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アジア・太平洋総合研究センター
Asia and Pacific Research Center

Policy and R&D trends in electrochemical devices in the Asia and Pacific regions: Toward the diffusion of clean energy

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This report is compiled as part of research that surveyed and analyzed science and technology innovation policies, research and development trends, and associated economic and social circumstances in the Asia-Pacific region. It is being made public on the APRC website and portal site to enable wide use by policymakers, associated researchers, and people with a strong interest in collaborating with the Asia-Pacific region; please see the websites below for more details.

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Executive Summary

Around the world, efforts are underway to decarbonize and lower emissions through the widespread use of renewable clean energy as a countermeasure to climate change and to address the depletion of fossil resources. Electrochemistry is one of the fundamental technologies required for the active utilization of such clean energy, and major countries around the world are competing in the research and development of devices that promote the storage and accumulation of electricity and the production and use of hydrogen.

In recent years, major countries in the Asia and Pacific region have also shown significant development in this field, and there is an urgent need to clarify the characteristics. This report focuses on three electrochemical devices: "batteries," which are power storage devices; "fuel cells," which are hydrogen utilization devices for converting power into hydrogen and further reconverting this hydrogen into electricity; and "water electrolysis," which are hydrogen production devices. It also examines the policies and R&D trends in five countries and regions (China, Korea, Taiwan, India, and Australia), and clarifies the characteristics of the Asia and Pacific regions.

Chapter 1 explains the background and outline of this research. Chapter 2 clarifies the R&D characteristics of electrochemical devices in the Asia and Pacific regions. Here, the research promotion system and major policies for electrochemical devices, and the R&D status in each country and region are summarized, with comparisons made among them. Furthermore, the report introduces research on the material science that makes up each device, the pursuit of the scientific principles that form the basis of their operating mechanism and the supporting large-scale infrastructure and advanced measurement and evaluation required for their R&D. Finally, we provide an overview of the distribution of research talent working on R&D of electrochemical devices, using data from publications in related academic fields.

Chapter 3 describes policies for promoting electrochemical R&D in the major Asia and Pacific countries and regions. For each of the five countries and regions mentioned above, we first summarize the overall science and technology innovation promotion system and funding allocation, followed by the major policies and major research programs related to electrochemistry. In each country and region, competition in batteries is centered on R&D of lithium-ion batteries and lithium-sulfur batteries, and the results of this research are being used in commercial applications such as electric vehicles under the generous support of each government. In addition, research on next-generation battery devices, including all-solid-state batteries and sodium-ion batteries, is being strongly promoted to realize a clean energy society. In the area of fuel cells, R&D of solid oxide fuel cells and other types of fuel cells has been conducted with the automotive industry in mind, and some of these have been put to practical use, but this has yet to happen on a large scale at the commercial level. Although not as much money has been invested in the research and development of water electrolysis when compared to storage batteries and fuel cells, some research institutes in China and India have published excellent results and aim to utilize hydrogen derived from clean energy in the future, along with the development of clean energy supply infrastructure. The goal of this is to use hydrogen derived from clean energy in the future, along with the development of clean energy supply infrastructure.

Table of Contents

1 Background and Outline of the Research

This study focuses on three electrochemical devices that contribute to the spread of renewable clean energy (hereinafter referred to as clean energy): batteries, fuel cells, and water electrolysis. This report summarizes the policies, research and development (R&D) trends, and technological challenges related to the R&D of electrochemical devices in five countries and regions (China, South Korea, Taiwan, India, and Australia). Furthermore, it clarifies the characteristics of the Asia-Pacific regions.

This chapter first overviews the background of the research; presents the selection criteria for devices, countries, and regions; and describes the research items and structure of this report.

1.1 Research Background

Increasing R&D related to hydrogen utilization, such as batteries, fuel cells, and water electrolysis, is a countermeasure to climate change and the depletion of fossil fuel resources. The two major measures to address this concern are (1) the replacement of existing fuels that emit greenhouse gases with energy sources that do not, and (2) the stable supply of electricity (storage and accumulation of electricity, conversion of electricity into hydrogen, and reconversion of hydrogen into electricity) derived from the alternative energy source in (1) above.

(1) As a countermeasure to climate change, a wide range of industries have been working to reduce emissions of carbon dioxide (CO_2), which account for a large proportion of greenhouse gases (GHG). Japanese companies have been actively working to reduce CO_2 emissions and developing technologies that consider both environmental and safety concerns [b1]. For example, focusing on the technological development of power sources, automobiles have evolved from internal combustion engine vehicles (ICVs) powered by fossil fuels to hybrid electric vehicles (HEVs) that use batteries, fuel cell vehicles (FCVs) powered by hydrogen, and battery electric vehicles (BEVs). With the advancement of automobile technology, there is a growing need to transition from fossil fuels, which have a finite supply and emit CO_2, to renewable energy sources that do not emit CO_2.

(2) However, if renewable energy, especially electricity generated by natural energy sources such as solar and wind power, is introduced on a large scale, the output fluctuates significantly. This creates a gap between power supply and demand, which can potentially lead to power outages. Therefore, it is necessary to absorb these fluctuations, convert them into carriers that can be transported in large volumes, and provide a stable supply to the consumption areas.

The reason for studying electrochemistry is that it is related to both (1) and (2) above and is one of the fundamental technologies involved in the active use of clean energy. In renewable energy use flow, batteries, fuel cells, and water electrolysis devices are positioned as shown in Figure 1-1. A schematic of the chemical reactions in each device, along with a description of the technological challenges, is detailed in the Appendix.

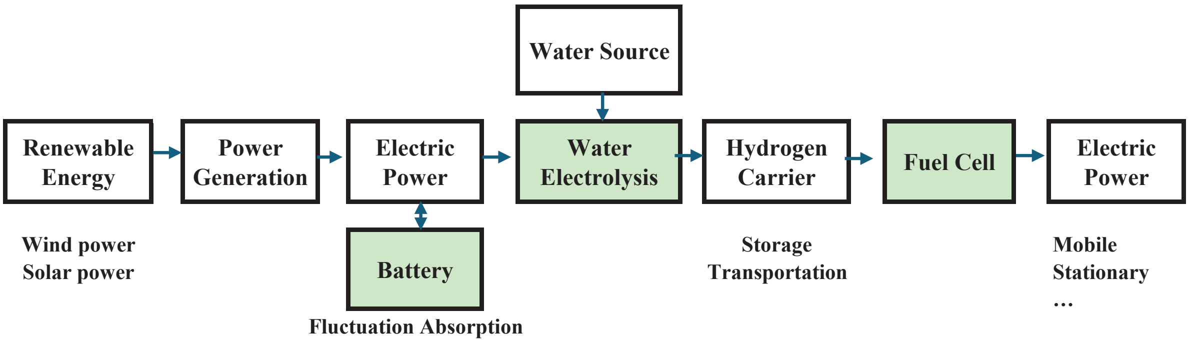


Figure 1-1 Positioning of three electrochemical devices for the stable use of renewable energy

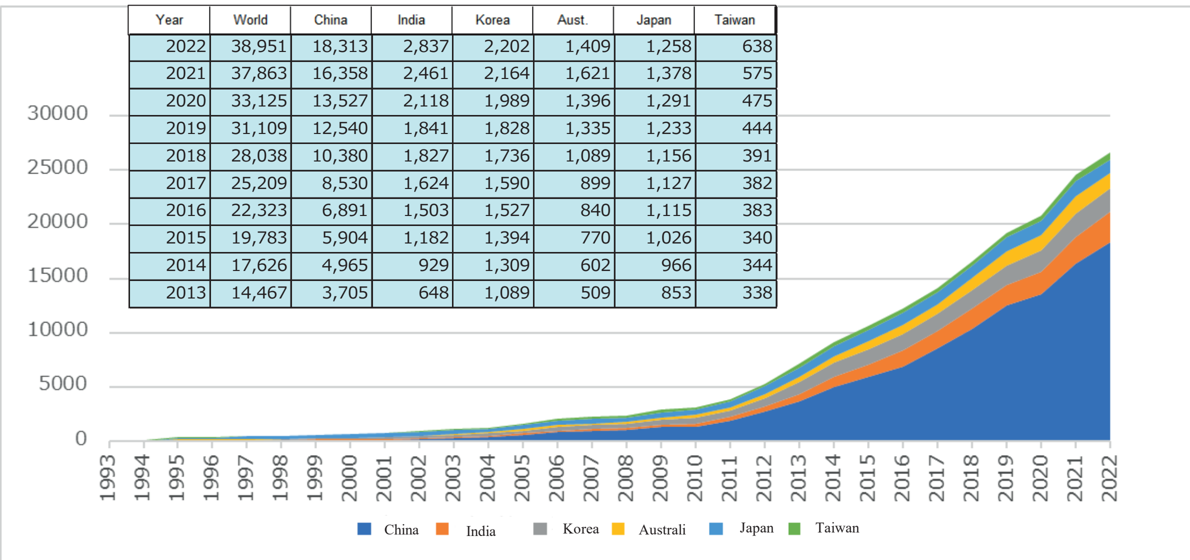
1.2 Selection of Countries and Regions for Research

Five countries and regions were selected as targets: China, South Korea (hereafter abbreviated as Korea, depending on the context), Taiwan, India, and Australia. The top 25 countries and regions in the world for all three electrochemical devices in terms of the total number of papers by device are shown in the Web of Science (WoS), an academic paper database provided by Clarivate (Table 1-1). These countries and regions have also seen a remarkable increase in the number of papers by device over the last decade, as shown in the time series (Figures 1-1 and 1-3). In other words, these countries and regions can be considered as those where research on electrochemical devices has grown significantly compared with other parts of the world.

Table 1-1 World ranking of the total number of papers on three electrochemical devices

	【Battery】		【Fuel Cell】		【Electrolysis】	
	World	367,605	World	172,958	World	42,810
1	**PEOPLES R CHINA**	118,525	**PEOPLES R CHINA**	42,626	**PEOPLES R CHINA**	12,608
2	USA	78,827	USA	35,831	USA	5,626
3	**SOUTH KOREA**	22,787	**JAPAN**	13,003	**JAPAN**	3,648
4	GERMANY	20,300	**SOUTH KOREA**	12,872	GERMANY	2,597
5	**INDIA**	20,165	**INDIA**	10,110	**SOUTH KOREA**	2,027
6	**JAPAN**	19,979	GERMANY	10,016	**INDIA**	1,854
7	ENGLAND	15,048	CANADA	7,394	RUSSIA	1,744
8	**AUSTRALIA**	13,708	ENGLAND	6,948	FRANCE	1,731
9	CANADA	13,067	FRANCE	6,724	CANADA	1,671
10	FRANCE	11,611	ITALY	6,205	ENGLAND	1,304
11	ITALY	11,154	SPAIN	4,623	ITALY	1,289
12	SPAIN	9,622	**TAIWAN**	4,567	SPAIN	1,253
13	**TAIWAN**	6,542	IRAN	4,313	**AUSTRALIA**	1,098
14	SINGAPORE	5,672	**AUSTRALIA**	3,539	BRAZIL	860
15	SWEDEN	4,777	RUSSIA	2,994	IRAN	756
16	NETHERLANDS	4,375	BRAZIL	2,717	TURKEY	733
17	IRAN	4,268	MALAYSIA	2,487	**TAIWAN**	619
18	BRAZIL	4,143	DENMARK	2,464	DENMARK	604
19	SWITZERLAND	4,112	SWEDEN	2,258	NETHERLANDS	587
20	RUSSIA	3,886	SWITZERLAND	2,183	SWITZERLAND	576
21	TURKEY	3,444	TURKEY	2,147	NORWAY	557
22	BELGIUM	3,253	NETHERLANDS	1,971	POLAND	545
23	SAUDI ARABIA	3,253	SINGAPORE	1,937	SAUDI ARABIA	426
24	POLAND	3,170	POLAND	1,902	UKRAINE	413
25	MALAYSIA	3,050	SAUDI ARABIA	1,603	SWEDEN	395

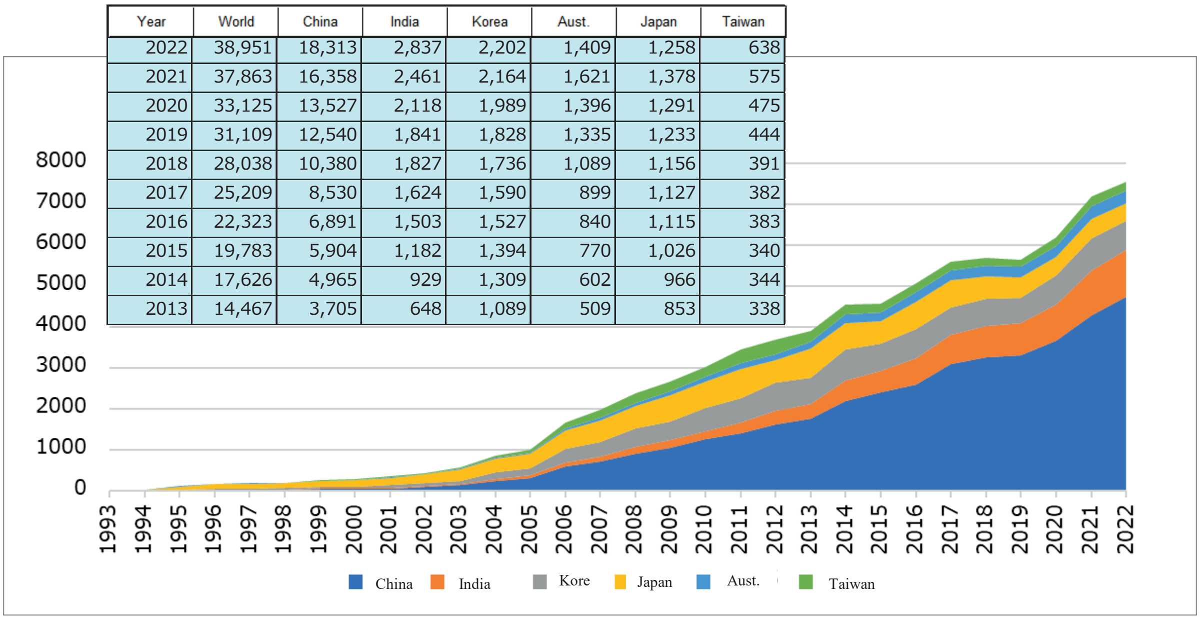
Source: Created by APRC based on academic literature data compiled from Web of Science



Year	World	China	India	Korea	Aust.	Japan	Taiwan
2022	38,951	18,313	2,837	2,202	1,409	1,258	638
2021	37,863	16,358	2,461	2,164	1,621	1,378	575
2020	33,125	13,527	2,118	1,989	1,396	1,291	475
2019	31,109	12,540	1,841	1,828	1,335	1,233	444
2018	28,038	10,380	1,827	1,736	1,089	1,156	391
2017	25,209	8,530	1,624	1,590	899	1,127	382
2016	22,323	6,891	1,503	1,527	840	1,115	383
2015	19,783	5,904	1,182	1,394	770	1,026	340
2014	17,626	4,965	929	1,309	602	966	344
2013	14,467	3,705	648	1,089	509	853	338

Battery

Figure 1-2　Number of papers published in top countries and regions in terms of number of references (battery)



Year	World	China	India	Korea	Aust.	Japan	Taiwan
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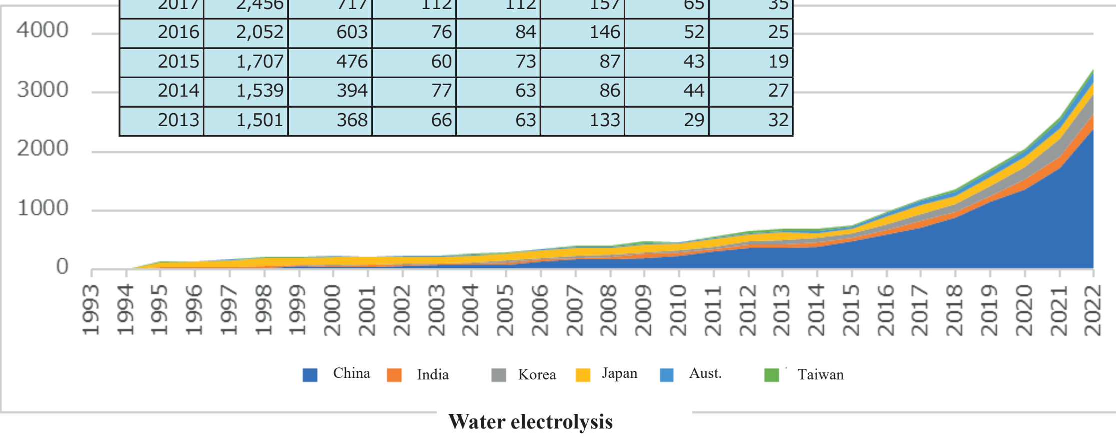
Fuel cell

Figure 1-3　Number of papers published in top countries and regions in terms of number of references (fuel cell)

Year	World	China	India	Korea	Japan	Aust	Taiwan
2022	4,945	2,397	247	343	195	161	68
2021	4,154	1,715	204	297	179	130	53
2020	3,571	1,358	169	211	174	89	42
2019	3,123	1,142	97	178	162	83	43
2018	2,655	879	108	118	147	78	33
2017	2,456	717	112	112	157	65	35
2016	2,052	603	76	84	146	52	25
2015	1,707	476	60	73	87	43	19
2014	1,539	394	77	63	86	44	27
2013	1,501	368	66	63	133	29	32



Source: Created by APRC based on academic literature data compiled from Web of Science

Figure 1-4 Number of papers published in top countries and regions in terms of number of references (water electrolysis)

1.3 Research Items

The research items are generally as follows, with slight variety depending on the country and region. To select the major funding programs, research institutions, and companies, the ranking of the number of papers by device over the last decade (2013–2022) on Web of Science (WoS) is used as a reference.

