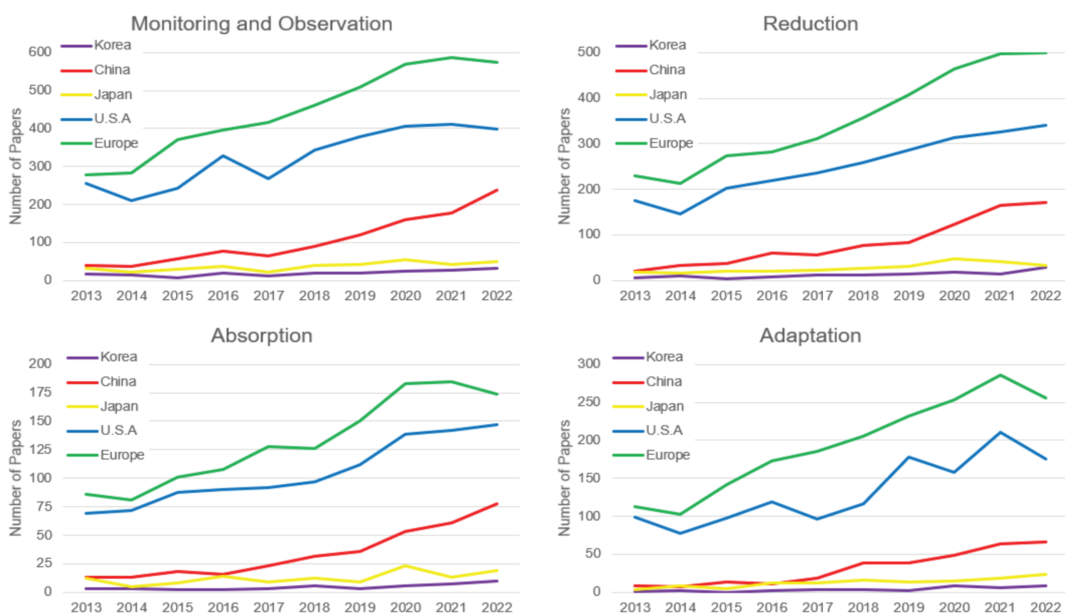

Figure 1: Annual number of papers in the 4 major groups by country

https://doi.org/10.52202/077185-0153

4.2 Analysis of Research Citations, Influence, and Technological Capability

This study assesses the marine climate technology research capacity of major countries by analyzing citation frequency, influence, and technological capability, with specific metrics detailed in Table 3. In monitoring and observation, Japan leads with the highest influence index over the past decade, while EU indicates the top technological capability. Despite South Korea's lower technological capability index, it surpasses China in influence. The 2022 citation frequencies further reveal Japan's dominance at 611.1, the highest, and China's at 134.4, the lowest. The reduction major group mirrors this pattern, with Japan's influence peaking at an index of 3.06 and EU standing out for its technological capacities. However, South Korea's indices in both areas lag, with its citation index at 143.8, below Japan's leading 448.9.

The absorption and adaptation groups continue to highlight the competitive landscape, with Japan maintaining the highest influence index and EU leading in technological capability across the board. South Korea's performance in both influence and technological capability remains comparatively modest, with its 2022 citation index at 72.6, far behind Japan's 263.3. In the adaptation major group, the United States emerges with the highest influence index, paralleled by EU's unmatched technological capability. Notably, the United States also leads the citation index at 303.2 in 2022, indicating significant research impact, whereas China records the lowest at 159.7. These findings underscore the correlation between publication trends and technological leadership. The high citation frequencies and influence indices of Japan and the EU reflect their strong technological capabilities and leadership in marine climate technology. South Korea and China, while making progress, need to enhance their research influence and technological proficiency to bridge the gap with leading countries.

