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A study on a political system for the advance in green hydrogen technology: a South Korea case study

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Abstract

Background Hydrogen energy, a type of renewable energy if produced without fossil fuel, has a critical issue in that most of it is still produced from carbon footprint heavy industries such as the fossil fuel industry. It is imperative to produce hydrogen from renewable sources on a global level so that the carbon footprint can be curbed. South Korea, along with other global economies such as the US, the EU, Japan and China, has shown its resolution to build a hydrogen economy with green hydrogen produced only from renewable sources. Since 2017, South Korea has been actively shaping its political actions and policies to develop the necessary technology for this transition. This study focuses on South Korea's actions and policies, using a political system model to better understand the shift towards a green hydrogen economy.

Results The analysis shows that budgeting for R&D projects has had a significant impact on scientific breakthroughs, advancements, and product development in the field of green hydrogen in South Korea. These actions have also affected market performance, resulting in increased interest and investment in green hydrogen. Although there have been significant advancements in the field of green hydrogen in South Korea, the current state of technology remains in its early stages of development. Most of the breakthroughs have been in water-to-hydrogen and biomass-to-hydrogen technologies. However, these technologies show promise as the foundation of a thriving hydrogen economy in South Korea. The analysis also indicates a strong market demand for green hydrogen technology. To support these efforts, the political system has focused its financial support on water-to-hydrogen technology and projects at the TRL 1–3 stage.

Conclusions The study concludes that ongoing financial and political support is necessary for areas showing outstanding performance to vitalize the hydrogen economy and facilitate the transition to a green hydrogen society in the future. Additionally, a robust legal framework is crucial to ensure steady growth of the green hydrogen economy, similar to those in other major hydrogen economies such as the US and Germany. This study serves as a case study of South Korea, showcasing the impact of political actions on the advancement of scientific technology.

Keywords Hydrogen energy, Renewable energy, Green hydrogen, Political system

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Background

Hydrogen energy, which emits zero carbon footprint when consumed, has been mostly produced from fossil fuels such as methane or natural gas [1]. This reality about hydrogen energy raises the question: "Is hydrogen energy actually a clean energy?" [2–5]. There has been a global consensus that this way of producing hydrogen is hardly sustainable [6–9]. Big economies such as the US, the EU, Japan and China have shown a resolution to replace hydrogen produced from natural gas (grey hydrogen) with hydrogen from water or biomass produced with renewable energy (green hydrogen) [10–14]. Grey hydrogen is solely produced from fossil fuels such as natural gas. Blue hydrogen is similar to grey hydrogen in that it is a fossil-fuel-based hydrogen but with carbon dioxide stored in the production process [9]. Green hydrogen is produced from renewable sources such as water powered with solar or wind energy. Green hydrogen is considered the most eco-friendly because it emits no carbon footprint and can safely store renewable energy [15].

Since the Moon administration came to power in 2017, South Korea has joined the global trend of pursuing a green hydrogen economy [2, 16–19]. In addition to meeting the requirements for a green hydrogen economy, such as social acceptance and community agreement, South Korea has made significant efforts to develop the technology aspect of green hydrogen due to its high dependence on energy imports (92.8%), as reported by the Ministry of Foreign Affairs [20]. Given its high dependence on energy imports, South Korea has made significant efforts to develop green hydrogen technology as a crucial component of its energy security strategy. To this end, the country has introduced over a dozen policies related to green hydrogen since 2017, laying the foundation for an institutionalized system necessary for a green hydrogen economy [21–23]. The implementation of such policies requires a set of environmental conditions such as demands, support, and a political system, as defined by David Easton [24]. Figure 1 in Easton's model provides a suitable theoretical framework to explain how social demands for green hydrogen are institutionalized into policies [24, 25]. In this case, the demands and support have come from within and outside of South Korea, such as the Paris Agreement of 2018 and the national will to domestically develop green hydrogen technology to achieve energy independence [26]. The South Korean government also aims to monetize the developed technology to facilitate energy exports [6, 19]. These demands as inputs drive the political system which leads to the outputs.