- R&D overview
- R&D funding (R&D expenditures and flows)
- Organizational structure for promoting R&D
- Relevant major policies
- Funding
- Major research programs
- International cooperations and collaboration
- Major research institutions and companies
- Large-scale research infrastructure

1.4 Report Framework

This report consists of this chapter, two subsequent chapters and an appendix.

Chapter 2 clarifies the R&D characteristics of electrochemical devices in the major countries and regions of the Asia and Pacific. Here, the major policies, research promotion systems, and electrochemical devices focused on in each country and region are summarized and compared. Additionally, to conduct R&D on each device, it is essential to research the materials that comprise it and explore the scientific principles that underpin its operating mechanism. This report introduces a large-scale research infrastructure that provides advanced measurements, evaluations, and computational infrastructure. Finally, we provide an overview of the distribution of research talent working on the R&D of electrochemical devices using researcher data from publications in related academic fields.

Chapter 3 outlines policies for promoting electrochemical R&D in major Asia-Pacific countries and regions. For each of the five countries and regions mentioned above, we first summarize the overall science and technology innovation (STI) promotion system and funding allocation and flows, followed by a discussion of the major policies and research programs related to electrochemical devices.

At the end of the report, electrochemical devices and technological challenges related to clean energy are provided as reference materials. We have collected technical information on "batteries," which are power storage devices, "water electrolysis," which are hydrogen production devices, and "fuel cells," which are hydrogen utilization devices. We summarize the characteristics, reaction mechanisms, and technological challenges of each electrochemical device, as well as approaches for creating innovative materials and resolving challenges through the pursuit of academic theories.

2 R&D Characteristics of Electrochemical Devices in the Asia and Pacific Regions

This chapter describes the R&D characteristics of electrochemical devices in major countries and regions of the Asia and Pacific, considering the policies and R&D trends in each country and region, as well as the mechanisms and technological challenges associated with the three electrochemical devices. Table 2-1 shows a summary of noteworthy research items compared across countries and regions.

Table 2-1 Summary of research results

	China	Korea	Taiwan	India	Australia
Research promotion system	The Ministry of Industry and Information Technology, the National Development and Reform Commission, and the Ministry of Science and Technology play central roles under the leadership of the State Council.	R&D is conducted by the Ministry of Science and ICT, and commercialization is conducted by the Ministry of Trade, Industry, and Energy.	Basic research was conducted by the NSTC, and application and development research was conducted by the NSTC and the Ministry of Economic Affairs.	Extensively implemented by the Ministry of New and Renewable Energy and the Ministry of Electronics and Information Technology, with DST playing a central role.	Basic research was conducted under ARC, and application and development research was conducted under DISR.
Major policies	Hydrogen is mentioned in the Energy Technology Innovation Action Plan (2016–2030) and has been commercialized on a large scale in the 14th Five-Year Plan.	National Strategic Technology Development Plan, National Strategy for Strengthening the Competitiveness of the Secondary Battery Industry, and First Basic Plan for Technology Development for Climate Change Response	5+2 Industrial Innovation Plan (2016) Taiwan 2050 Net Zero Policy (2021), etc.	National Mission for Electric Vehicles, Clean Energy Materials Initiative	National Hydrogen Strategy (under review)
Priority R&D areas	Batteries (Li-ion, Li-S batteries)	High-energy-density lithium and next-generation lithium secondary batteries (all-solid state, sodium, etc.)	Increased investment in batteries by both industry and government. Hydrogen production and utilization are in the early stages of development, but are being promoted as priority areas for investment.	Attracting high attention to the market, but dependent on battery cell imports, focusing on clean energy research in recent years.	Li-air batteries – Li-S batteries. Basic research on hydrogen production and utilization is also being conducted in accordance with national strategies.
Representative research institution	Chinese Academy of Sciences and its affiliated organizations, Tsinghua University, Harbin Institute of Technology	Seoul National University, Hanyang University, KAIST, UNIST, KIST, KIER	Industrial Technology Research Institute, National Taiwan University of Science and Technology, National Taipei University of Technology	Indian Institute of Technology (IIT) Delhi, CSIR CECRI	Deakin University, University of Wollongong (UOW), UTS, UNSW, and CSIRO.
Representative companies	CATL, BYD, CALB, Gotion, EVE Energy, and other world-class manufacturers in bipolar plates, catalysts, and exchange membranes.	Three major conglomerates: LG Energy Solutions, SK On, and Samsung SDI. LG Chemicals and Other Materials.	(Batteries) Conglomerates such as Hon Hai Precision Industry, Formosa Plastics, and Formosa Cement. (Fuel cells) Kaori Heat Treatment Co., Ltd., Chung-Hsin Electric & Machinery Mfg Corp..	State-owned enterprises such as International Oil Corporation Limited (IOCL) and Bharat Heavy Electricals Limited (BHEL). Ventures from the Center for Battery Engineering and Electric Vehicles (C-BEEV).	CSIRO-originated ventures: Hadean, Endua (water electrolysis)
International collaboration status	Collaboration with major overseas electric vehicle manufacturers in China (CATL, Guoxuan High-Tech Co., Ltd., SVOLT), construction of factories overseas, etc.	The U.S., China, and India, in that order, have the most international co-authored papers. KIST has established a joint research center in India.	The NSTC conducted a joint research project with the BMBF (Germany) between 2017 and 2020. These themes included lithium battery safety, high energy density, and all-solid-state batteries.	Competing while cooperating with China. In Korea, KIST has established a joint research center and cooperates extensively with IIT and other institutions. In addition, industry-academia collaboration between the U.S. and Japan is ongoing.	Emphasis on Cooperation between China and India. Joint research with other major countries, such as the U.S., the U.K., and Japan, and collaboration with Japanese companies.

Source: Created by APRC

2.1 Research Promotion Systems and Major Policies

As mentioned in Chapter 1, the background for the rapid progress in the R&D of secondary batteries is the decarbonization of automobiles. Currently, the research and development competition among countries and regions is shifting from secondary batteries for mobile devices to next-generation secondary batteries with high capacities and outputs. In particular, competition for the large-scale commercialization of next-generation secondary batteries for automobiles is intensifying.

Given that China and India are among the world's largest carbon dioxide (CO_2) emitters, clean energy research and development are recognized as national priorities in both countries. China first mentioned hydrogen as a clean energy source in its "Energy Technology Revolution Action Plan (2016–2030)" and envisioned its large-scale commercialization in its 14th Five-Year Plan. India has set the manufacturing of electric vehicles as one of its national missions. It promotes the development and introduction of battery exchange systems, such as battery swaps, in parallel with research into faster charging. The automobile industry is not as active in Australia as it is in countries like China and Korea; therefore, Australia is strengthening its R&D in peripheral processes, such as assembly and recycling.

Korea and Taiwan have positioned these three electrochemical devices as key drivers of economic growth, alongside semiconductors and displays. Korea has added two areas, namely "secondary batteries" and "advanced mobility," to its "National Strategic Technology Mission-Centric Strategic Roadmap (I)" (August 2023). Major conglomerates, such as Samsung SDI, SK On, and LG Chemicals, are establishing joint research systems with universities and research institutes to facilitate the large-scale commercialization of all-solid-state batteries. While Taiwan has included "green power and renewable energy industry" in its "Program for Promoting Six Core Strategic Industries," it has limited experience in battery devices for four-wheeled vehicles. These require high output and large capacity, and should be strengthened in cooperation with the industry in the future.

Furthermore, hydrogen has attracted considerable attention as a next-generation clean energy source in the global trend toward decarbonization. From the hydrogen perspective, storage batteries, water electrolysis, and fuel cells can be regarded as necessary technologies for "absorbing power fluctuations in renewable energy," "converting electricity into hydrogen," and "utilizing hydrogen," respectively. All government plans and national strategies in the countries and regions covered in this survey generally began to mention "hydrogen" around the mid-2010s. China and India strongly recognize clean energy R&D as a key issue. For example, China released its "National Medium and Long-Term Plan for the Development of Hydrogen Energy Industry" in 2022. By contrast, in India, the Department of Science and Technology (DST) announced the "National Green Hydrogen Mission" in 2023, based on its recognition of the current situation regarding the hydrogen economy [c11]. In 2019, Australia announced its National Hydrogen Strategy to become a leading global producer of hydrogen. The strategy has been under review since February 2023 with the aim to "accelerate commercialization," "resolve technical uncertainties," and "establish domestic supply and demand capabilities" [c12].

2.2 Efforts in Each Country and Region by Device

China ranks among the world's top R&D sectors for all three devices in this research. In addition, China and Korea, which have strengths in next-generation secondary batteries for automobiles, and other countries and regions with relatively little experience or knowledge of automobiles have different focuses on devices and technological challenges.

Research has focused on lithium-ion (Li-ion) and lithium-sodium (Li-S) batteries. CATL, the largest company in China, has a 35% global market share in the sales and manufacturing of lithium-ion batteries (as of the end of 2023)[1]. They also hold an overwhelming share in the sales and manufacturing of lithium-ion iron phosphate (LFP) batteries. In addition, since around 2009, the company has also begun researching sodium-ion batteries[2], which are more abundant in the Earth's crust than lithium or other substances, as a next-generation battery. Australia also promotes technological developments in the field of batteries based on its national research portfolios. In particular, the Energy Storage Research Team of the Commonwealth Scientific and Industrial Research Organization (CSIRO), which leads applied research for industrialization, is conducting R&D with a view toward lithium-air batteries and lithium-sulfur batteries.

R&D competition is intensifying in major countries worldwide. In the Asia and Pacific regions, the Chinese central government has announced the "Medium-to-Long-Term Plan for the Development of the Hydrogen Energy Industry (2021–2035)" in 2022, starting with the "Energy Technology Revolution Innovation Action Plan (2016–2030)." It has also begun to promote the development of devices utilizing hydrogen energy on a full scale [c4]. In Korea, KIST is collaborating with Korea University to conduct research on fuel cells and water electrolysis at the Hydrogen and Fuel Cell Research Center. The government has been working to establish a supply chain with a policy of importing hydrogen from overseas rather than producing it; however, recent discussions focused on establishing a domestic production base. In Taiwan, fuel cells have also reached industrial maturity, with the Atomic Energy Commission's Nuclear Energy Research Institute, National Central University, ITRI, and other bases as centers for the development and use of production technology centered on solid oxide fuel cells. Nevertheless, the key to the widespread use of fuel-cell vehicles (FCVs) in the automotive industry is to reduce the cost of hydrogen production. All countries and regions will likely need to establish government subsidy systems and other arrangements.

Regarding water electrolysis (hydrogen production), all countries and regions have just begun basic research, and the number of published papers is still only approximately one-tenth of those on batteries. However, several basic studies on water electrolysis are underway in China, and many companies are related to water electrolysis and fuel cells. In Korea and Taiwan, hydrogen energy development is in its early stages, and laboratories at major universities are working to develop low-cost, high-performance hydrogen production technologies. In Australia, as part of a review of the national strategy, optimal collaboration with Japanese hydrogen production and storage (including liquefaction) technologies,

1 https://www.lifepo4-battery.com/News/CATL-battery-market.html

2 See also Chapters 4 and 5 of the JST Research Report "R&D Trends in Next-Generation Batteries from the Perspective of Leading Chinese Researchers" FY2021-RR-06.

primarily led by CSIRO, is being considered. In India, researchers are conducting studies to improve the efficiency of alkaline water electrolysis (AWE) [c1].

2.3 Large-scale Research Infrastructure

Basic upstream research is important in R&D competition. In recent years, we have entered an era in which advanced measurement and computational infrastructures are being utilized to enhance the efficiency of experiments by leveraging the accumulation and utilization of big data. The development of such facilities is large-scale and beyond the investment risks of a single company. Therefore, major countries in Europe, the U.S., Asia, and the Pacific region are developing large-scale research infrastructures, such as accelerators, with government support, and the sharing of research facilities is progressing.

(1) Measurement and evaluation infrastructure

In Japan, the representative large-scale research infrastructure for measurement and evaluation is SPring-8 (a large-scale synchrotron radiation facility), which boasts the world's highest performance. SPring-8 features multiple beamlines and supports the quality of research on electrochemical devices and materials. For example, it is difficult to sequentially capture the state of an electrocatalyst during a reaction; however, it is now possible to understand its behavior through in situ (real-time) measurements. Recently, in 2023, a new 3GeV high-brilliance synchrotron radiation facility for soft X-rays (NanoTerasu) was completed in the "Science Park" area of Tohoku University's new Aobayama campus. These instruments have garnered high praise and attracted international attention. Professor S. Basu, who is conducting catalytic research at the Indian Institute of Technology (IIT) Delhi, evaluates that "Japan is a leading country in the field of measurement and evaluation, and is playing an important role in the development of measuring instruments and sensors" [c1].

In contrast, in the Asia and Pacific region, infrastructure development is progressing in the following order: China, Korea, Taiwan, and India, with Japan topping the list. First, "the Beijing Electron Positron Collider (BEPC)"[3], China's pioneering first-generation synchrotron radiation facility, is in operation in Beijing, and "the Shanghai Synchrotron Radiation Facility (SSRF)"[4], a third-generation synchrotron radiation facility, is operating in Shanghai. "The High Energy Photon Source (HEPS)"[5], a fourth-generation synchrotron radiation facility, began operation in 2024, and construction of "the Hefei Advanced Light Facility (HALF)"[6], another fourth-generation synchrotron radiation facility, has begun in Hefei City, Anhui Province. In Korea, two units, the PLS-II and PAL-XFEL, are in operation at the Pohang University of Science and Technology (POSTECH). In Taiwan, two units, the Taiwan Light Source and the Taiwan Photon Source, are in operation at the National Synchrotron Radiation Research Center. In India, large-

3 https://spc.jst.go.jp/news/170104/topic_1_06.html
4 https://spc.jst.go.jp/news/110603/topic_4_04.html
5 https://spc.jst.go.jp/news/240401/topic_4_02.html
6 https://spc.jst.go.jp/news/230904/topic_3_02.html

scale accelerators have been established in Kolkata, New Delhi, Indore, and Mumbai; new accelerators are currently under construction in Kolkata.

(2) Computational infrastructure

Computational infrastructure, along with the measurement and evaluation infrastructure, is a research infrastructure shared on a national scale. Below, we introduce the National Supercomputing Centers (NSCCs) in each country and region, which will also be discussed in Chapter 3.