Table 3: 2022 research and technology indices by country

Major Groups	Index	South Korea	China	Japan	United States	EU
Monitoring and Observation	Citation	172.3	134.4	611.1	318.6	266.9
	Influence	0.9	0.7	3.1	1.6	1.3
	Capability	28.5	159.7	150.1	637.2	767.9
Reduction	Citation	143.8	164.6	448.9	322.4	257.9
	Influence	0.7	0.8	2.2	1.6	1.3
	Capability	19.8	138.6	72.9	541.3	635.0
Absorption	Citation	72.6	126.2	263.3	260.5	239.3
	Influence	0.4	0.7	1.4	1.4	1.3
	Capability	3.8	52.2	26.5	202.9	220.6
Adaptation	Citation	244.8	159.7	234.7	303.2	263.2
	Influence	1.2	0.8	1.1	1.5	1.3
	Capability	10.6	50.7	26.0	256.8	324.2

4.3 Analysis of Research Paper Trends by Subcategories

Throughout the analysis period, the monitoring and observation major group saw a publication of 9,314 papers, with a notable focus on marine climate change phenomena and Impact observation, which accounted for 4,534 papers or 48.7% of the group's total output. Air pollution was another significant subcategory, contributing 2,644 papers, approximately 28.4% of the total. EU emerged as the leading publisher across both subcategories, demonstrating substantial research activity in these areas. The distribution of publications underscores the dominant research contributions from EU and the United States, with China, South Korea, and Japan also making significant contributions, albeit to a lesser extent.

In the reduction major group, a total of 7,269 papers were published, with port sector emission reduction, marine renewable energy generation, marine climate sector energy potential estimation, and greenhouse gas reduction efficiency and process improvement as the primary subcategories. Port sector emission reduction alone comprised 1,481 papers or 20.4% of the total, highlighting a keen interest in

 https://doi.org/10.52202/077185-0153

carbon-neutral vessel technology. Marine renewable energy generation dominated the group's discourse, representing 43.3% of the publications, where EU again led in output, underscoring the region's commitment to sustainable energy research.

The absorption major group, encompassing marine greenhouse gas capture and storage and blue carbon development and management subcategories, contributed a smaller yet focused set of 2,882 papers. Marine greenhouse gas capture and storage, in particular, accounted for a significant portion of the research within this group, with EU maintaining a leadership position in publication count. Additionally, adaptation research, aimed at addressing the direct impacts of climate change, was covered in 3,756 papers, focusing on infrastructure adaptation, fisheries and ecological Sector, and managing marine warming subcategories. The fisheries and ecology subcategory represented the largest share, indicating a strong emphasis on ecological resilience and sustainability. EU's leading role in publications across these subcategories reaffirms its position as a key player in climate change adaptation research. Collectively, the research findings on marine climate change technology, spanning the major groups of monitoring and observation, reduction, absorption, and adaptation, are detailed in Table 4.

Table 4: Research paper distribution across major groups and subcategories

Major group	Subcategory	Total papers	EU	United States	China	Japan	South Korea
Monitoring and Observation	Climate Change Phenomenat	4,534	2,037	1,682	522	197	96
	Air Pollution	2,664	1,096	941	406	142	79
Reduction	Ports	1,481	693	525	176	54	33
	Energy Potential Estimation	208	126	42	31	6	3
	Renewable Energy	3,150	1,667	1,028	275	125	45
	Greenhouse Gas Reduction	817	382	269	112	36	18
Absorption	Carbon Capture and Storage	286	130	98	38	16	4
	Ocean-Based Carbon Removal	836	401	285	106	31	13
	Blue Carbon	505	261	157	60	22	5
Adaptation	Infrastructure Adaptation	634	330	206	64	23	11
	Fisheries and Ecological Sector	1,679	862	649	108	47	13
	Managing Marine Warming	946	504	282	96	49	15

4.4 Technology Level and Technology Gap

The systematic analysis of technological levels and gaps in marine climate technology among the five major countries, spanning four major groups and twelve subcategories, has unequivocally positioned the United States as the technological frontrunner, establishing it as the benchmark with a technology level set at 100%. This analysis ranks the EU (91%), Japan (76%), South Korea (64%), and China (60%) in subsequent order. The technological gaps relative to the United States are assessed at 1.3 years for the EU, 3.3 years for Japan, 5.7 years for South Korea, and 6.7 years for China, indicating a substantial difference in technological capabilities with a gap of approximately 40%, or about 7 years, between the United States and China. Particularly, in the major groups of monitoring and observation, and reduction, the United States has been identified as maintaining the highest technology level, with further analysis revealing the order of EU (89%, 95%), Japan (77%, 76%), South Korea (65%, 65%), and China (59%, 57%).