Laws and policies are critical components of building a green hydrogen economy in South Korea, and they are among the outputs of the political system. Since there are currently only a few legal frameworks related to hydrogen, such as a single hydrogen safety law [2], the dozen or so green hydrogen policies introduced since 2017 are the primary outputs. The purpose of this study is to examine the political system and analyze its output of policies for green hydrogen technology. Specifically, this study aims to define and analyze the relationship between the political system and green hydrogen policies. Since politics involves multiple factors [27–30], a study of the political system can take various forms. For instance, researchers have used literature research to understand Bangladesh's policy for greening its brick industry [31], a game-theoretic model to examine the change in market behavior resulting from Pakistan's climate policy [32], and a survey to learn about the influence of Korean policy on perceptions of hydrogen fuel cell vehicles [17]. Others have used indicator-based analysis to identify the causes and effects of water policies in India [33], an evolutionary game model to analyze the impact of national policy on new energy vehicles (NEV) [34], and Data Envelopment Analysis (DEA) to evaluate the impact of a policy by examining the outputs of government-funded research projects [35].

Evaluating government-funded research projects in terms of their budgets and outputs provides an effective and measurable way to see how political action, such as funding research and development (R&D) projects, affects the advancement of technology. To our knowledge, the analysis of policies and government-funded projects in terms of green hydrogen in South Korea has not been carried out yet. In this study, the political system, an authoritative allocation of resources according

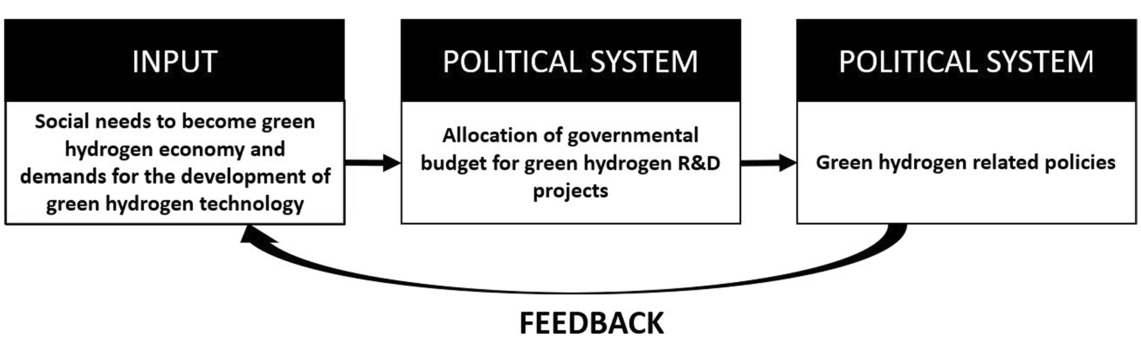

Fig. 1 Schematic of political system

to David Easton's study, is defined as the distribution of national budgets for green hydrogen R&D research projects as presented in Fig. 1 [24]. Accordingly, the elements of the political system are defined as the political actions of budgeting and their impacts, which are the outputs of financed R&D projects, such as journals or patents. The major contributions of this work are to help the South Korean government understand the political system for the advancement in green hydrogen technologies for future planning and to show where South Korea, a large global economy, is positioned with respect to green hydrogen energy.

The rest of the article is structured as follows. Methods provides the methodology of the data collection and the analysis of the political system and policies. Results and Discussion show the analysis of the political actions of budgeting, the project outputs, and the policies. The conclusions presents the conclusion and policy recommendations.

Methods

Data collection

The method for the data collection is summarized in Table 1. First, hydrogen, especially green hydrogen, related policies were found on the websites of government ministries and government websites for policy information. For the government budget analysis, the data on government-funded hydrogen projects during 2017–2021 were collected from the website of the National Science & Technology Information Service (NTIS). NTIS is a South Korean governmental database service which provides government-funded R&D project data. A total of 5824 hydrogen projects were identified, of which 2098 were green hydrogen projects. Last of all, the data of the project outputs were also collected from the NTIS website. Specifically, 13,684 journals, 5613 patents, 72 technology, and 39 business data from hydrogen projects were collected. In the case of patents and journals, duplicate outputs were counted and deleted. Journal data, peer-reviewed articles, including scientific research articles, review articles, conference articles and letters. Patent data include domestic and international patents. The technology case means the case of sold technology developed in a government-funded R&D project. The case of business means a research project developing into a business.