In Japan, the supercomputer "Fugaku" is a system with the world's highest level of overall performance, featuring a large-scale computing infrastructure that contributes to the realization of Society 5.0. For various research projects conducted in Japan that require high-speed scientific computation, the creation of new scientific and social results and their implementation in society are being promoted using "Fugaku," while supporting the creation of world-leading results. This effort involves building a system of collaboration with academia, industry, and government organizations.

In China, the CAS Institute of Computing Technology (established in 1956) has received the National Science and Technology Progress Award and the National Natural Science Award for its "Research on Software Systems Supporting Infrastructure" and "New Model of Deep Learning Processor System Structure." It is highly regarded both nominally and in reality. Also among local NSCCs, the NSCC in Jinan City, Shandong Province (established in 2011), used a proprietary architecture, the Shenwei CPU, in its "Sunwei Bluelight" and became the first in China to exceed 1 PF (petaflops). In addition, the NSCC, located within Sun Yat-sen University in Guangzhou, boasts the highest performance in the country with its next-generation system, "Tianhe Xingyi." It was released on December 6, 2023, and has doubled the specifications in many areas including computation, networking, storage, and application services compared to its predecessor, "Tianhe No. 2" (released in 2013)[7]. In addition, Tianhe No. 3, which was developed and installed in 2018 at the National Supercomputing Tianjin Center, is expected to achieve the highest performance in China and worldwide if put into practical use.

The Korea Basic Science Institute (KBSI) has eight supercomputers, ranking ninth globally. India has committed to the "National Supercomputing Mission (NSM)" as one of its national missions, and 29 computers have been deployed to date in universities and research institutes across the country, including IIT, IISER, and IISc. There were eight PF-class supercomputers.

2.4 Research Talent

Here, we utilize publication data from the field of electrochemistry to provide an overview of the distribution of researchers across countries and regions. Using international conference proceedings and peer-reviewed original papers published since 1990 from Scopus, an academic paper database provided by Elsevier, a keyword search was conducted for "battery," "fuel cell," and "water electrolysis" to create a group of researchers who are authors of papers on each electrochemical device. Next, we plotted the

[7] The official websites of each organization are listed below. "The Tianhe No. 2" received high praise, ranking in the top 500 in the world.

trend in the number of co-authors (calculated using the increase in the number of co-authors each year for the last 10 years [2014–2023] as a regression coefficient, hereafter referred to as “co-authors trend”) on the horizontal axis and the citation index (the total number of citations of papers published by the relevant author from 2014 to 2023, on a log scale) on the vertical axis in a scatter plot for each of the three devices[8].

Below, we analyzed the distribution of researchers for each of the three devices using scatter plots.

(1) Distribution of researchers by device

Regarding batteries (Figure 2-1), Chinese researchers are overwhelmingly more numerous in terms of the number plotted on the scatter plot (n value, hereafter referred to as “number of plots”). Many of them show significantly high values for both the number of co-authors trend (X value) and the citation index (Y value). Indian researchers have the second-largest number of plots after those in China, but few are distributed in high-citation index areas. Compared to Japan, the distribution of Korean researchers is slightly more extensive, with a higher proportion of Korean researchers concentrated in highly cited areas. Although the number of plots of Australian researchers is small compared to that of other countries and regions, both their co-author trend and citation index expand into a higher area. Taiwanese researchers have the second-lowest number of plots after Australia; few of them have a citation index in the high range, and the trend of co-authors is also lower than that in other countries.

[8] As previous research that estimates researchers who are attracting attention from a similar perspective, see also JST/CRDS research report, “International Trends in Quantum Technology as Seen in Papers and Patent Maps,” CRDS-FY2021-RR-08, pp. 45–47, and JST/APRC research report, “Synthetic Biology-Related Research Activities in the Asia and Pacific Regions as Seen through Paper Analysis,” APRC-FY2023-TP-01, pp.51–54.

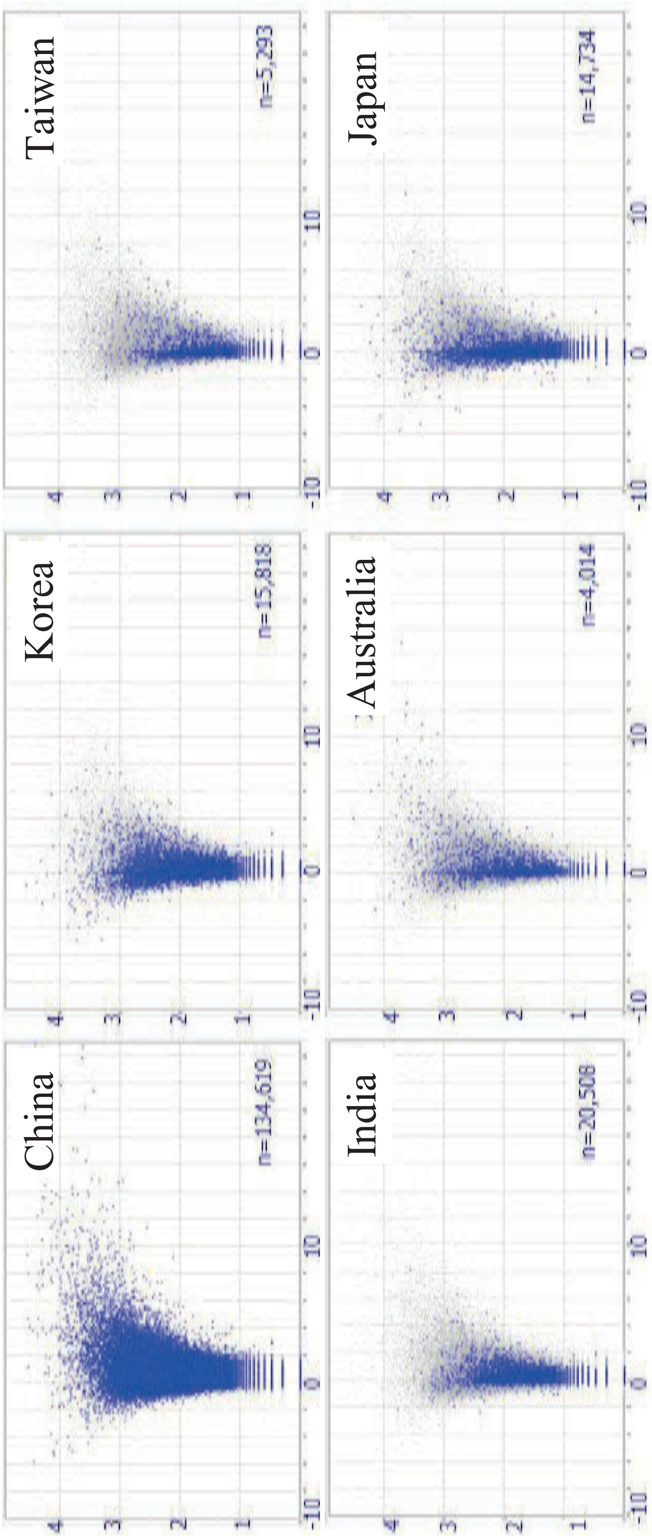


Figure 2-1 Researcher map (battery)

Source: Created by APRC

For fuel cells (Figure 2-2), the number of plots of researchers was smaller in all countries than for batteries, and the spread of the distribution tended to be more limited. Nevertheless, China shows a large number of those distributed in areas with a higher co-author trend and citation index. Korea has a large number of people distributed in areas with high citation indices. India, Australia, and Taiwan were mostly distributed around zero in the co-authors' trend, indicating little increase or decrease over the past 10 years.

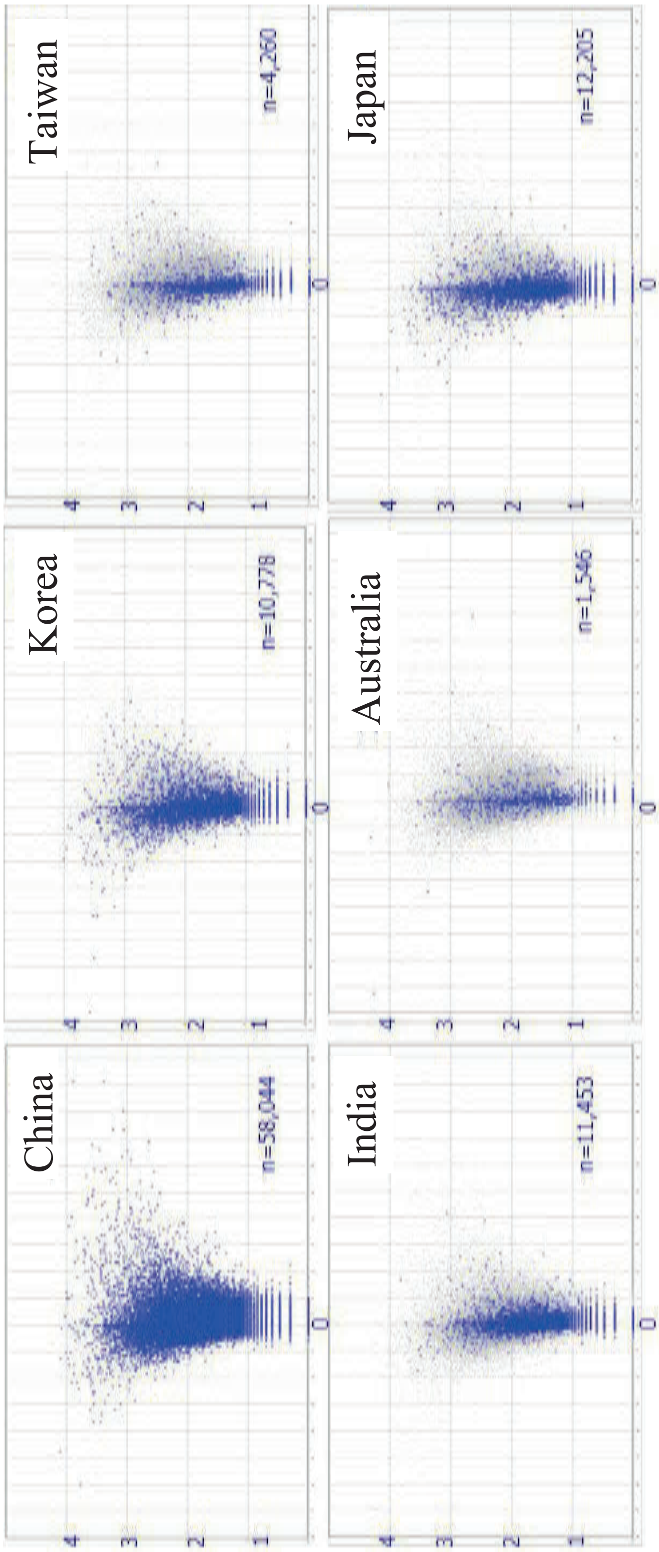


Figure 2-2 Researcher map (fuel cell)

Source: Created by APRC

Finally, for water electrolysis (Figure 2-3), the number of plots was even smaller than that for the fuel cells. Many Chinese researchers show high values for both co-author trends and citation indexes. In all five countries and regions except China, the co-author trend of researchers is generally low, indicating that they tend to pursue their research independently. Even in this situation, Korean researchers tend to be distributed across areas with high citation indices. In addition, although the number of plots of Australian researchers is smaller than that of other countries and regions, both the co-author trend and citation index extend to a higher area.

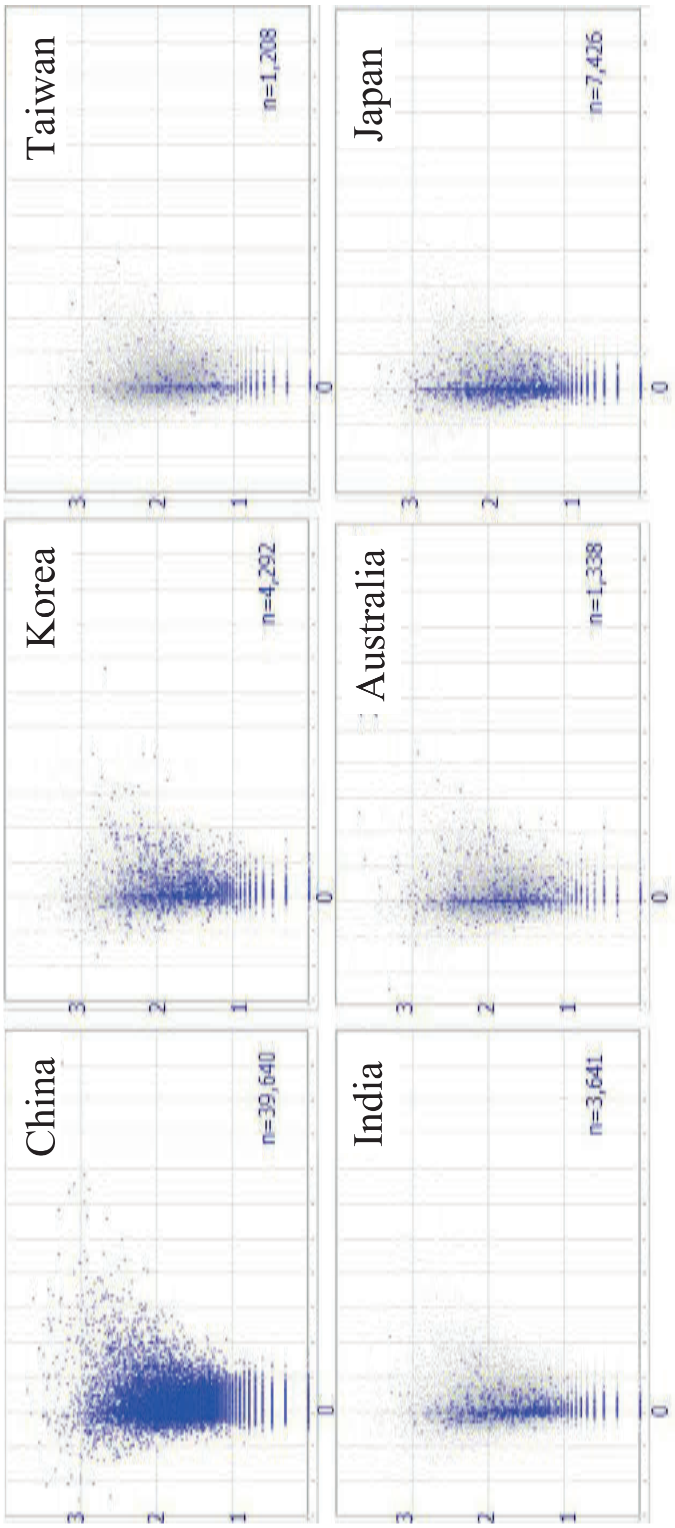


Figure 2-3 Researcher map (water electrolysis)

Source: Created by APRC

3 Policies and R&D Trends in Major Countries and Regions in Asia and Pacific

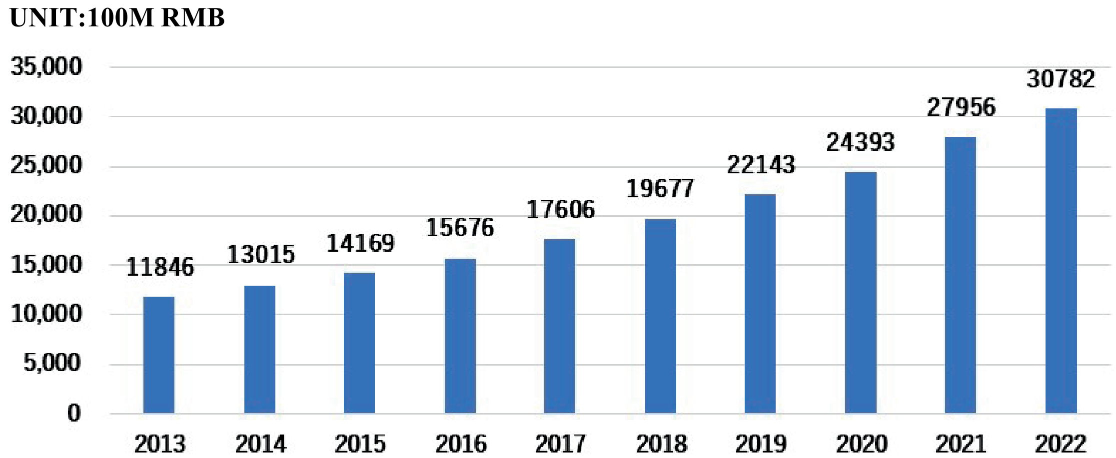
As mentioned in Chapter 1, China ranked first in the total number of papers on the three electrochemical devices, followed by South Korea, India, Australia, and Taiwan. This chapter describes the policies and R&D trends of each country and region in geographical order (East Asia, South Asia, and Oceania).