https://doi.org/10.52202/077185-0153

Similarly, in the Absorption and Adaptation major groups, the United States leads, with South Korea's technology levels assessed at 64% and 62% respectively. The technological gaps with EU, Japan, and China are detailed as 0.7 years, 2.9 years, 4.9 years, and 6.8 years in the Absorption group, and 0.6 years, 3.2 years, 5.1 years, and 6.9 years in the Adaptation group, respectively. This analysis confirms that the United States and EU consistently rank in the top group across all major groups, with Japan and South Korea in the leading group and China in the chasing group. The study reaffirms the technological leadership of the United States and EU, while providing a detailed examination of how Japan, South Korea, and China are positioned in the advancement of marine climate technology. The technology levels and gaps across the four major groups for the aforementioned major five countries are shown in Figure 2.

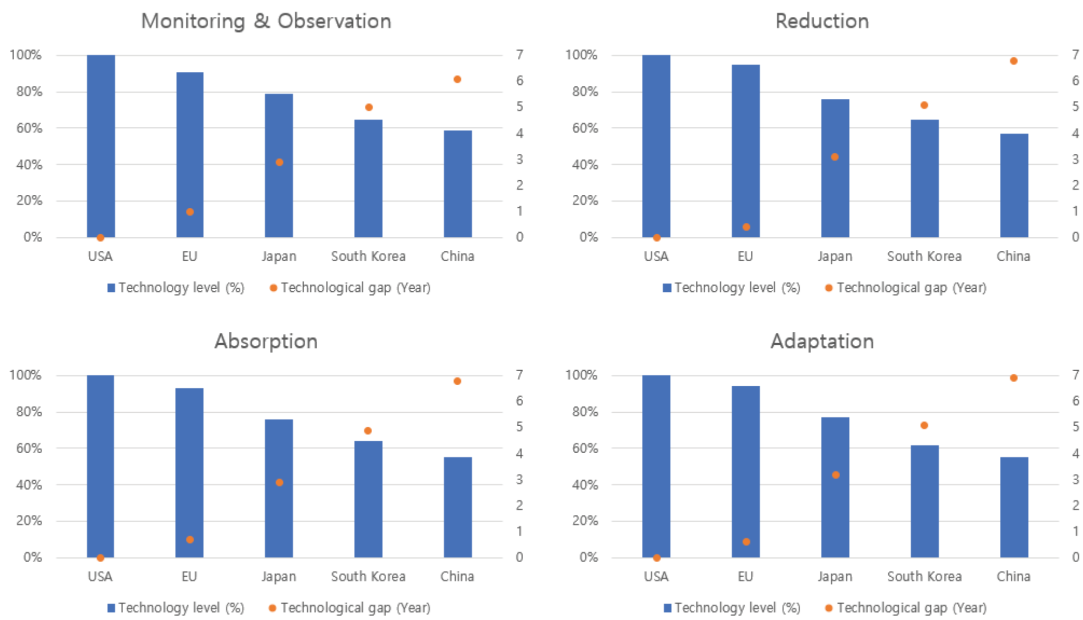

Figure 2: Technology level and gap in major groups by country

In the realm of marine climate technology, the Delphi survey delineates the technological standings and disparities across major groups and subcategories, underscoring the United States as the paramount leader. Within the Monitoring and Observation major group, the survey identified the United States as the forefront in marine climate change phenomena and impact observation technology, with South Korea's technology level at 67%, benchmarked against the United States, followed by EU at 89%, Japan at 77%, and China at 57%. The technological gaps compared to the United States are quantified as 1.1 years for EU, 3.3 years for Japan, 4.9 years for South Korea, and 6.7 years for China. Similarly, for marine atmospheric pollution observation, the United States leads, with South Korea's technology level at 62%, and the technological gaps showing to 1.1 years for EU, 3.1 years for Japan, 5.9 years for South Korea, and 6.5 years for China.