Table 1 The type of data, its source and chosen data for analysis

Type of data	Source	Data for analysis
Policies	Websites of the government ministries	Year Ministry Objectives
Projects	NTIS	Year Budgets Technology Readiness Level (TRL)* Type of green hydrogen technology
Project outputs	NTIS	Journal information Patent information Technology case Business case

* TRL is assessed based on technology concepts, requirements, and capabilities and consists of 9 levels with the first level being the most basic and the last level being the most mature

Analysis

Political system

The political system consists of two parts: political action and its impacts. In the political system, political action is an allocation of the national budget to green hydrogen R&D projects. Political action is analyzed in terms of the size of the budget and the type of projects to be funded. The impacts of political actions are measured and analyzed based on scientific and market performance, which are both important and representative. The indices for scientific impacts include journals and patents. The indices for market impacts are the number of sold technologies and the number of business cases. The scientific and market impacts are studied by year, technology, and TRL of projects.

Policies

The green hydrogen policies are the outputs of the political system. The policies are analyzed yearly and by their main objectives. Further analysis is carried out in terms of how the policies are aligned with the elements of the political system such as political actions and the impacts.

Results

Budget analysis as political action

The political system is analyzed by examining the political action of budgeting. The analysis is carried out in three categories: the budget, the technology readiness level (TRL) of projects, and the types of developed technologies. Firstly, government funding for hydrogen projects and green hydrogen projects increased nearly 3.5fold from 2017 to 2021, as shown in Table 2. About a quarter of the total hydrogen budget was allocated to green hydrogen projects, while the remaining 75% of the budget was spent on hydrogen storage, utilization (e.g., fuel cells), and safety-related projects. This indicates a significant increase in financial support for green hydrogen R&D projects. Compared to the annual average increase of 5.8% in R&D project budgets from 2016

Table 2 Yearly budgets for hydrogen and green hydrogen projects in 2017–2021

	(Unit: 10^8 Won(10^8 USD))					
	2017	**2018**	**2019**	**2020**	**2021**	**Total**
Hydrogen projects	1886 (1.45)	1739 (1.34)	2382 (1.83)	3974 (3.06)	6641 (5.11)	16,624 (12.8)
Green hydrogen projects	372 (0.286)	436 (0.336)	666 (0.513)	841 (0.648)	1239 (0.954)	3555 (2.74)
Fraction	0.19	0.25	0.28	0.21	0.18	1