3.1 China

In China, the Ministry of Science and Technology, the Ministry of Industry and Information Technology, and the National Development and Reform Commission collaborate to publish the largest-scale research results worldwide. China has been framing a series of important policies, such as storage batteries and energy mentioned for the first time in the 12th Five-Year Plan, the commercialization of new energy storage proposed in the medium- to long-term plan (2016–2030), and the prospects for hydrogen energy in 2022 outlined in the 14th Five-Year Plan. Regardless of the type of electrochemical device, the Chinese Academy of Sciences and its affiliated research institutes are the overwhelming centers of research, followed by Tsinghua University and the Harbin Institute of Technology. Regardless of the type of electrochemical device, the Chinese Academy of Sciences and its affiliated research institutes are unrivaled research centers, followed by Tsinghua University and the Harbin Institute of Technology. Chinese companies have dominated global battery cell manufacturing since the commercialization of lithium-ion rechargeable batteries and have published outstanding research papers on water electrolysis, which is attracting attention as a next-generation technology. In recent years, there has been a rapid growth in hydrogen- and fuel-cell-related companies, such as SinoHytec, SINOSYNERGY, and REFIRE Group Limited.

3.1.1 Research Funding

Research and development expenditures in China have been increasing annually, exceeding RMB 3 trillion (approximately JPY 57 trillion, calculated at 1 yuan = 19 yen) in 2022 (Figure 3-1-1). The ratio of R&D expenditure to GDP also increased from 0.11% year-on-year to 2.55%. Investment in basic research is on the rise but remains at approximately 6% (6.32% in 2022). Companies lead development research, whereas universities and research institutions mainly conduct basic research (see Table 3-1-1). Applied research is actively promoted in research institutions outside universities.



Sources: National Bureau of Statistics of China "National Science and Technology Expenditure Statistics Bulletin (2013-2022)"

Figure 3-1-1 Trends in research and development expenditure in China

Table3-1-1 Research stage classified by the China National Bureau of Statistics

Research stages	2017	2018	2019	2020	2021
Basic research	975.5	1,090.40	1,335.60	1,467.00	1,917.00
Applied research	1,849.20	2,190.90	2,498.50	2,757.20	3,145.40
Development research	14,781.40	16,396.70	18,309.50	20,168.90	22,995.90
Total (RMB 100M)	17,606.10	19,677.90	22,143.60	24,393.10	27,956.30

Source: China National Bureau of Statistics, China Statistical Yearbook 2022

Table 3-1-2 Research and development expenses by implementing sector (2020)

Unit: RMB 100M	Total	Basic Research	Applied research	Development research
Whole country	24,393.11	1,467.00	2,757.24	20,168.88
Private company	18,673.75	95.61	565.18	18,012.96
Research institute	3,408.82	573.92	1,084.52	1,750.38
University	1,882.48	724.84	964.18	193.47
Others	428.05	72.63	143.36	212.07

Source: China Science and Technology Statistics Yearbook 2021

Table 3-1-3 Funding programs m

Funds	Research stage	Field of research	Scale of budget	No. of publication
NSFC	Basic Research	Natural sciences	RMB 35.194 billion[9]	1,121,384[10]
National Key Research and Development Program	Mainly applied and development research	Research with significant social utility in the field of public welfare, industrial innovation competitiveness, independent innovation capabilities, and scientific and technological research related to national security.	RMB 46.833 billion[11]	926[12]
National Science and Technology Major Project	Mainly applied and development research	Breakthroughs for core and bottleneck technologies[13]		26,993[14]
Technology Innovation Induction Plan		Strengthening the capacity of regions		
Research Centers and Human Resources Program		Fostering human resources		

Sources: Referred to and compiled from various materials.

The Ministry of Science and Technology is responsible for the practical management of major national science and technology projects, fundamentally under the guidance of the State Council. The National Development and Reform Commission, under the State Council, is responsible for pursuing policy research to promote social development plans based on science and technology, formulating plans for their implementation, guiding necessary structural adjustments and economic reform, and providing guidance to the Ministry of Science and Technology on National Science and Technology Major Projects. The Technology Innovation Induction Plan, Research Centers, and Human Resources Program are mainly promoted by local governments[15].

[9] For the 2023 budget, refer to the "2023 Department Budget" of the National Natural Science Foundation of China (NSFC). https://www.nsfc.gov.cn/publish/portal0/zfxxgk/04/08/

[10] As of August 21, 2023, See https://kd.nsfc.gov.cn/.

[11] See the 2023 funding spent by the Ministry of Science and Technology. https://www.safea.gov.cn/xxgk/xinxifenlei/fdzdgknr/bmyjs/202303/P020230420570343194281.pdf

[12] The results of a search on Web of Science for the National Key R&D Program of China. https://www.webofscience.com/wos/woscc/summary/cdc95c35-80ea-4d47-b625-9bbe079d123d-9ee35b5b/relevance/1

[13] 13 major projects are underway under this program. https://www.most.gov.cn/ztzl/zdzx/index.html

[14] Search results for "National Science and Technology Major Project" in Web of Science. https://www.webofscience.com/wos/woscc/summary/dbb71cf4-096c-4e4d-b81d-3e8b4c925091-9ee335e6/relevance/1

[15] For more details, refer to the JST/APRC Research Report, "The paths of the policies and measures taken by the Chinese government for strengthening basic research and improving research managements," March 2022. https://spap.jst.go.jp/investigation/downloads/2021_rr_01_en.pdf

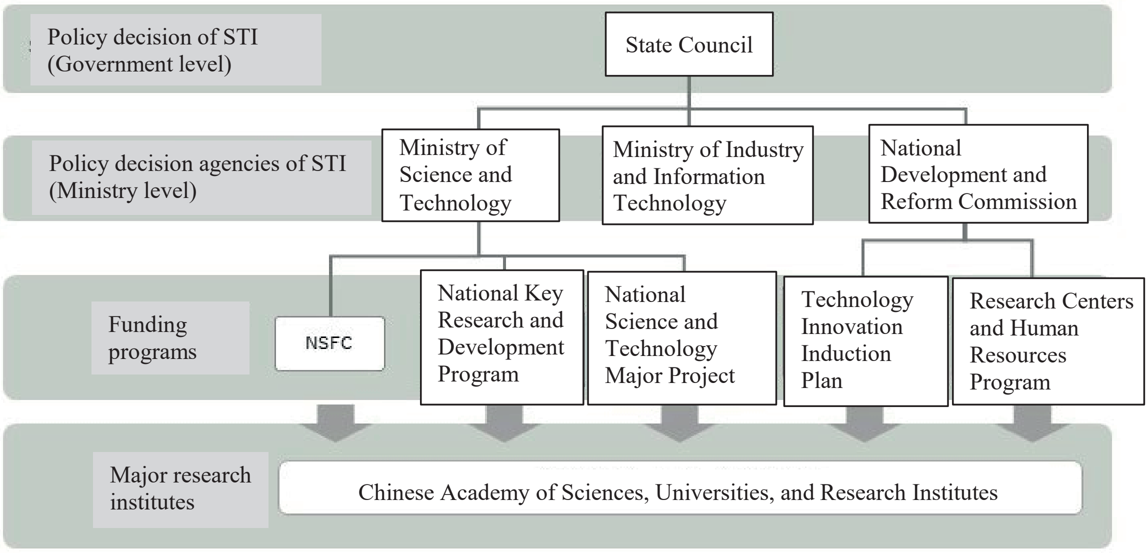
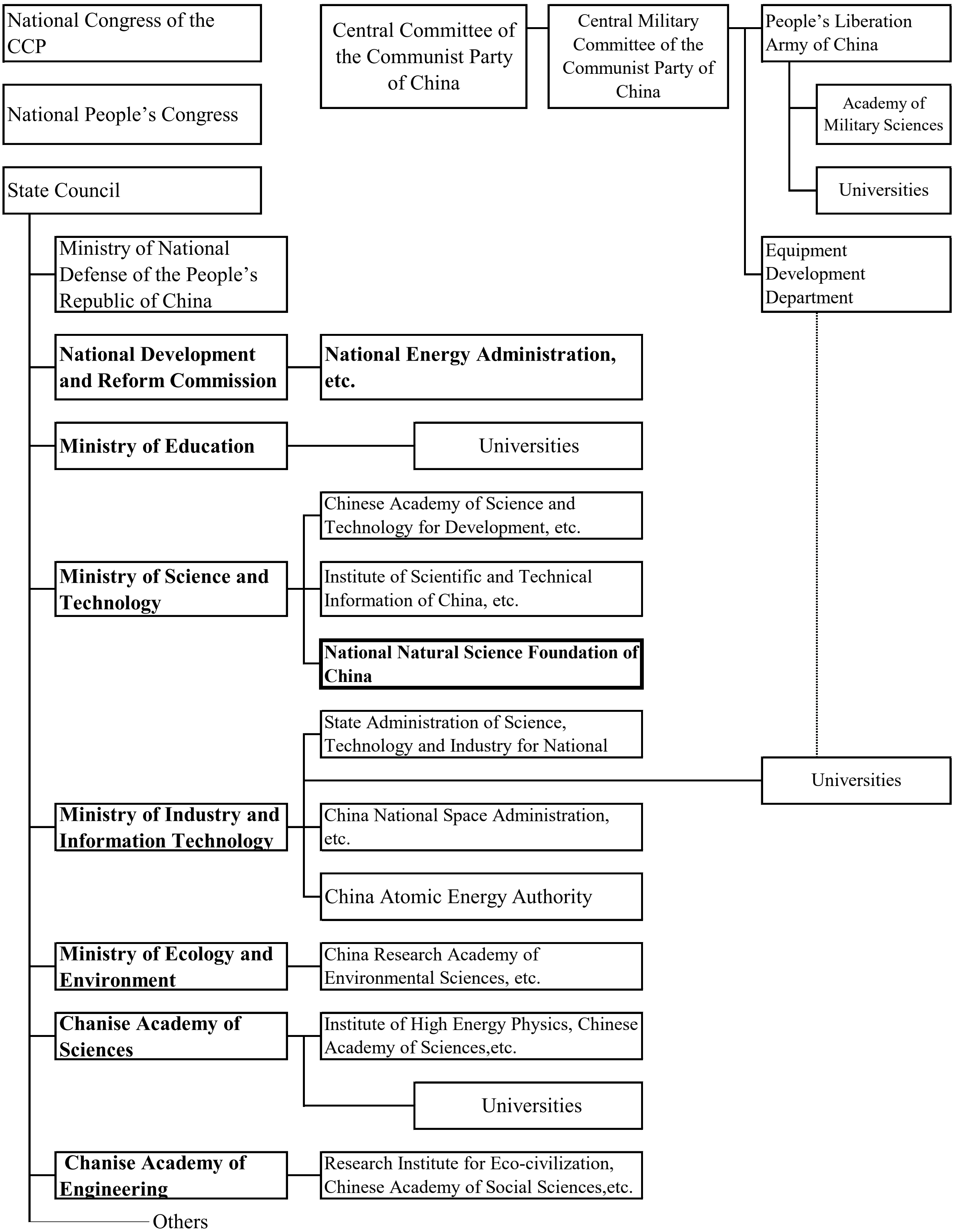


Figure 3-1-2 Flow of research funds

3.1.2 Research Promotion System

Before discussing electrochemistry in detail, this report introduces the organizations involved in formulating science and technology innovation (STI) policies. Figure 3-1-3 shows the names of the major organizations and their structural relationships.

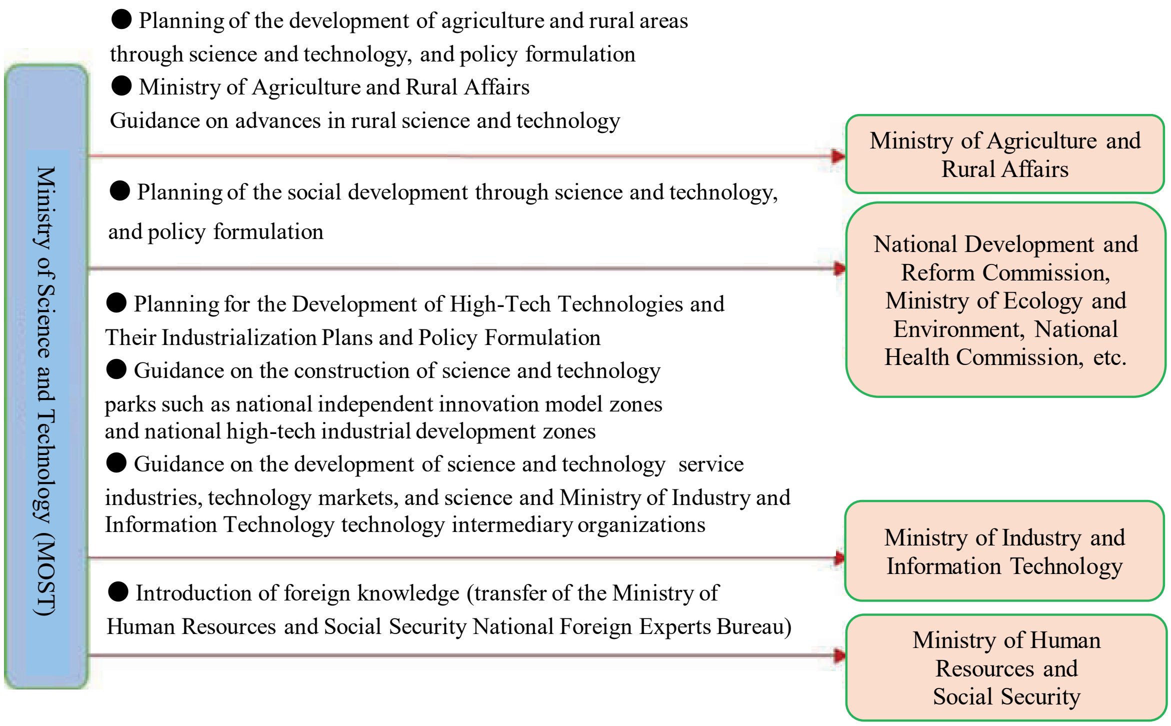


Source: [a2]

Figure 3-1-3 STI policy-related organizations in China

Previously, the policy for science and technology was managed by the Ministry of Science and Technology (hereinafter referred to as MOST); however, in March 2023, massive organizational restructuring took place, and many MOST missions were transferred to other ministries and agencies. Consequently, many ministries and agencies have become involved in promoting science and technology. In other words, in addition to the MOST, the Ministry of Industry and Information Technology (hereinafter referred to as MIIT) and National Development and Reform Commission (hereinafter referred to as NDRC) play important roles in this field.

The transferred missions are shown in Figure 3-1-4. The NDRC oversees policy planning related to science and technology. Simultaneously, MIIT is responsible for high-tech industries, technology, the science and technology services industry, and other fields with a high possibility of technological application and encouraging technological development. In addition, in the case of scientific and technological issues related to agriculture, there were concerns that the Ministry of Agriculture, Forestry, and Fisheries and MOST were both involved, resulting in the duplication of work. Recent reforms clarified the jurisdiction of each ministry, leading to streamlining and improved efficiency.



Source: Science Portal China (SPC) "News from Beijing: Reorganization of the Ministry of Science and Technology of China"

Figure 3-1-4 Organizational Reform of MOST

Then, what are the major missions[16] of MOST after the reorganization?