In the reduction major group, the United States excels in port sector emissions reduction, with South Korea at 66% of the United States technology level, alongside EU at 95%, Japan at 76%, and China at 58%. The gaps from the United States perspective are 0.8 years for EU, 3.2 years for Japan, 4.7 years for South Korea, and 6.7 years for China. Contrarily, EU emerges as the leading entity in marine climate sector energy potential estimation and marine renewable energy generation technologies, with South Korea's technology levels pegged at 68% and 64% respectively, against the leading technology holder. The technological discrepancies from EU's stance are 0.7 years for the United States, 2.4 years for Japan, 4.4 years for South Korea, and 5.2 years for China in energy potential estimation, and for renewable energy generation, the gaps are 0.4 years for the United States, 2.9 years for Japan, 5.1 years for South Korea, and 6.6 years for China.

https://doi.org/10.52202/077185-0153

In the absorption major group, EU is distinguished as the dominant leader in marine greenhouse gas capture and storage technology, showcasing a technological prowess with South Korea's technology level at 64%, behind the United States at 93%, Japan at 78%, and ahead of China at 55%, all benchmarked against EU. The technological gaps, expressed relative to EU, manifest as 0.8 years for the United States, 2.8 years for Japan, 4.7 years for South Korea, and 6.9 years for China. In the realm of ocean-based carbon removal technology, the United States secures its leadership with South Korea's technology level recorded at 63%, trailing behind EU at 93%, Japan at 75%, and leading over China at 56%. The gaps range from 0.8 years for EU to 6.7 years for China, compared to the United States Similarly, in the Adaptation major group, the United States is identified as the pioneer in infrastructure adaptation technology with a sequence of national technology levels starting with EU at 94%, Japan at 78%, South Korea at 62%, and China at the lowest with 54%, showcasing gaps from 0.6 years for EU to 7.2 years for China. The United States also leads in fisheries and ecological sector impact adaptation technology, positioning South Korea's technology level at 63%, with EU at 93%, Japan at 79%, and China at 56%. The technological discrepancies from the United States perspective range from 0.7 years for EU to 6.8 years for China. The information regarding the technical level and gap for subcategories is presented in Figure 3.

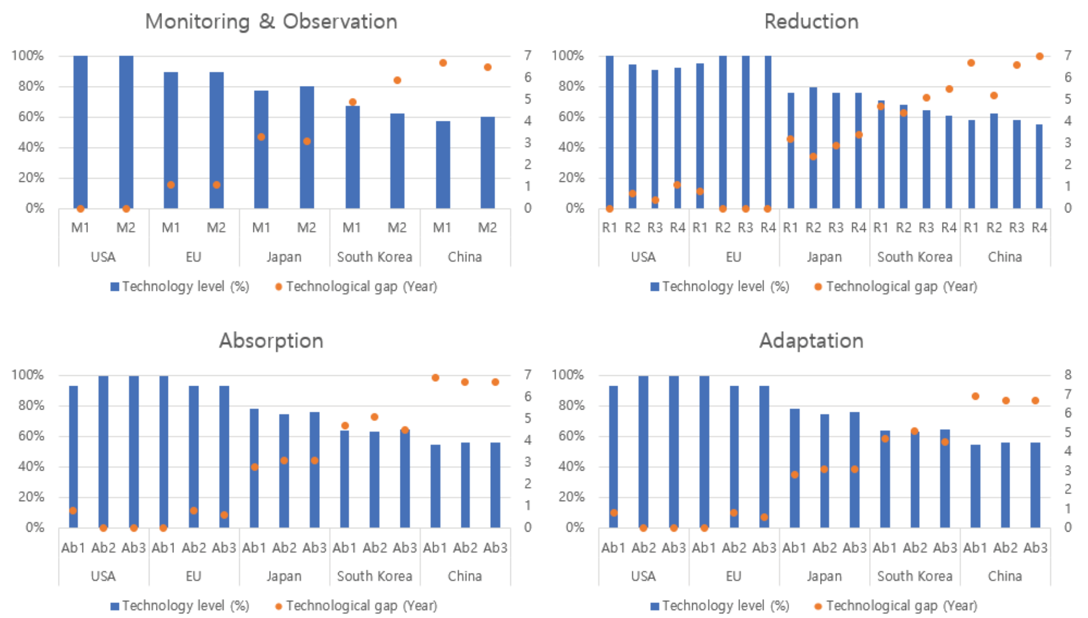

Figure 3: Technology level and gap in subcategories by country

4.5 Barriers to Technological Progress: Analysis of Causes, Stages, and Threats

Survey results from experts suggest that the primary cause of the gap in South Korea's technological level, in comparison to countries with top technology is the lack of support in basic research areas. In order of relevance, the lack of support in basic research areas received the highest rating (4.5 points), followed by a shortage of R&D personnel (4.3 points), insufficient R&D funding (4.0 points), inadequate government support policies (3.8 points), and weak R&D infrastructure (facilities and equipment) (3.4 points). Additionally, the narrow scope of the domestic demand market (2.7 points), inadequate commercialization of developed technologies (2.5 points), a lack of R&D technical information (2.3 points), weak domestic collaboration (among industry, academia, and research institutions at 2.2 points, and poor international cooperation (1.6 points) were identified as contributing factors.