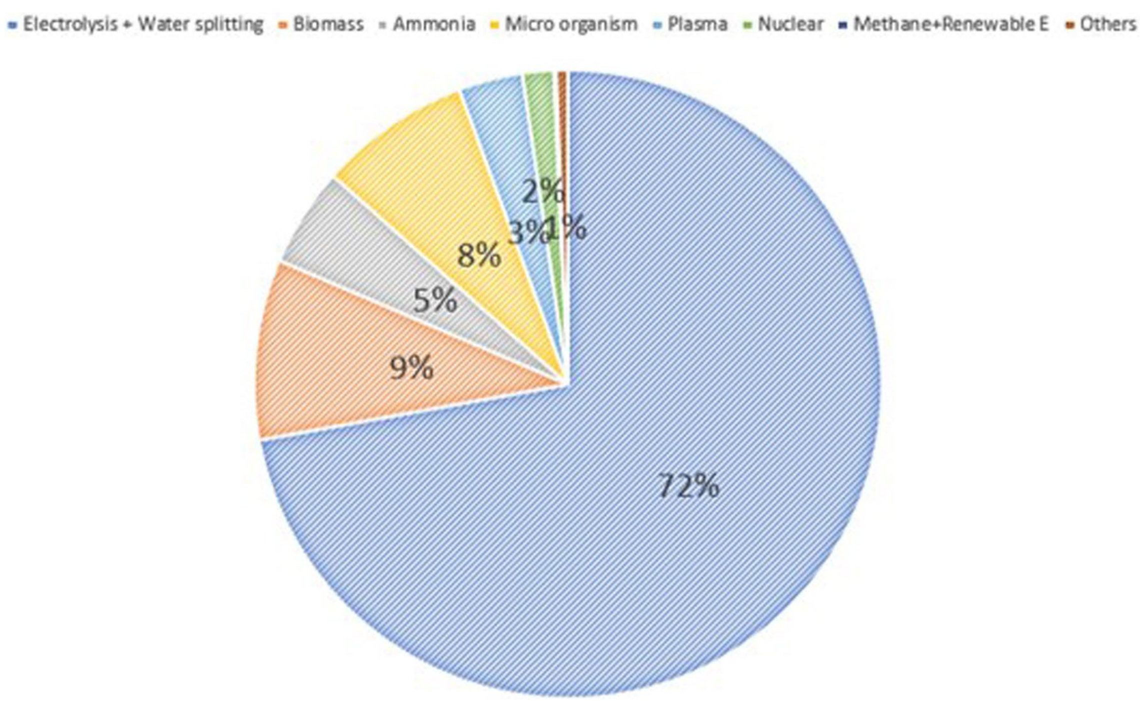

Fig. 2 Budget composition of green hydrogen projects by its goal technology to develop

to 2020, the 233% increase for green hydrogen research is considerably higher [36].

The next part to assess is the budget scale for specific green hydrogen technologies. As shown in Fig. 2, a majority (72%) of the green hydrogen budget has been allocated for water-to-hydrogen technology projects. The water-to-hydrogen projects concern processes to extract hydrogen from water using any type of energy source, including nuclear and plasma energy. The rest of the green hydrogen projects concern the production of hydrogen from biomass or ammonia and various technologies such as microorganisms, plasma, and nuclear power-aided hydrogen production which is also called yellow hydrogen. It can be said that the emphasis is given to water-to-hydrogen technology with a majority of the budget allocated there. Biomass technology is the second most invested technology.

Table 3 Budgets for different TRLs of green hydrogen projects (20172021)

	(Unit: 10^8 Won(10^8 USD))			
	TRL 1–3	**TRL 4–6**	**TRL 7–9**	**NI***
Budget	1429 (1.1)	802 (0.618)	1160 (0.893)	162 (0.125)
No. of projects	1097	208	256	55
Increase rate per year	40	60	80	–

* Not identified or the others

Lastly, the budget scale for green hydrogen R&D projects on different TRLs is analyzed as shown in Table 3. The analysis reveals that projects on TRL 1–3 were funded the highest between 2017 and 2021, accounting for 41% of the total green hydrogen budget. There is not a big difference between the budget size for TRL 1–3 projects and TRL 7–9 projects. The regression analysis found that the projects on TRL 1–3 are funded with the lowest yearly increase rate of 40 (10^8won/year), which indicates that more budget was allocated to projects on higher TRLs as the year progressed. It can be said that the allocation of funding for the fundamental level of green hydrogen technology has not been prioritized in the previous years of political actions.

Impacts as political action

The policy impacts are analyzed in terms of the outputs of the funded green hydrogen projects which are journal, patent, sold technology, and business case. First, yearly outputs are studied and presented in Table 4. In the span of 2017–2021, green hydrogen projects yielded numerous scientific accomplishments, including 3258 scientific journals (non-SCI and SCI articles), 990 patents, 72 sold technologies, and 39 business cases. In comparison to the average performance of total R&D projects of 2015–2020 in Table 5, the outputs except for journals have underperformed. Here, the 6-year average between 2015 and 2020 was utilized for comparison because this is the most recent available data. The most plausible reason for this is that the research field of green hydrogen technology in South Korea is too rudimentary to start producing these outputs. These types of outputs can come in the future according to the time-lag effect. The time-lag effect means years or sometimes decades could be required for research projects to start producing outputs. Another proof that the field is still on a rudimentary level is the fact that only scholarly performance (journal) met the average level of total R&D projects with the rest of market-related outputs underperforming because the first output from research projects tends to be research journals.