Their scope includes promoting enhanced functioning for realizing a New-Style Whole-of-Nation System, optimizing the management of the entire chain of scientific and technological innovation, spurring the practical application of scientific and technological results, and striking a balance between scientific and technological advancement and economic and social development. They also cover strengthening macro-management responsibilities in strategic planning, institutional reform, resource allocation, comprehensive coordination, policy regulations, supervision, and inspection.

The following missions remain under the jurisdiction of the State Council: National Basic Research and Applied Basic Research; construction of national laboratories; the National Science and Technology Major Project; establishment of a national technology transfer system; transfer of scientific and technological results; integration of industry, academia, and research; establishment of a regional scientific and technological innovation system; establishment of a science and technology supervision and evaluation system; enhancement of credibility in scientific research; international science and technology cooperation; establishment of scientific and technological human resources organizations; and related responsibilities, such as national scientific and technological awards.

3.1.3 Related Key Policies

The key policies related to electrochemical devices (batteries, fuel cells, and water electrolysis) are analyzed in this section. It is the first time that the Chinese government mentioned rechargeable batteries and energy storage in the 2014 "12th Five-Year Plan." The "National Innovation-Driven Development Strategy (2016)" and "Made in China 2025 – Implementing Plan for Energy Equipment (2016)" also emphasize technological development and applications related to green energy, new energy, and core energy equipment. Table 3-1-4 summarizes key policies related to electrochemical devices over the past five years. As is evident at first glance, many policies have been announced in a short period; of them, the most important policies are highlighted and summarized below.

[16] For information on the major missions of MOST, please refer to SPC "News from Beijing: Reorganization of the Ministry of Science and Technology of China"

As a medium- to long-term strategy for hydrogen energy and fuel cells, the central government has released the "Energy Technology Innovation Action Plan (2016–2030)[17]." This was the first policy to consider hydrogen energy as a part of the national energy policy. The plan mentions 15 technologies that will be developed with a focus on, among other things, coal detoxification and clean mining technologies, advanced nuclear technologies, high-efficiency solar energy utilization technologies, and hydrogen energy and fuel cell technologies. There are two focus areas. The first involves the development of core technologies related to large-scale hydrogen production, storage materials, transportation, and hydrogen stations. The other is the development of technologies such as proton exchange membrane fuel cells (PEMFC), methane fuel cells (MFC), solid oxide fuel cells (SOFC), and metal air fuel cells (MeAFCs).

During the 13th Five-Year Plan period (2016–2020), the development of the electrochemical field was in a transitional phase from the demonstration of the results of research and development to the early stages of commercialization. Significant progress has been made in the research and development of technologies and equipment, organization of demonstration projects, exploration of business models, and formulation of laws and regulations, leading to a steady scale-up of applications. With the start of the 14th Five-Year Plan in 2021, the policy focus in the field of electrochemistry has shifted from the R&D stage to large-scale commercialization. The "Guiding Opinions on Accelerating the Development of New Energy Storage"[18] (No. 9 in the table), published in 2021, sets a clear target of increasing the scale of new energy storage[19] facilities to more than 30GW by 2025. This target is approximately ten times larger than the cumulative installed capacity of 3.8 GW by 2020.

The "New Energy Storage Development Plan During China's '14th Five-Year Plan' Period"[20] (No. 10 in the table) states that by 2025, the new energy storage industry will develop from the initial stage of commercialization to the stage of large-scale commercialization. It also emphasized that its innovation capabilities for new energy storage technologies and independent development capabilities of core technologies and equipment were significantly improved, and a system for developing standards and specifications and a mature business model were installed. It also states that the cost of related energy storage systems should be reduced by more than 30% to improve the performance of the electrochemical energy storage technology. By 2030, the goal will be to achieve the independent development of core technologies and equipment for new energy storage and to realize world-class technological innovation and industrialization, thereby achieving full commercialization of the new energy storage industry.

In March 2022, the Chinese government released its first hydrogen industry development plan, the "Medium- and Long-Term Plan for the Development of the Hydrogen Energy Industry (2021–2035)"[21] (No. 11 in the table). The plan sets specific numerical targets, including producing 50,000 fuel cell vehicles

[17] https://www.gov.cn/xinwen/2016-06/01/content_5078628.htm

[18] https://www.ndrc.gov.cn/xxgk/zcfb/ghxwj/202107/t20210723_1291321.html

[19] New energy storage refers to energy storage technologies other than pumped one, that primarily supply electricity, and includes new lithium-ion batteries, flow batteries, compressed air energy storage, and mechanical energy storage. ("The New Energy Storage Industry Enters a Phase of Rapid Growth," China Economy and Industry Frontline from People's Daily Online Japanese Edition, November 29, 2023), https://project.nikkeibp.co.jp/bpi/atcl/column/19/112400436/

[20] https://www.ndrc.gov.cn/xwdt/tzgg/202203/P020220321550104020921.pdf

[21] https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202203/t20220323_1320038_ext.html

by 2025, 100,000 to 200,000 tons of green hydrogen annually, and reducing carbon dioxide emissions by 1–2 million tons annually through the use of green hydrogen. By 2030, the government aims to build and widely apply a hydrogen production and supply system using clean energy, and to strongly support the goal of peaking carbon emissions. By 2035, it plans to establish a hydrogen energy industry system and create diversified application forms.

Table 3-1-4 Key Policies of the Chinese Central Government Related to Electrochemical Devices

	Publication date	Publishing body	Title of policy	Contents
1	February, 2018	NDRC, National Energy Administration	Guidance emphasizing the improvement of the power system's regulation capacity and operational efficiency	Introduce large-scale energy storage facilities in the North-East, Northern North China, and Northwest regions, where energy waste is serious.
2	August, 2019	NDRC, National Energy Administration	Opinion on the Establishment of a Power Futures Market Hub	Adjustment of electricity subsidy services and futures markets, introduction of a system whereby electricity users bear part of the subsidy costs, and encouragement of storage facilities and other entities to participate in the service market.
3	January, 2020	National Energy Administration, Ministry of Emergency Management, State Administration for Market Regulation	Measures for implementing the strengthening of the standardization of energy storage	Establishment of a standard system for energy storage, promotion of a standardization model, and international standardization for energy storage.
4	January, 2020	Ministry of Education, NDRC, National Energy Administration	Action Plan for Energy Storage Technology Discipline Development (2020-2024)	Expand the number of departments related to energy storage technology at universities. Establish a graduate school for energy storage. Create a platform for industry-academia collaboration and innovation.
5	May, 2020	National Energy Administration	Guidance on Establishing a Sound, Long-term Mechanism for Clean Energy Consumption	Create market mechanisms that favor clean energy consumption, enhance the regulatory capabilities of power systems, and focus on innovation in clean energy consumption models.
6	March, 2021	National People's Congress	14th Five-Year Plan for National Economic and Social Development and Long-Term Goals Outline through 2035	Develop plans for advancing cutting-edge science and technology, including hydrogen energy and energy storage, to support future industries. Promote the smartification of network infrastructure and power systems. Enhance the competitiveness of clean energy in consumption and storage.
7	March, 2021	NDRC, National Energy Administration	Guiding opinions on promoting the integration of power generation, grids, demand, and storage & the development of multi-energy complementarity	Manageably distribute stored energy and promote the integration of wind, solar, water, and fire energy.

8	May, 2021	NDRC	The Opinions on Further Improving the Pricing Mechanism for Pumped Storage	Maintain the existing two-tier electricity pricing policy while improving the pricing mechanism for pumped storage hydroelectric power. Create a method for determining electricity prices through competition and strengthen coordination with the development of the electricity market.
9	July, 2021	NDRC, National Energy Administration	Guiding Opinions on Accelerating the Development of New Energy Storage	In order to achieve carbon neutrality, the development of new types of stored energy will be utilized as a means of improving the adjustment capacity, efficiency, and security of the electric power system.
10	February, 2022	NDRC, National Energy Administration	Implementation Plan for the Development of New Energy Storage during the 14^{th} Five-Year Plan Period	Achieve a breakthrough in rapid testing of battery cycle life and technology for evaluating deterioration, and focus on technological development related to the sorting and recovery of retired batteries.
11	March, 2022	NDRC	Medium and Long-term Plan for Hydrogen Energy Industry Development	First national policy on hydrogen energy

Source: Created by APRC by referring to the websites of various Ministries

3.1.4 Research Funds and Research Programs

(1) Outlines

There are many types of research funds supporting electrochemical devices in China. This section introduces the top funding programs according to the number of papers published in the last 10 years (2013–2022) by device type, as identified by the Web of Science (hereinafter referred to as WoS).

The top funding programs included the National Natural Science Foundation of China (NSFC), major fundamental research funds for central universities, the China Postdoctoral Science Foundation, the National Key Research and Development Program of China, and the Chinese Academy of Sciences. Many of the major fundamental research funds for central universities and the China Postdoctoral Science Foundation are not disclosed, because the universities receiving support adopt a method of independently determining research themes and projects. The National Basic Research Program of China (973 Program) merged with the National Key Research and Development Program in 2015[22]. For this reason, this paper focuses on the NSFC, the National Key Research and Development Program of China, and the Chinese Academy of Sciences, introducing the administrative agencies in charge, research programs, and funding scales. Although not discussed in this section, numerous funds are available at the local level, such as those in Beijing and Shanghai, as well as those at the central level.

[22] The decision to merge was announced in 2014.

Table 3-1-5 Major research funds related to electrochemical devices, based on the number of papers published in China

Agencies of research funds	Storage buttery	Fuel cell	Water electrolysis
National Natural Science Foundation of China (NSFC)	66,008	20,889	6,874
Fundamental Research Funds for The Central Universities	9,917	3,240	1,300
China Postdoctoral Science Foundation	5,998	1,691	568
National Basic Research Program of China	4,716	1,690	293
National Key Research and Development Program of China	4,028	1,576	404
National Key Technologies R&D Program of China.	3,889	969	390
Chinese Academy of Sciences	2,314	737	303
Natural Science Foundation of Jiangsu Province	2,768	313	234
China Scholarship Council	2,079	715	234
Natural Science Foundation of Shandong Province	1,881	560	244
National Natural Science Foundation of Guangdong Province	1,771	623	135
Ministry Of Education, China 111 Project	1,757	487	213

Note: White columns indicate regional funds. Source: Web of Science

(2) National Natural Science Foundation of China (NSFC)

As shown in Tables 3-1-5, the NSFC accounts for the largest share of funding for electrochemical devices. Since its establishment in 1986, the NSFC has been operating under the leadership of the central government and the State Council, drawing on the expertise of specialists and focusing on supporting basic research. In 2007, the National Natural Science Foundation Regulations were enacted, and the organization grew into a systematically organized entity with organizational, process, and fund management. In 2018, under the "Decision on Deepening Reform of Party and State Institutions," NSFC became a relatively independent organization under the jurisdiction of the Ministry of Science and Technology, rather than the State Council, and now independently sets annual support plans and programs and carries out reviews and supervision. Even when the Ministry of Science and Technology is reorganized in 2023, the NSFC's supervising ministry remains unchanged.

As of August 2023, the NSFC implemented 15 programs. The details are presented in Table 3-1-6. While in the case of the National Key Research and Development Program and National Science and Technology Major Project, certain themes to be studied or resolved are determined in a top-down manner at the stage of solicitation, more than 60% of research projects by NSFC are funded in the framework of the research program category "General Program." Its applicants are free to select any topics in a bottom-up manner. In terms of project numbers, the General Program and various funds, such as Youth Scientist Funds, dedicated to younger scientists, are most prevalent. However, these projects are characterized by smaller funding scales and relatively shorter implementation periods compared to "Key Program" and "Major Project."

Table 3-1-6 List of NSFC Research Programs

Name of Program	Outlines
① General Program	The most standard program for researchers engaged in basic research, allowing them to independently select topics within the scope of funding.
② Key Program	A program that is for researchers with a certain level of research experience. It targets research themes that have the potential for further development with support.
③ Major Program	A program that studies important scientific issues related to the national economy, society, scientific and technological development, and national security.
④ Major Research Plan	A program that supports research themes related to the national economy, social development, and national security, focusing on important national strategic needs and cutting-edge science.
⑤ Young Scientist Program	A program in which young researchers independently select topics and conduct basic research within the scope of support.
⑥ Regional Science Program	This program focuses on supporting researchers engaged in basic research in ethnic minority areas (autonomous regions and autonomous prefectures), inter alia, those in certain areas thereof lagging in scientific and technological development.
⑦ Excellent Young Scientist Fund	A program that supports young researchers with outstanding achievements in basic research, so that they can independently select research topics.
⑧ National Distinguished Youth Science Fund	A program that supports young researchers with outstanding achievements in basic research in selecting their own themes and conducting innovative research.
⑨ Innovation Research Group	A program in which talented middle-aged and young researchers take the lead in conducting innovative research on a single important research theme.
⑩ Basic Science Center Program	A program that focuses on cutting-edge international science, brings together talented researchers from the domestic and international community, conducts joint research, and produces internationally renowned research results.
⑪ Tianyuan Fund for Mathematics	A funding program that supports scientists in exploring the characteristics and principles of mathematics.
⑫ Special Fund for Research on National Major Research Instruments	A program that supports the research and development of major research instruments and equipment with original creative ideas.
⑬ International Cooperation and Exchange Programs	A program that creates a foundation for international joint research through exchange activities with overseas science funding organizations and scientific research institutions.
⑭ Research Fund for International Scientists	A program to support outstanding foreign researchers who can conduct basic research while staying in China. It includes three subprograms: The Research Fund for International Young Scientists (RFIS-I), The Research Fund for International Excellent Young Scientists (RFIS-II), and The Research Fund for International Senior Scientists (RFIS-III).
⑮ Programs of Joint Funds	A program that addresses scientific issues based on the actual needs of companies, local communities, and various organizations, and conducts research.

Source: Created by APRC based on the NSFC website

According to the "2022 Annual Report of National Natural Science Foundation of China," funding for 2022 amounted to over RMB 38.9 billion[23], supporting a total of 51,593 projects.

Based on projects terminated in the last five years (2018–2022) in the database operated by the NSFC Big Data Knowledge Management Service Platform, the scale of support for projects related to electrochemical devices is as follows: The keywords used were storage batteries, fuel cells, and water electrolysis." The percentage of projects per device is shown on the following page:

① Since secondary batteries include[24] both storage batteries and rechargeable batteries, a search for "secondary batteries" (Figure 3-1-5) shows that 47 projects have been supported, with a total support amount of RMB 22.17 million (approximately JPY 421 million). The amount of support funds for each project ranges widely from RMB 200,000 (approximately JPY 3.8 million) to RMB 2.7 million (approximately JPY 51 million), and the title of the latter project is "Research on high-capacity solid-state lithium secondary battery using lithium alloy negative electrode."[25]

② A search for "fuel cell" brings up 357 projects (Figure 3-1-6), and the project with the largest amount of funding is "Integrated modeling and control method of vehicle fuel cell system and vehicle dynamics system,"[26] with project funding amounting to RMB 3.65 million. In fuel cell-related projects, the support amounts range widely from 180,000 to 3.65 RMB million.

③ A search for "water electrolysis" yields 10 projects, with a total funding amount of RMB 4.109 million (approximately JPY 78 million) (Figure 3-1-7). The project receiving the largest amount of funding is "Study on Electrocatalytic hydrogenolysis of lignosulfonate in black liquor of papermaking based on hydrogen production by alkaline water electrolysis," [27] which has a budget of RMB 650,000.