Regarding the technological development stages, the United States, which holds the leading position in marine climate technology, is in the maturity phase (rated at 4.5 points), while South Korea is in the growth stage (2.8 points). According to the data from 2023, the most significant threat to the

https://doi.org/10.52202/077185-0153

development of marine climate technology overall is the risk associated with private investment (4.3 points). This risk was identified as the most substantial threat, followed by the urgency of technological development (4.2 points), and the scale of infrastructure (4.0 points). Medium threat levels were associated with the likelihood of success in technology development (3.3 points), difficulty in acquiring technology (3.2 points), and the originality of the technology (3.0 points), showing a close similarity to the initial results.

5 CONCLUSIONS

This study aims to provide foundational data for formulating technological development strategies in the marine climate technology sector by analyzing research trends and current technological level analyses across four major groups and twelve subcategories in five major countries: South Korea, the United States, China, Japan, and the EU. Quantitative analyses were conducted on research papers to assess research and technological trends, while qualitative analyses through expert Delphi surveys evaluated the technological levels and gaps. The analysis of research trends from 2013 to 2022 revealed consistent increase in research activities across all major areas of marine climate technology, including monitoring and observation, reduction, absorption, and adaptation. The EU emerged as the leader in research output, followed by the United States, highlighting their strong research capabilities and technological leadership. Japan demonstrated the highest influence index in monitoring and observation, while the EU showed the top technological capability. Despite South Korea's lower overall technological capability index, it surpassed China in research influence, suggesting a potential for growth in technological proficiency. China's steady increase in research activities reflects its rapid growth, although its technological impact remains lower compared to leading countries.

The TS index highlighted that the EU and the United States possess the highest technological capabilities, scoring 767.9 and 637.2 respectively. This strong correlation between high research output and technological leadership underscores the importance of impactful research. Japan's significant influence index of 3.06 in the reduction category further emphasizes its strong research impact and technological standing. The Delphi survey results for South Korea indicated that the primary factors contributing to technological gaps include a lack of support in basic research, insufficient R&D funding, and inadequate government policies. South Korea, while making progress, needs to address these areas to enhance its technological capabilities. Additionally, through the analysis of technology levels and gaps, it was found that, except for marine renewable energy generation technology and greenhouse gas reduction efficiency and process improvement technology, South Korea demonstrates a technological gap of approximately 5.7 to 6.7 years behind the United States in most technological areas. Therefore, addressing the identified gaps in basic research support and R&D funding will be crucial for South Korea to enhance its overall technological capabilities.

Securing a leading technological position in marine climate technology is crucial for addressing global environmental challenges and achieving sustainability goals. In this regard, this study has performed quantitative and qualitative evaluations of research papers as R&D outputs, which can be utilized as foundational data for strategizing leadership in future marine climate technology. Further research should continue to monitor and analyze technological trends and gaps, focusing on specific areas where improvements are needed. Through these efforts, countries can develop effective strategies to enhance their technological capabilities and contribute to the global effort in combating climate change.

REFERENCES

Abel, N., Gorddard, R., Harman, B., Leitch, A., Langridge, J., Ryan, A., & Heyenga, S., 2011, Sea level rise, coastal development and planned retreat: analytical framework, governance principles and an Australian case study, *Environ. Sci. Policy*, vol. 14, no. 3: p. 279-288.

Choi, K.R., Kim, J.H., & Yoo, S.H., 2020, Public perspective on constructing sea forests as a public good: A contingent valuation experiment in South Korea, *Mar. Policy*, vol. 120: p. 104146.