Secondly, the outputs per specific technologies were analyzed and shown in Table 6. Most of the scientific and marketable achievements were made in water-to-hydrogen technology. These projects accounted for the majority (80%) of journals, patents, and technology cases related to green hydrogen. The result makes sense, considering the majority of the green hydrogen budget was allocated to the technology. It is also noticeable that the highest amount of business cases came from biomass technology which is a significant achievement because biomass technology acts as a bridge technology between a grey and green hydrogen economy.

Table 4 Yearly outputs of journals, patents, technology, and business from green hydrogen projects

	2017	2018	2019	2020	2021	Total
Journals	481	596	515	668	998	3258
Patents	257	232	262	208	31	990
Technology	15	12	11	31	3	72
Business	12	8	15	3	1	39

Table 5 Average value of R&D project outputs (2016–2020) [35]

	Journals (SCIE only)	Patents	Technology	Business
Total R&D project (2015–2020)	204,042 (0.63/project)	253,850 (0.75/project)	45,857 (0.14/project)	148,900 (0.46/project)
Green hydrogen projects (2016–2021)	2163 (0.74/project)	990 (0.34/project)	72 (0.03/project)	39 (0.02/project)

Table 6 Outputs of journals, patents, technology, and business cases per each green hydrogen technologies

	Water-to-hydrogen	Hydrogen from biomass	Hydrogen from ammonia	Microorganism aided process	The others
Journals	2599 (80%)	246 (7.5%)	47 (1.4%)	114 (3.4%)	252 (7.7%)
Patents	795 (78%)	71 (8.3%)	27 (3.3%)	58 (6.3%)	42 (4.1%)
Technology	32 (82%)	3 (7.6%)	1 (2.5%)	3 (7.6%)	0 (0%)
Business	32 (44%)	34 (47%)	1 (1.3%)	3 (4.1%)	2 (2.7%)

Table 7 Outputs of journals, patents, technology, and business case per projects on varying TRLs

	TRL 1–3	TRL 4–6	TRL 7–9	NI*
Journals	2467 (75%)	360 (11%)	200 (6.1%)	231 (7.0%)
Patents	591 (60%)	162 (16%)	204 (20%)	33 (3.5%)
Technology	4 (5.5%)	6 (8.3%)	57 (79%)	5 (6.9%)
Business	30 (76%)	4 (10%)	5 (12%)	0 (0%)

[*] Not identified or the others

Table 8 The comparison of the entire technology and green hydrogen sector in terms of project outputs

	Total R&D projects	Green hydrogen technology projects
Journals	75% from TRL 1–3 projects	75% from TRL 1–3 projects
Patents	34% from TRL 1–3 projects	60% from TRL 1–3 projects
Technology	72% from TRL 7–9 projects	79% from TRL 7–9 projects
Business	78% from TRL 7–9 projects	76% from TRL 1–3 projects

Lastly, an analysis of the performance of projects on different TRLs is presented in Tables 7 and 8. The majority of journals, patents, and business cases were produced by projects on TRL 1–3, while projects on TRL 7–9 with more advanced technology scored highest in terms of monetization. The performance in terms of journals is consistent with the trend seen in the annual report by NTIS, which showed that 75% of published journals in all fields were from projects on TRL 1–3 in 2016–2020. In terms of patents, while the NTIS analysis of total patents in all fields in 2015–2021 shows that 34.42%, 20.34%, and 45.2% of patents were, respectively, from TRL 1–3, 4–6, and 7–9 projects, as much as 60% of green hydrogen patents came from projects on TRL 1–3. This is likely due to the fact that the highest amount of green hydrogen budget was allocated to projects on TRL 1–3, as evidenced by the fact that 1,097 projects were in the TRL 1–3 range. In terms of technology cases, most technology in all fields (72.2%) from 2015 to 2020 came from projects on the highest TRL of 7–9, as advanced technologies are more marketable. For green hydrogen projects, 79% of technology cases were from TRL 7–9 projects, which is consistent with the trend seen in past years of total R&D projects. In terms of business cases, most businesses from total R&D projects from 2015–2020 came from the most advanced level of projects (TRL 7–9), with only 5.4% of business cases from projects on TRL 1–3. However, for green hydrogen projects, most business cases (76%) came from projects on TRL 1–3, which is significantly higher than the average and extraordinary. It is noteworthy that patents and business cases showed different results compared to the total 6-year-average value, which could indicate either the existence of accumulated green hydrogen technology at the level of TRL 1–3 in specific areas or high demand for a fundamental level of green hydrogen technologies in the market, given that patents and business are more performance-driven than academic journals.