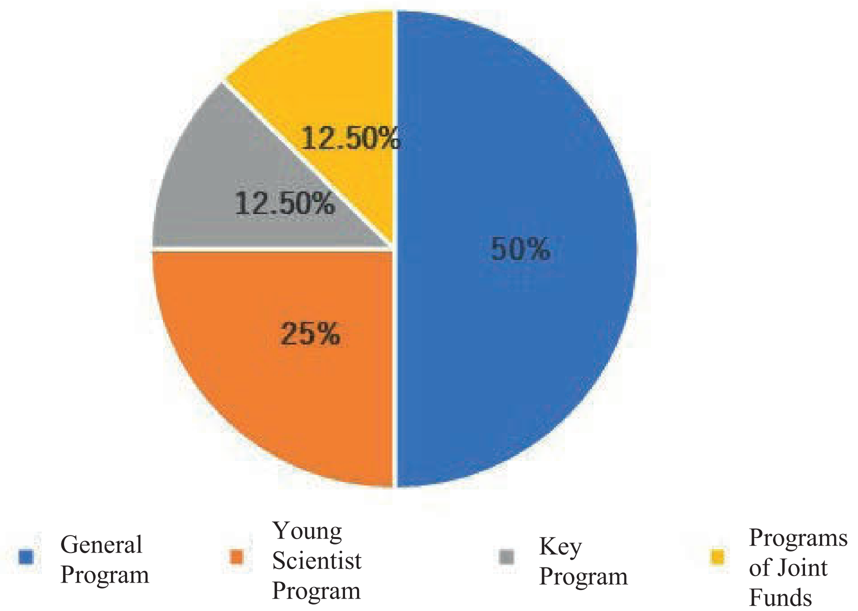


Figure 3-1-5 Percentage of funding programs when searching for "secondary batteries"

[23] Please refer to https://www.nsfc.gov.cn/publish/portal0/ndbg/2022ndbg/01/info89680.htm The exact amount is RMB 3,890,915.69.

[24] For the definition of storage batteries in Chinese, please refer to https://baike.baidu.com/item/%E8%93%84%E7%94%B5%E6%B1%A0/990661?fr=ge_ala

[25] https://kd.nsfc.gov.cn/finalDetails?id=5c47f804bc0ae8005d1535145c069190

[26] https://kd.nsfc.gov.cn/finalDetails?id=1a57ca116dd658b8d7c5e94dd0382bf1

[27] https://kd.nsfc.gov.cn/finalDetails?id=f36bcb07e911f5372da5572a7e0c026f

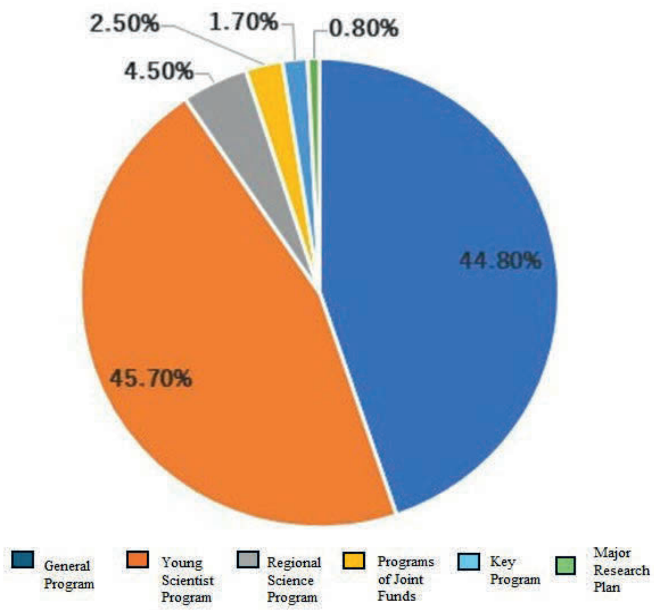
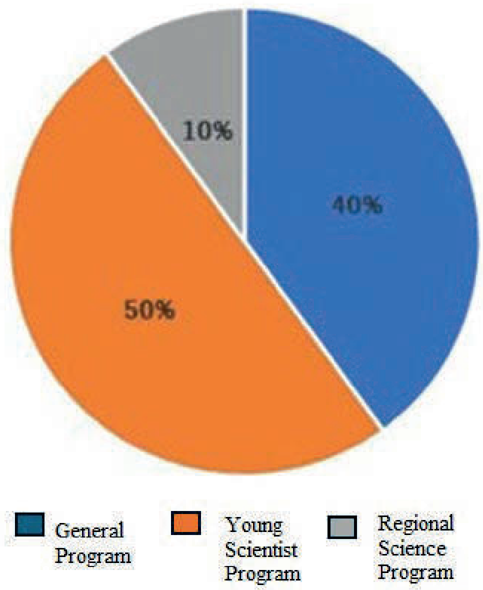


Figure 3-1-6 Percentage of funding programs when searching for “fuel cell”



Source: Created by APRC based on NSFC Big Data Knowledge Management Service Platform

Figure 3-1-7 Percentage of funding programs when searching for “water electrolysis”

Many projects related to electrochemical devices are funded by the General Program and Young Scientist Programs, and most receive relatively small funds. For the Key Program, the amount of support for each project was RMB 3 million or more, and for the Major Research Plan, it was RMB 600,000 or more.

(3) National Key Research and Development Program

The National Key Research and Development Program aims to solve major core scientific and technological issues in various key areas of national economic and social development. In 2014, the MOST implemented reforms to its scientific research management system. The National Key Research and Development Program was created by integrating the previously separate the following Program: "National Key Basic Research Development Program (973 Programs)," "National High-tech Research Development Program (863 Programs)," "National Science and Technology Support Program," "International Science and Technology Cooperation and Exchange Special Projects," "Industrial Technology Research and Development Funds," and "Public Industry Scientific Research Special Projects"[28], and has been managed under the jurisdiction of all the Ministry of Science and Technology since 2015.

Among the key fields for the 14th Five-Year Plan period (2021–2026), those related to electrochemical devices include "Research on Energy Storage and Smart Grid Technology (储能与智能电网技术)" and "Hydrogen Energy Technology (储能与智能电网技术)." According to the application guidelines, RMB 667 million[29] and RMB 795 million[30] will be invested in funding projects related to the former and latter themes, respectively. The funding projects adopted under these key themes are listed in Tables 3-1-7 and 3-1-8, respectively. The topics covered in these projects, such as "safety and reliability," "control," and "battery life," are areas that China has been focusing on over the past five years.

[28] Please refer to pp.27-28 of APRC report, "Study on the mechanism of discovery and promotion of the excellence in China's R&D system"
[29] Please refer to http://www.21spv.com/news/show.php?itemid=106904
[30] Please refer to https://wenku.baidu.com/view/94919cea83eb6294dd88d0d233d4b14e85243eec.html?_wkts_=1692153852794&bdQuery=%E6%B0%A2%E8%83%BD%E6%8A%80%E6%9C%AF+%E6%8C%87%E5%8D%97pdf%E3%80%802021

Table 3-1-7 List of projects selected in the field of “Research on Energy Storage and Smart Grid Technology”

	Project number	Project title	Implementing organization	Period (year)
1	2021YFB2400100	Research on gigawatt-hours lithium-ion storage system technology	Contemporary Amperex Technology	4
2	2021YFB2400200	Essentially safe solid-state lithium-ion battery technology with a capacity of megawatt-hours	Tianjin Risesun Mengguli New Energy Science & Technology Co., Ltd.	4
3	2021YFB2400300	Manufacturing of inherently safe metal-sulfur-based energy storage batteries	Shanghai Jiao Tong University	4
4	2021YFB2400400	Core materials and technologies for low-cost hybrid supercapacitors and their demonstration research on megawatt-scale systems	GMCC Electronic Technology WuXi Ltd	4
5	2021YFB2400500	Research on Mainstream Dynamic Rapid Support Technology for Transient Frequency and Voltage in PV/Wind Power Plants	China Electric Power Research Institute	4
6	2021YFB2400600	Research on key technologies for lightweight, flexible DC offshore converter platforms	China Huaneng Group Clean Energy Technology Research Institute Co., Ltd.	4
7	2021YFB2400700	Research and application of key technologies for intelligent coordinated control of large-scale energy storage system clusters	China Three Gorges Corporation	3
8	2021YFB2400800	Research on response-driven intelligence analysis and enhanced control technology for large-scale grid stability	China Electric Power Research Institute	3
9	2021YFB2400900	Technical research on controlling failures in phase switching of multi-feed high-voltage direct current transmission systems	Global Energy Internet Research Institute Co., Ltd.	4
10	2021YFB24001000	Research on highly reliable protection and monitoring technology for transformer substations based on autonomous chips	China Electric Power Research Institute	3

11	2021YFB24001100	Research on core technology related to flexible low-frequency power transmission	State Grid Zhejiang Electric Power Co Ltd	4
12	2021YFB24001200	Research on core technologies for interactive regulation to expand flexible resource virtual power plant aggregation	China Electric Power Research Institute	3.75
13	2021YFB24001300	Core technologies for synergistic effects and mutual operation of distribution network business resources	China Electric Power Research Institute	4
14	2021YFB24001400	Research, development, and application of new environmentally friendly insulating gases	China Electric Power Research Institute	4
15	2021YFB24001500	Dielectric film for dry DC capacitors	Tsinghua University	4
16	2021YFB24001600	Research on core technologies for high-voltage high-power switchable device drivers	Global Energy Internet Research Institute Co., Ltd.	4
17	2021YFB24001700	Research on key technologies for multi-physical field simulation of high-voltage electrical equipment and software development	Beijing Yundiao Supreme Science and Technology Co., Ltd.	4
18	2021YFB24001800	Research on accelerated aging analysis and life prediction technology for storage batteries	China Electric Power Research Institute	4
19	2021YFB24001900	Intelligent sensing technology for lithium-ion batteries used in energy storage	Beijing Institute of Technology	4
20	2021YFB24002000	Safety technology is applied throughout the entire life cycle of lithium-ion storage systems	China Southern Power Grid Company Limited, Peak Load and Frequency Control Power Generation Co., Ltd.	3
21	2021YFB24002100	Research on on-load tap changer technology and equipment for converters and transformers	China Electric Power Research Institute	3

Source: Ministry of Science and Technology, "National Science and Technology Information System, Public Service Platform"

Table 3-1-8 List of projects selected in the field of “Hydrogen Energy Technology “

	Project number	Project title	Implementing organization	Period (year)
1	2021YFB4000100	Foundations of materials and processes for electrolytic hydrogen production from variable power sources such as solar and wind energy	Global Energy Internet Research Institute Co., Ltd.	4
2	2021YFB4000200	Low-cost PEM water electrolysis substrate preparation technology and demonstration for hydrogen production application	Nankai University	4
3	2021YFB4000300	Development of core technology and equipment for high-efficiency, high-output alkaline water electrolysis cells	Dalian Institute of Chemical Physics (DICP), Chinese Academy of Sciences	4
4	2021YFB4000400	Renewable Energy Electrolytic Hydrogen Production - Key Technologies and Applications for Low-Temperature, Low-Pressure Ammonia Synthesis	Fuzhou University	4
5	2021YFB4000500	100,000 tons of renewable energy, Renewable hydrogen synthesis and ammonia demonstration project	Sichuan Energy Internet Research Institute, Tsinghua University	4
6	2021YFB4000600	Materials for high-density hydrogen storage and technology for their reversible absorption and desorption of hydrogen	Nankai University	4
7	2021YFB4000700	Development of hydrogen production equipment for hydrogen liquefaction plants	Technical Institute of Physics and Chemistry, Chinese Academy of Sciences	4
8	2021YFB4000900	Analysis of leakage, combustion, and explosion behavior of gaseous and liquid hydrogen containers and accessories, and their material requirements	Dalian University of Technology (DUT)	3
9	2021YFB4001000	Technology and specifications for transporting and centralized storage of hydrogen fuel cell vehicles loaded with bottled hydrogen gas	China Automobile Technology and Research Center Co., Ltd	3

10	2021YFB4001100	Research on new perfluorinated proton membranes in the trans temperature range	Shanghai Jiao Tong University	3
11	2021YFB4001200	Development of low-cost, long-life alkaline film fuel cell stacks	Soochow University	4
12	2021YFB4001300	High-efficiency, long-life membrane electrode technology for power plants	Shanghai Jiao Tong University	4
13	2021YFB4001400	Core technology for tubular solid oxide fuel cell power generation units and reactors	Xi'an Jiaotong University	4
14	2021YFB4001500	kW Solid Oxide Fuel Cell (SOFC) Power Generation System and Core Technology for High-Reliability Reactors	China University of Petroleum (UPC)	4
15	2021YFB4001600	Core technologies for low- and medium-pressure pure hydrogen and doped hydrogen gas pipelines and their applications	China University of Petroleum (UPC)	3
16	2021YFB4001700	Core technology for integrated energy supply systems for households using solid polymer electrolyte fuel cells (PEFC)	Qingdao Institute of Bioenergy and Bioprocess Technology, Chinese Academy of Sciences	4
17	2021YFB4001800	Integration of core technologies for hydrogen power generation and energy supply systems, and demonstration of their application in multiple scenarios	Shandong National Center of Technology Innovation for Fuel Cell	4

Source: Ministry of Science and Technology, "National Science and Technology Information System, Public Service Platform"

(4) China Academy of Science

The Chinese Academy of Sciences (CAS), the highest academic institution for natural sciences in China, was established in 1949. The CAS is a huge organization with 145 organizations under its jurisdiction: 106 research institutions, 15 administrative agencies, 14 reorganized agencies[31], 2 educational institutions, and 8 support agencies. There were 43 affiliated research institutes in Beijing alone (Technical Institute of Physics and Chemistry, etc.) and 71 institutes outside Beijing (Dalian Institute of Chemical Physics, Hefei Institute of Physical Science, etc.). These research institutes are large in scale and have basic policies as independent organizations, although they are affiliated with the CAS. CAS invested in 32 companies, including the Chinese Academy of Sciences Advanced Materials Technology Co., Ltd., and CAS Quantum Network Co., Ltd. With many organizations under its umbrella, CAS's budget far exceeds that of other research institutions, with a budget of RMB 170.8 billion[32] for fiscal 2023. This amount is more than four

31 This is a China-specific expression to indicate changes in the nature of an organization or the proportion of capital investment. For example, a state-owned enterprise may become a semi-public organization jointly operated by the government and private companies, or it may become a completely private company.

32 For information on the organization and budget of the Chinese Academy of Sciences, please refer to the "Chinese Academy of Sciences 2023 Departmental Budget." https://www.cas.cn/xxgkml/zgkxyyb/czjf/ysjs/202303/P020230328780420565579.pdf.

times that of Tsinghua University.

This study examined five major funding programs offered by CAS exclusively to its affiliated institutes: ① Strategic Leading Science and Technology Program, ② Priority Research Program, ③ Science and Technology Human Resources Program, ④ Science and Technology Collaboration Program, ⑤ Science and Technology Platform Program. The CAS operates its own project resource platform, which provides support for project applications and other matters.

① The Strategic Leading Science and Technology Program is a funding program established by the CAS with the approval of the State Council Executive Meeting. It supports scientific and technological research related to improving China's international competitiveness, economic and social development, national security, and technological innovation. It consists of Category A strategic science and technology; Category B, basic and interdisciplinary scientific research; and Category C, core technology for solutions. Category A includes stem cell and regenerative medicine research projects, and Category B includes quantum system correlation control research projects.

② The Priority Research Program promotes projects across disciplines and organizations, focusing on key areas designated by the CAS. Priority areas were aligned with the National Plan. This program focuses primarily on basic research-oriented issues and strategic scientific and technological themes to support scientific and technological breakthroughs. There are three types of programs in this category: basic science and technology, high-tech research and development, and continuous development research. Over 180 projects were supported during the 13th Five-Year National Plan. One of its hallmarks is that it provides stable support that enables researchers engaged in basic research to devote themselves to their work.

③ The Science and Technology Human Resources Program was established with the aim of fostering international competitiveness among young researchers and includes a general human resources program, a specially invited researcher program, a young team program for basic research, and a special invitation research program. In addition, numerous projects to support young researchers are being promoted, including the Regional Development Scholars Project, the Western Young Scholars Project (for young researchers from inland areas), and the Young Interdisciplinary Team Project. The special invitation research program supports mid-career researchers, known as core talent, and consists of a basic research division and a technological breakthrough division.

④ The Science and Technology Collaboration Program was established with the aim of promoting scientific and technological cooperation between the CAS and companies, as well as joint research and exchange with research institutions in other countries. It includes programs such as the Global Issues Challenge Program, which encourages the joint consideration of global issues, and the Inter-Institutional Cooperation Program, which supports joint research with research institutions in other countries.