Crisp, J., Pelletier, D., Duffield, C., Adams, A., & Nagy, S.U.E., 1997, The Delphi method?, *Nurs. Res.*, vol. 46, no. 2: p. 116-118.

 https://doi.org/10.52202/077185-0153

Flostrand, A., Pitt, L., & Bridson, S., 2020, The Delphi technique in forecasting–A 42-year bibliographic analysis (1975–2017), *Technol. Forecast. Soc. Change*, vol. 150: p. 119773.
Gattuso, J.P., Magnan, A.K., Bopp, L., Cheung, W.W., Duarte, C.M., Hinkel, J., ... & Rau, G.H., 2018, Ocean solutions to address climate change and its effects on marine ecosystems, *Front. Mar. Sci.*, vol. 5: p. 410554.
Halpern, B.S., Frazier, M., Potapenko, J., Casey, K.S., Koenig, K., Longo, C., ... & Walbridge, S., 2015, Spatial and temporal changes in cumulative human impacts on the world's ocean, *Nat. Commun.*, vol. 6, no. 1: p. 1-7.
Haleem, A., Mannan, B., Luthra, S., Kumar, S., & Khurana, S., 2019, Technology forecasting (TF) and technology assessment (TA) methodologies: a conceptual review*, Benchmarking: An Int. J.*, vol. 26, no. 1: p. 48-72.
Hoegh-Guldberg, O., Caldeira, K., Chopin, T., Gaines, S., Haugan, P., Hemer, M., ... & Tyedmers, P., 2019, The ocean as a solution to climate change: Five opportunities for action, World Resources Institute: p. 112.
Kanama, D., 2013, Development of technology foresight: Integration of technology roadmapping and the Delphi Method, In: Technology roadmapping for strategy and innovation: Charting the route to success, p. 151-171.
Keller, J., & von der Gracht, H.A., 2014, The influence of information and communication technology (ICT) on future foresight processes—Results from a Delphi survey, Technol. *Forecast. Soc. C*hange, vol. 85: p. 81-92.
Kuzminov, I., Bakhtin, P., Khabirova, E., & Loginova, I.V., 2018, Detecting and validating global technology trends using quantitative and expert-based foresight techniques, Higher School of Economics Research Paper No. WP BRP, 82.
Li, X., Fan, M., Zhou, Y., Fu, J., Yuan, F., & Huang, L., 2020, Monitoring and forecasting the development trends of nanogenerator technology using citation analysis and text mining, *Nano Energy*, vol. 71: p. 104636.
Lin, J.C., & Chen, W.M., 2016, Harvesting Green Energy from Blue Ocean in Taiwan: Patent Mapping and Regulation Analyzing, In: Sustainable Energy-Technological Issues, Applications and Case Studies, IntechOpen.
Pace, L.A., Borch, K., & Deidun, A., 2023, Bridging knowledge gaps towards 2030: the use of foresight for the strategic management of a sustainable blue economy, *Sustainability*, vol. 15, no. 13: p. 10026.
Poloczanska, E.S., Burrows, M.T., Brown, C.J., García Molinos, J., Halpern, B.S., Hoegh-Guldberg, O., ... & Sydeman, W.J., 2016, Responses of marine organisms to climate change across oceans, *Front. Mar. Sci.*, vol. 3: p. 180581.
Trégarot, E., D'Olivo, J.P., Botelho, A.Z., Cabrito, A., Cardoso, G.O., Casal, G., ... & de Juan, S., 2024, Effects of climate change on marine coastal ecosystems–A review to guide research and management, *Biol. Conserv.*, vol. 289: p. 110394.
Vargas Martínez, E.E., Hoyos Concha, J.L., Acevedo Rincón, J.F., Montes Hincapié, J.M., Rojas Fernández, G.L., Zartha Sossa, J.W., & Palacio Piedrahita, J.C., 2017, Priority technologies and innovations in the fishing agribusiness by the year 2032. Foresight study through the Delphi method.
Web of Science Group. 2024. Web of Science. [Accessed 2023 Dec. 2]. Available from: https://clarivate.com/webofsciencegroup/ko/
Zhang, H., Zheng, Y., Zhou, D., & Long, X., 2018, Selection of key technology policies for Chinese offshore wind power: a perspective on patent maps, *Mar. Policy*, vol. 93: p. 47-53.

ACKNOWLEDGEMENT

None.

https://doi.org/10.52202/077185-0153