Policy analysis

Hydrogen policies appeared early in the 2000s but they were mainly concerning fuel cell vehicles and their market. Starting in 2017 with the Moon administration in power, however, green hydrogen-related policies started appearing and 11 major policies were published in the span of 2017–2021. The summary is given in Table 9.

The goals of the policies are summarized as follows. The goals consist largely of three parts: financial research support for green hydrogen R&D projects, low TRL projects, and projects with certain technology. In terms of financial support, the policies promise to increase the budget support for green hydrogen R&D projects over the years. The policies regarding expansive R&D support for green hydrogen technology in 2020 and 2021 agree well with the political actions of 2017–2021 that the funding for green hydrogen R&D has increased more than threefold. The policies mention the financial support for R&D projects to develop the technology, green hydrogen production sites/facilities, and for building infrastructures for green hydrogen. This agreement is especially important considering the analysis of project outputs that the domestic level of green hydrogen technology is on a rudimentary level which requires increasing and steady financial support. Also, the agreement means that the political action of budgeting for green hydrogen R&D projects has been supported by political foundations such as the policies which can guarantee steady support for the sturdy growth of green hydrogen technology. As for the TRL of projects, the goal, as specified in the policies with the budget plan published in 2020 and 2021, is to prioritize the budget support for R&D projects on fundamental levels of technology (TRL 1–3). This is to ensure South Korea is equipped with fundamental green hydrogen technology by 2026. This focus on TRL 1–3 is because policymakers have acknowledged that South Korea lacked fundamental green hydrogen technology. This can be supported by the analysis of the impacts of political actions and project outputs, which shows that the scientific and market performances do not reach the average level of total R&D projects except for journals. Even if the political actions of the past years have not prioritized the funding for TRL 1–3 projects, the funding can increase with the introduction of the policy. With this momentum, political actions in the future can boost both the scientific and market performance of

Table 9 Title, publishing ministry and goal of green hydrogen policies (2017–2021)

	Title	Publishing Ministry	Goal
2017	Renewable Energy 3020 Implementation Plan [21]	Ministry of Trade, Industry and Energy	Production of hydrogen with renewable energy surplus (Power to gas)
2018	Report of the Ministry of Industry and Energy in 2019 [37]	Ministry of Trade, Industry and Energy	Expansion of renewable water electrolysis facility in short to long-term plan
2019	Roadmap for development of hydrogen energy[38]	Ministerial meeting on science and technology	Development of water electrolysis technology with solar and wind energy to meet the production goal of (50 kWh/kg-H2, 100 MW) By 2030
	Roadmap to revitalize the hydrogen economy [39]	Joint ministries	Increase of CO2-free green hydrogen production and usage
2020	The Korean version of the New Deal comprehensive plan [40]	Joint ministries	Expansive R&D support for core technology for green hydrogen production
	5th basic plan for renewable energy [22]	Ministry of Trade, Industry and Energy	Increase in green hydrogen production and mass production of 100 MW green hydrogen by 2030
	The budget for the top 40 projects in 2021 [23]	Ministry of Economy and Finance	Achievement of basic level technology development for green hydrogen production by 2026
2021	Climate/Environmental R&D Project Plan for 2021 [41]	Ministry of Science and ICT	Research support plan for green hydrogen technology
	2050 carbon neutral scenario [42]	Joint ministries	Increase in green hydrogen production
	Energy carbon neutral innovation strategy [43]	Joint ministries	Strengthening the supply base of water electrolysis hydrogen
	Carbon neutral industrial energy R&D strategy [44]	Ministry of Trade, Industry and Energy	Development of technologies for green hydrogen production

TRL 1–3 projects. Lastly, the policies regarding electrolysis in 2018, 2019 and 2021 show the governmental will to focus on water-to-hydrogen technology—especially electrolysis in connection with other renewable energies such as solar and wind power. This governmental goal is set to be achieved with short to mid-term plans. As for biomass technology, the South Korean government plans to utilize the technology as a bridge between grey and green hydrogen technologies. The announcement of the policies was accompanied by the political actions of budget allocation to meet the objectives. For example, the majority of green hydrogen budgets have been allocated to water-to-hydrogen technology which resulted in several scientific and market outputs. Especially, the biomass-to-hydrogen projects have produced several business cases which help the national goal of using it as a bridge technology. This agreement between political actions and policies can result in synergy to produce increasing impacts of political actions.