⑤ The Science and Technology Platform Program supports the management of large-scale experimental facilities, laboratories, and platforms.

Information on individual projects is strictly managed. However, some research results have been disclosed through websites and other means. Table 3-1-9 summarizes the significant achievements related to electrochemical devices.

Table 3-1-9 Major achievements related to electrochemistry by CAS

	Implementing organization	Major achievement	Member of research
1	Dalian Institute of Chemical Physics	Research on the potential for low-carbon development of flow batteries	Xianfeng Li, Changkun Zhang
2	Dalian Institute of Chemical Physics	Presentation of the zinc storage mechanism in zinc ion battery cathode pore materials	Weishen Yang, Kaiyue Zhu
3	Hefei Institute of Physical Science	By introducing serine cations (Ser+, C3H8NO3) into the zinc salt electrolyte, selective orientation growth of zinc (100) was achieved, thereby effectively suppressing the growth of zinc dendrites and improving the reversible charge-discharge performance and cycle stability of the battery.	Hulin Hua
4	Qingdao Institute of Bioenergy and Bioprocess Technology	Significant results were achieved in phase modulation, stability improvement of organic solar cells (OSCs), and in the efficient preparation of OSC using a molecular peripheral functional group modification scheme.	Xichang Bao
5	Ningbo Institute of Materials Technology and Engineering	There has been a new development in research on the corrosion mechanism of seawater electrolysis anodes. In addition to Cl-, it was discovered that Br- in seawater is more harmful to nickel-based anodes.	Zhiyi Lu
6	Ningbo Institute of Materials Technology and Engineering	A practical, cost-effective, and scalable cathode has been developed that produces hydrogen at industrial current densities and supports long-term stable seawater electrolysis.	Wenwen Xu
7	Guangzhou Institute of Energy Conversion	Based on the characteristics of power and heat fluctuations during automobile transportation, thermal management issues are addressed from a time dimension perspective, thereby creatively proposing a “time-varying” thermal management method, and developing a new thermal management system equipped with a heat peak regulator.	Fangming Jiang
8	Suzhou Institute of Nano-Tech and Nano-Bionics	The recyclability and sustainability of fuel cells are demonstrated.	Xiaochun Zhou
9	Dalian Institute of Chemical Physics	Ultra-fast hydrogen anion conduction at room temperature is achieved.	Ping Chen, Hujun Cao
10	Dalian Institute of Chemical Physics	Research results have been achieved in the design and construction of porous electrodes with low interfacial mass transfer resistance for high-temperature polymer electrolyte membrane fuel cells (HT-PEMFC).	Suli Wang, Gongquan Sun

Source: Created by APRC, referring to the Chinese Academy of Sciences news and articles

3.1.5 Major Research Institutions and Major Companies

As mentioned above, research institutions in the field of electrochemistry can be divided into two groups: CAS (including affiliated organizations) and other research institutions. The CAS dominates the field regardless of the type of device used, such as storage batteries, water electrolysis, and fuel cells. Based on the WoS data from 2013 to 2022, the research institutions are listed in order of the number of papers by device, as shown in Tables 3-1-10 to 3-1-15.

Table 3-1-10 Top 10 CAS and their Affiliated Organizations in the Field of Storage Batteries

	Name of organization	Number of papers
1	CAS	13,839
2	University of China Academy of Science	4,015
3	University of Science and Technology of China	3,092
4	Institute of Physics, CAS	1,005
5	Shanghai Institute of Ceramics, CAS	844
6	Changchun Institute of Applied Chemistry, CAS	841
7	Dalian Institute of Chemical Physics, CAS	728
8	Ningbo Institute of Materials Technology and Engineering, CAS	716
9	Institute of Chemistry, CAS	653
10	Institute of Process Engineering, CAS	650

Table 3-1-11 Top 10 Other Organizations in the Field of Storage Battery

	Name of organization	Number of papers
1	Tsinghua University	4,475
2	Central South University	4,017
3	Beijing Institute of Technology	2,831
4	Harbin Institute of Technology	2,697
5	Shanghai Jiao Tong University	2,655
6	Zhejiang University	2,374
7	Huazhong University of Science and Technology	2,280
8	Tianjin University	2,197
9	Shandong University	1,928
10	Peking University	1,912

Table 3-1-12 Top 5 CAS and their 5 Affiliated Organizations in the Field of Water Electrolysis

	Name of organization	Number of papers
1	CAS	1,534
2	University of China Academy of Science	466
3	University of Science and Technology of China	255
4	Dalian Institute of Chemical Physics, CAS	136
5	Institute of Process Engineering, CAS	121

Table 3-1-13 Top 5 Other Organizations in the Field of Water Electrolysis

	Name of organization	Number of papers
1	Tsinghua University	423
2	Harbin Institute of Technology	401
3	University of Science and Technology Beijing	321
4	Central South University	276
5	Chongqing University	211

Table 3-1-14 Top 10 CAS and their Affiliated Organizations in the Field of Fuel Cell

	Name of organization	Number of papers
1	CAS	4,723
2	University of China Academy of Science	1,289
3	University of Science and Technology of China	1,131
4	Dalian Institute of Chemical Physics, CAS	541
5	Changchun Institute of Applied Chemistry, CAS	473
6	Shanghai Institute of Ceramics, CAS	223
7	Ningbo Institute of Materials Technology and Engineering, CAS	173
8	Fujian Institute of Research on the Structure of Matter, CAS	168
9	Institute of Coal Chemistry, CAS	158
10	Institute of Process Engineering, CAS	156

Table 3-1-15 Top 10 Other Organizations in the Field of Fuel Cell

	Name of organization	Number of papers
1	Tsinghua University	1,361
2	Harbin Institute of Technology	1,216
3	Tianjin University	1,064
4	South China University of Technology	882
5	Xi'an Jiaotong University	830
6	Huazhong University of Science and Technology	816
7	Shanghai Jiao Tong University	780
8	Chongqing University	657
9	Tongji University	637
10	Wuhan University of Technology	611

As is clear from the above information, research and development in the field of electrochemistry is being led by CAS and its affiliated organizations, Tsinghua University, and the Harbin Institute of Technology.

Based on the above table, the following section provides an overview of major research institutions and companies in the field of electrochemistry in China. As they are categorized, research institutions fall into two main groups: "CAS and its affiliated organizations" and "universities."

CAS and its affiliated organizations

CAS has a number of research institutes under its umbrella, like the Institute of Physics, with Chen Liquan[33], an academician of the Chinese Academy of Engineering, who's called the "father of lithium batteries" in China, as a member of the Chinese Academy of Sciences. Here, several notable organizations and research teams in the field of electrochemistry are discussed.

(1) Institute of Solid-State Physics (ISSP), Hefei Institutes of Physical Science, CAS[34]

ISSP was established in March 1982 by renowned physicist Kê T'ing-sui[35]. It is designated as a key laboratory for material physics by the CAS, a key laboratory for nanomaterials and technology in Anhui Province, an engineering laboratory for special metals in Anhui Province, and a nanomaterial engineering technology center in Anhui Province. The ISSP has trained many highly skilled professionals in physics,

[33] Regarding Chen Liquan, please refer to the following information: "Introduction to Chen Liquan, Institute of Physics, Chinese Academy of Sciences" , http://www.iop.cas.cn/rcjy/yszj/?id=741 ; "Innovation China, Introduction Page of Chen Liquan," https://www.kczg.org.cn/xuezhe/details?id=5370 ; "THE HO LEUNG HO LEE FOUNDATION, Introduction of Chen Liquan," http://www.hlhl.org.cn/news/findnews/showsub.asp?id=541 ; "Chen Liquan, a leading researcher in lithium-ion batteries in China," http://quan.cnpowder.com.cn/article.php?artid=310

[34] For details, please refer to its homepage http://www.issp.cas.cn/old/rcdw/yjjh/

[35] The details can be known in http://www.imr.cas.cn/zt/kxrs/gts_kxrs/202305/t20230515_6754602.html

materials physics, and chemistry, and currently has over 220 master's and doctoral students. Of the 181 staff members, 41 were researchers, and 75% (31 people) were selected for the "National Science Fund for Distinguished Young Scholars" or "National Hundred and Thousand and Ten-thousand Talent Project," thereby making it a research institute with many talented individuals.

The institute has eight research departments: Nanomaterials and Component Technology Research Department, Solid Defect Research Department, Physical and Quantum Materials Research Department, Environmental Materials and Pollution Control Research Department, Functional Materials Physics and Components Research Department, Polymer and Composite Materials Research Department, Energy Materials and Component Manufacturing Research Department, and Materials Application Technology Development. Each research department comprises numerous research teams; however, the latest achievements of the ZHANG Yunxia and ZHAO Bangchuan teams are introduced here.

① ZHANG Yunxia team [36]

In August 2023, Zhang's team from the Nanomaterials and Component Technology Research Department announced that, through years of research, they had succeeded in recycling waste cobalt acid lithium battery cathode materials and upgrading them to high-performance, high-voltage cobalt acid lithium cathode materials.

The research team led by Zhang used a one-pot solid-state reactive sintering method to repair composition and structural defects, reconstruct the outer surface, and combine the triple effects of element doping, thereby achieving an effect of "hit three targets with one arrow" and upgrading waste lithium cobalt oxide into high-voltage lithium cobalt oxide cathode material. The high-voltage lithium cobalt oxide cathode material obtained by this method has a capacity of 188.2 mAh per gram at a cut-off voltage of 4.5 V, with an excellent performance of 92.5% capacity retention after 100 cycles and 86.4% capacity retention after 300 cycles.

Currently, more than 100,000 tons of lithium-ion batteries are generated annually from mobile electronic product waste worldwide. If not treated properly, this can cause serious environmental damage and waste metal resources. As the demand for battery energy density increases, raising the cut-off voltage is one of the most effective strategies for improving energy density. Therefore, recycling waste lithium cobaltate into high-voltage lithium cobaltate can significantly contribute to the sustainable use of metal resources. This research was published in "Advanced Energy Materials."

② ZHAO Bangchuan team[37]

The research team led by ZHAO Bangchuan of the Functional Materials Physics and Components Research Department has obtained a series of advances in research on electrode materials for high-performance aqueous zinc-ion batteries, and, through the synergistic effects of magnetic field-

[36] Hefei Institute of Physical Science, Chinese Academy of Sciences: Hitting three targets with one arrow : regenerating cathode materials from waste lithium iron phosphate batteries, http://www.issp.cas.cn/gts/xwzx/cmsm/202308/t20230830_751101.html

[37] Hefei Institute of Physical Science, Chinese Academy of Sciences: Advances in electrode material research for zinc-ion batteries, http://www.issp.cas.cn/gts/xwzx/kyjz/202306/t20230607_743945.html

electrochemical defect engineering, achieved research and development of an ultra-long-life VS2-based aqueous zinc-ion battery, which was published in the journals "Materials Horizons"[38] and "Small."[39]

Aqueous batteries are expected to have a wide range of applications in the field of large-scale energy storage owing to their high safety and low cost. They are considered complementary devices to lithium-ion batteries. Among these, aqueous zinc-ion batteries are attracting interest owing to their high theoretical specific capacity of 820 mAh/g and the low redox potential of zinc metal, which is -0.76 V vs NHE. However, as Zn dendrites precipitate at the anode, ZIBs are recognized to have a low energy density and less than the ideal cycle life. Therefore, the design and preparation of high-energy-density cathode materials and the suppression of zinc dendrite precipitation have become two key factors in the development of high-performance zinc-ion batteries. Zhao et al. successfully synthesized an accordion-shaped VS2 material by combining electrochemical defects at high charge-cutoff voltages. The VS2 material lattice has a unique structure that enables Zn^{2+} transport along the c-axis, thereby realizing three-dimensional Zn^{2+} transport along the ab plane and c-axis, effectively reducing the electrostatic interaction between zinc ions and VS2, and exhibiting a high specific capacity and high rate performance.

(2) Institute of New Energy Technology[40], Ningbo Institute of Materials Technology and Engineering, CAS

The establishment of the Ningbo Institute of Materials Technology and Engineering was discussed by the CAS and the Zhejiang Provincial People's Government beginning in April 2004. It was formally approved by the Central Committee of Compilation and Translation in March 2006. The Ningbo Institute of Materials Technology and Engineering has four research institutes under its umbrella, including the New Energy Technology Research Institute. The New Energy Technology Research Institute has more than 500 researchers. It is responsible for more than 600 funded projects, including the NSFC, National Science and Technology Major Projects, Zhejiang Province's key research and development plans, and Ningbo City's Innovation 2025 major projects. Over 1,000 papers have been published, and more than 600 patents have been filed.

Here, a solid-state secondary battery research group[41] at the Institute is introduced as a notable research team. The team consisted of three researchers (Xiayin Yao, Jinghua Wu, and Zhe Peng), two postdoctoral fellows, and approximately 40 master's and doctoral students. The main research areas include solid electrolyte materials, structural optimization of electrode/solid electrolyte interfaces, and solid battery technologies. All the materials, devices, and platforms necessary for solid battery research are available to the team, including solid lithium/sodium-sulfur batteries, corresponding solid battery systems such as solid sodium batteries, and solid metal-air batteries. The team has been awarded numerous central and local funding projects, has published more than 190 SCI papers[42], and has applied for more than 80 patents.

[38] Mater. Horiz., 2023, DOI: 10.1039/d3mh00303e
[39] Small, 2023, DOI: 10.1002/smll.202207998
[40] For details, please refer to Website http://energy.nimte.cas.cn/
[41] Solid-state secondary battery research group, Ningbo Institute of Materials Technology and Engineering, CAS, https://yaoxy.nimte.ac.cn/
[42] Papers published in journals listed in Clarivate's Science Citation Index.

(3) Dalian Institute of Chemical Physics, CAS[43]

The Dalian Institute of Chemical Physics is a research institute with a long history, having been established in March 1949. At the time of its establishment, it was named the Dalian University Research Institute; however, in 1961, it was renamed the Institute of Chemical Physics, CAS. It became the Dalian Institute of Chemical Physics in 1970. In 2007, the institute established a national clean energy laboratory.

Dalian Institute of Chemical Physics focuses on catalytic chemistry, industrial chemistry, chemical lasers, molecular reaction dynamics, modern analytical chemistry, and biotechnology. Since its establishment, it has created many outstanding researchers, with 20 scientists elected as academicians of the CAS and the Chinese Academy of Engineering, one elected as an international member of the Canadian Academy of Engineering, and one elected as an international member of the European Academy of Engineering. By the end of 2022, 32 students were awarded the National Distinguished Youth Science Fund, and 20 received support from the Excellent Young Scientist Fund. Currently, 869 doctoral and 795 master's students are enrolled in this study. From 2013 to 2022, the Dalian Institute of Chemical Physics published 11,855 SCI papers, of which 5,684 were published in journals with an IF index of over 5, and 2,576 were published in Science, Nature, and other journals with an IF index of over 9. The number of patents applied for was 12,901, and the number of patents registered was 6,222. "Chinese Journal of Catalysis" and "Journal of Energy Chemistry," published by the Dalian Institute of Chemical Physics, have been recognized as "Key Journals" as "the most internationally influential academic journal in China" by the Chinese Action Plan for Developing Excellent Scientific Journals.

The institute has many organizations under its umbrella, including 19 laboratories (research centers), 7 national laboratories, and 5 university-level laboratories. The research team[44] led by Xianfeng Li and Huamin Zhang of the Energy Storage Technology Research Department is introduced. Our research team is researching the large-scale preparation and application of membrane materials for high-performance, low-cost, alkaline flow batteries. Through a continuous roll-to-roll membrane manufacturing process, they enabled the large-area preparation of non-fluorinated cationic conductive membranes and their technical application in alkaline flow batteries for energy storage. Liquid-flow battery energy storage technology offers advantages such as safety, reliability, long life, and high efficiency, making it a suitable technology for large-scale energy storage. Therefore, cost reduction, particularly that of ion-conducting membrane materials, which are the main components used in flow batteries, is extremely important for promoting the practical application of flow batteries.