Discussion

Starting in 2017, the Moon administration in South Korea started introducing a series of political actions and green hydrogen policies aimed at building a green hydrogen economy. These actions have undoubtedly helped to institutionalize and legitimize fundamental blocks for a hydrogen economy in South Korea. This study focuses on analyzing the political system, which encompasses political actions and their impacts as well as the policies, using David Easton's theoretical framework. The analysis reveals how green hydrogen R&D projects have been funded in recent years and their impacts on scientific advancement in green hydrogen technology.

The analysis of the political action of budgeting shows that the budget for green hydrogen has increased significantly by 250%, compared to the 5.8% yearly budget average for total R&D projects. Furthermore, the analysis shows that most of the green hydrogen budget (72%) has been spent on water-to-hydrogen technology development, with TRL 1–3 projects receiving the highest funding with a marginal difference from other TRL projects.

The analysis of the impact of political actions—project outputs—shows that yearly scientific and market outputs from green hydrogen projects, except for journal publications, underperformed compared to the annual average value of total R&D projects, which could suggest that the field is quite rudimentary and in need of more time to generate performance according to the time-lag effect. Additionally, most of the journals, patents, and sold technologies are from the projects to develop water-to-hydrogen technology with close to half of the business cases from biomass projects. For the TRL of projects, a significantly high percentage of patents and business are from the projects on TRL 1–3, possibly indicating that the accumulated knowledge and the high demand for the fundamentals of green hydrogen technology in the market.

The analysis of policies in relation to the political system reveals that green hydrogen policies have a summarized objective to focus the budget on the projects on TRL 1–3 and water-to-hydrogen technology with an increasing budget over the years. This objective aligns with the past years of political actions, aiming to increase the green hydrogen budget with a focus on water-to-hydrogen technologies. Given that green hydrogen technology is still on a rudimentary level, these policies are crucial for the technology's development by helping to ensure steady and predictable budget planning. The policy to focus the budget on TRL 1–3 projects, which is not in line with the past years of political actions, is expected to encourage funding for projects that lead to an advance in scientific and market performance on a fundamental level.

This study's limitation is that it only analyzed projects on an individual level. Future research could expand on this by analyzing and comparing projects with varying budget sizes and outputs.

Conclusions

In South Korea, the year 2022 saw the inauguration of a new administration, which signifies a potential shift in policy objectives. This study shows that the demands, political actions, accumulated impacts of political actions and policies have risen and resulted in the advance in green hydrogen technology in South Korea. In order to vitalize the hydrogen economy and shift to a green hydrogen society in the future, it is necessary to continue to financially and politically support areas that are showing outstanding performance. A sturdy legal framework also helps support the steady growth of the green hydrogen economy, akin to those of the US and Germany. Research by Muhammad and Rasyikah has also shown that establishing proper legal frameworks, such as laws, can ensure government financial support for a technology [18]. The results of this study are expected to provide comprehensive insights into establishing policies in South Korea as well as foreign countries with an interest in green hydrogen-related policies. In order for foreign researchers to replicate the study, the data on governmental budget spending should be available and accessible for this type of analysis. The budget data should be also labeled with essential information such as descriptions or keywords of funded projects, the funded year, and other essential metrics.

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Author contributions
Material preparation and data collection were performed by MY and data analysis was performed by BY. The first draft of the manuscript was written by MY and BY. MY, WJ, JL and BY commented on the first draft of the manuscript.

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Availability of data and materials
All data analyzed during the current study are included in this published article. The datasets analyzed during the current study are available from the National Science and Technology Information Service website at https://www.ntis.go.kr/ThMain.do.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that there are no competing interests.

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