(4) Qingdao Institute of Bioenergy and Bioprocess Technology, CAS

The Qingdao Institute of Bioenergy and Bioprocess Technology is a national scientific research institution jointly established in 2009 by the CAS, Shandong Provincial Government, and Qingdao Municipal Government. The institute focuses on new energy, stored energy, new organisms, and new materials and offers postdoctoral courses in biology, chemical processes, and related technologies. Their

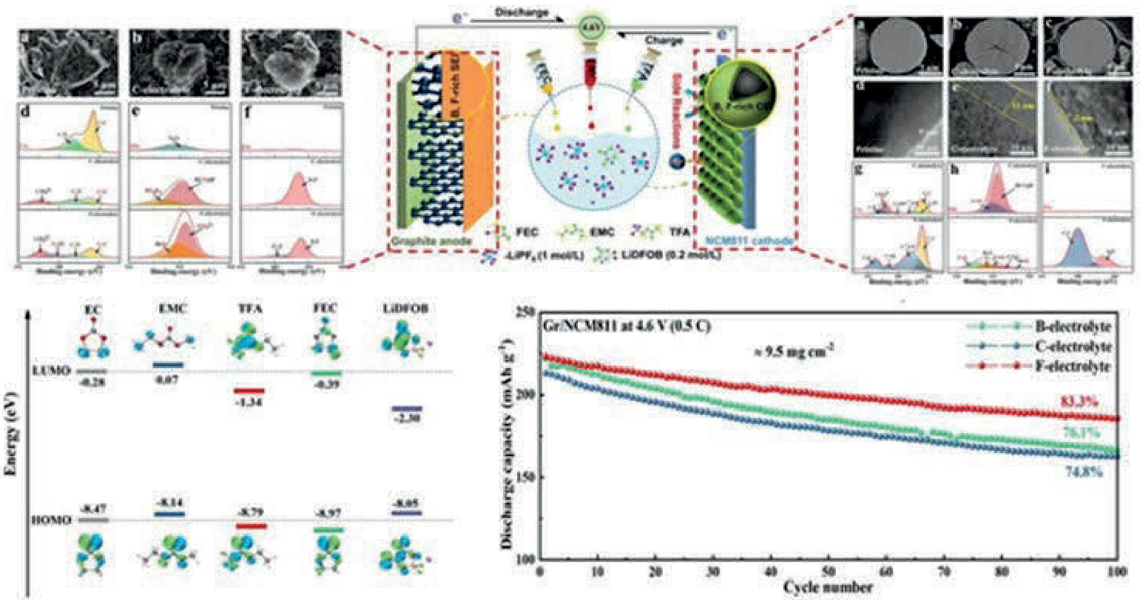
[43] For details, please refer to http://www.dicp.cas.cn/gkjj_1/skjj/

[44] Dalian Institute of Chemical Physics, Promoting research on membrane materials for alkaline flow batteries, https://www.cas.cn/syky/202203/t20220325_4829349.shtml

doctoral programs in biology, materials science and processes, chemical processes and related technologies, and materials and chemical processes are renowned first-class disciplines.

Through its “human resources system engineering” initiative, the Institute has already established 37 innovation research teams and has been selected as a “national entrepreneurship and innovation demonstration base.” There were 12 academics and high-level talent, 26 national-level talent program experts, and 121 provincial-level talent program experts. Among them, six were selected for the National High-Level Talent Special Support Program, National Distinguished Youth Science Fund, and Excellent Young Scientist Fund; 32 were selected as experts under the National and Chinese Academy of Sciences Talent Attraction Program; and 42 won large-scale provincial funding projects. Owing to its large pool of talented personnel, the institute is responsible for multiple national funding projects and major projects for the Chinese Academy of Sciences, with notable output in the fields of hydrogen energy and fuel cells, new solar energy cells, and synthetic biology technology. By the end of 2022, the institute had undertaken 2,269 funding projects and obtained an RMB of 2.723 billion in scientific research. The number of SCI papers published was 4,029, and the number of patent applications was 1,828, with 860 registered patents.

In the field of electrochemistry, advanced energy-storage materials and technology research teams[45] led by Wu are noteworthy. This research team has been engaged in research[46] on cathode materials and high-performance electrolytes for many years. Recently, it has achieved remarkable advances in the development and application of high-voltage electrolyte systems. Related research has been published in the Chemical Engineering Journal.



Source: Development of Scientific Research, Qingdao Institute of Bioenergy and Bioprocess Technology.

Figure 3-1-8 Electrode/electrolyte interface performance, DFT calculation, and full-cells cycling performance of high-pressure fluorine-based electrolyte systems

45 Qingdao Institute of Bioenergy and Bioprocess Technology, CAS: “Development of high-voltage electrolyte for constructing high-energy-density lithium battery systems,” http://www.qibebt.cas.cn/news/kyjz/202203/t20220324_6403048.html

46 ACS Appl. Mater. Interfaces 2020, 12, 49666; ACS Appl. Mater. Interfaces 2022, 14, 12264. The details of results of related research can be found at https://www.sciencedirect.com/science/article/pii/S1385894722014371

This team developed a new high-voltage fluorine-based electrolyte system (Figure 3-1-8), which increased the operating voltage of NCM811 cathode materials from 4.2V to 4.6V and expanded the upper limit and application range of ternary catalyst systems, thereby solving the following two important issues. First, the team succeeded in significantly improving the specific capacity and operating voltage of the high-nickel ternary cathode system and suppressing the structural phase transitions of the NCM8n cathode, transition metal ion leaching, and secondary particle generation under high-voltage conditions. Another point is the reduction in polarization by suppressing metal-ion dissolution and secondary particle cracking in the NCM8n anode under high-voltage conditions, which increases the energy density and catalyst cycle performance. In other words, owing to the successful construction of a stable cathode–electrolyte interface (CEI) and solid electrolyte interface (SEI), high-load ternary batteries with high nickel content were able to achieve stable cycling even under high-voltage conditions. In particular, the Li||NCM811 half-cells[47] maintained a high specific capacity of 247.2 mAh/g at an operating voltage of 4.6 V, a cycle capacity retention rate of 81.4% (0.5C 200 cycles), and a high-power capacity of 154.5 mAh/g (5C). In addition, Graphite ||NCM811 full-cells maintained a high specific capacity of 185.7 mAh/g even after 100 cycles at 4.6V.

China Tsinghua University

Tsinghua University is well-known not only in China but also internationally. In the World University Rankings 2021, Tsinghua University is ranked 20th worldwide, the highest among Asian universities. It is also known as the "cradle of engineers" because it has produced many industrial chemists. Three departments mainly conduct research related to electrochemistry: the Institute of Nuclear and New Energy Technology, the School of Materials Science and Engineering, and the Department of Chemical Engineering.

(1) Institute of Nuclear and New Energy Technology[48]

The Institute for Nuclear and New Energy Technology was established in 1960, and in 1964, it successfully conducted a shield test experiment on a power reactor using a shielding test reactor. This was the first nuclear reactor in China to be independently researched, designed, tested, and operated. In November 1989, the institute successfully operated the world's first "integrated natural circulation shell-type heat generator" using a 5 MW low-temperature nuclear heating reactor, which it had designed and constructed itself. This was the first reactor in the world to adopt a new type of hydrodynamic control rod.

Research in the field of new energy began in the 1990s, with a focus on nickel-metal hydride batteries, fuel cells, lithium-ion batteries, and their materials. Since 2005, this institute has been conducting

[47] Half-cells and full-cells are used in the research and development of lithium-ion batteries and post-lithium-ion batteries. Half-cell is a structure (batteries) that uses lithium for the positive and negative electrodes. Full-cell is a structure that uses conventional electrode materials for both the positive and negative electrodes. Please refer to https://www.syero-chem.com/entry/2022/07/06/214311

[48] https://www.inet.tsinghua.edu.cn/

research on biomass energy and biochemistry. The institute has demonstrated strong research capabilities in areas such as the chemical synthesis of materials, experimental assembly of lithium-ion batteries, assembly and system integration of fuel cell stacks, research on ethanol fuel production through biomass fermentation, and biokerosene refining.

The Division of New Energy & Material Chemistry[49] at the institute is renowned as a center for training high-level technical personnel in hydrogen energy and ion batteries, with fuel cells and ion batteries as the main areas of research. The survey was conducted by one academician, three researchers, four assistant researchers, two high-level engineers, two engineers, and more than 20 graduate students. This was the first laboratory in China to conduct hydrogen energy research under the 973 Program (National Program on Key Basic Research Project). In the preparation of cathode materials for lithium-ion batteries, this division has successfully developed a new process called the crystallization control-solid phase reaction. The development of high-density spherical cathode materials for lithium-ion batteries, which offer many advantages, won a silver medal at the 5th China International Invention Expo. In addition, numerous research achievements have been made regarding solid polymer fuel cells, direct methanol fuel cells, and low- and medium-temperature solid oxide fuel cells. This division has published more than 180 SCI papers and has filed more than 40 patent applications.

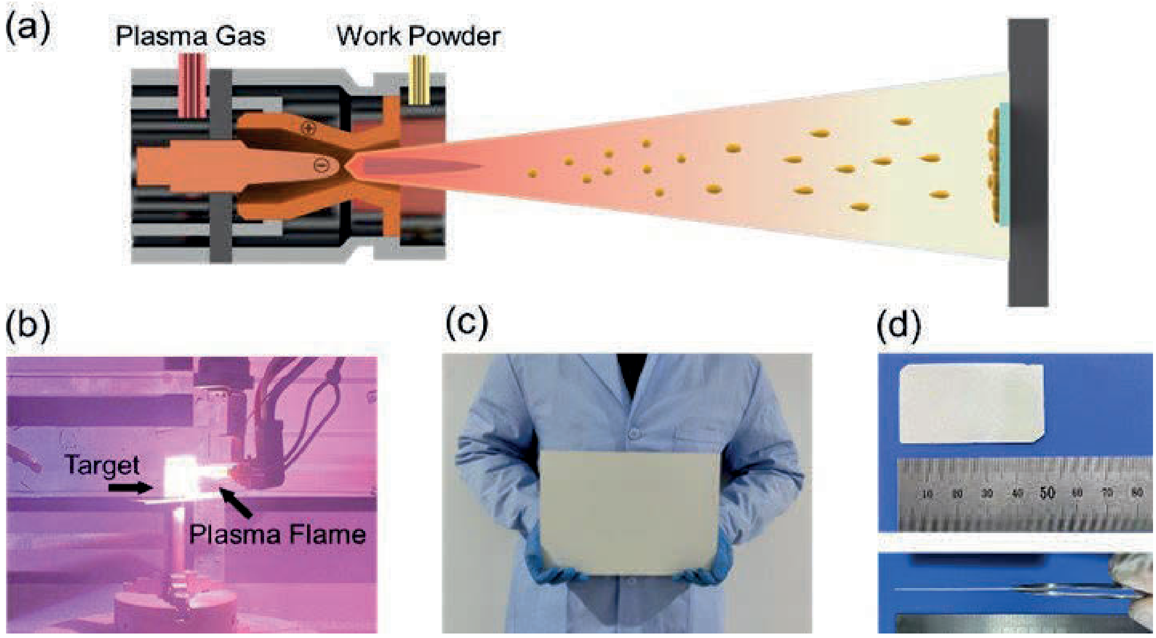
(2) School of Materials Science and Engineering[50]

The School of Materials Science and Engineering was newly established in 2012 by integrating the Department of Materials Science and Engineering and the Materials Processing Division within the Department of Mechanical Engineering. It consists of 100 faculty members (including 41 professors and 35 associate professors), 7 academicians, 10 award recipients of the National Distinguished Youth Science Fund, 8 award recipients of the Excellent Young Scientist Fund, approximately 300 undergraduate students, approximately 200 master’s students, and approximately 400 doctoral students. The school embodies China's policy emphasis on interdisciplinary fusion, ranking 10th globally in materials science in the 2022 QS World University Rankings.

Recently, a research team[51] led by Professor Hui Wu of the School has gained attention. The research team studied a method for producing thin films of the lithium-ion solid electrolyte $Li_7La_3Zr_2O_{12}$ (LLZO) using atmospheric plasma spraying (APS). It succeeded in producing LLZO thin films with controllable areas and thicknesses. The LLZO thin films obtained through post-processing, such as annealing, exhibited excellent electrochemical and mechanical properties. The APS preparation method is cost-effective and efficient, presenting new possibilities for the mass production of solid electrolyte membranes. With the development of the electric vehicle industry, the demand for lithium-ion batteries with higher energy density and safety is steadily increasing. However, many challenges remain in the further development and practical application of all-solid-state batteries (ASSBs). One of these is the lack of technologies

49 Division of New Energy & Material Chemistry https://www.inet.tsinghua.edu.cn/jgsz/yjs/xxnyjclhxyjs_202s_.htm
50 https://www.mse.tsinghua.edu.cn/xyjj/xyjj.htm
51 Major research achievements are known in https://zhuanlan.zhihu.com/p/636062829 and https://www.mse.tsinghua.edu.cn/info/1061/2862.htm

for cost-effective and large-scale manufacturing of high-quality solid-state electrolytes capable of mass-producing high-quality solid electrolyte membranes with polymer separators of approximately the same thickness as the polymer separators in conventional lithium-ion batteries. Therefore, the research team introduced APS into the solid electrolyte preparation and transported LLZO particles through argon gas to the spray gun of an atmospheric-pressure plasma sprayer, thereby forming droplets in which the LLZO powders melted and moved under high plasma temperatures and collided with the substrate, successfully forming a uniform LLZO film. This series of processes is illustrated in Figure 3-1-9.



Source: Tsinghua University's News

Figure 3-1-9 Plasma spraying equipment and LLZO films obtained by plasma spraying

Related research was published in "Advanced Energy Materials" under the title "Rapid Processing of Uniform, Thin, Robust, and Large-Area Garnet Solid Electrolyte by Atmospheric Plasma Spraying." [52]

(3) School of Civil Engineering[53]

Established in 1946, the School of Civil Engineering includes chemical engineering, technology, materials science, and engineering, all of which are renowned as top-tier disciplines in China. The School of Civil Engineering ranked 13th in the 2022 QS World University Rankings, while its chemical engineering and technology department and the materials science and engineering department ranked 1st and 3rd, respectively, in the U.S. News & World Report rankings and 1st in the Academic Ranking of World Universities (ARWU), demonstrating their high level of research capabilities. Its main research fields include energy chemical engineering, microchemical processes, material chemical engineering, industrial biocatalysis, and environmental chemistry. The graduates included several politicians, including Xi Jinping,

[52] Links to related papers : https://onlinelibrary.wiley.com/doi/10.1002/aenm.202300809
[53] https://www.chemeng.tsinghua.edu.cn/bxgk/hxgcxjj.htm

29 academicians, and 15 university presidents, all of whom were outstanding individuals. Currently, there are 73 faculty members and 4 academicians, including 25 researchers selected as Highly Cited Researchers (HCR) by Elsevier and Clarivate. Over the last five years, the school has published over 1,130 SCI papers and won 13 awards, including the State Scientific and Technological Progress Awards. The amount of funds for projects is also increasing annually, currently standing at RMB 2.5 million per person.

The School of Civil Engineering has research teams led by Wang Xiaolin, Wang Baoguo, Yu Lixin, Wang Haihui, and Liu Kai. Here, the Liu Kai research team[54] is currently conducting research on lithium-ion battery separators and materials for all-solid-state batteries. The research team is mainly engaged in research on polymer energy storage materials and safety materials for lithium-ion batteries. In particular, by combining crown ethers and lithium anions in traditional supramolecular chemistry, the team succeeded in designing and synthesizing asymmetric-like lithium salts (LiFEA) that exhibit crown-ether-like folded molecular structures with physicochemical properties such as a high dipole moment, high donor number (DN), solubilization of specific organic/inorganic compounds, and high Li+ mobility (tLi+). Commercially available carbonate electrolytes based on LiFEA exhibit excellent fast charging and discharging performances, along with a new SEI self-cleaning mechanism. This mechanism can improve the incompatibility between commercially available carbonate electrolytes and lithium anodes under high current density conditions. After 100 rapid cycles (charging: 1.46 mA/cm2, discharging: 3.66 mA/cm2), the soft pack battery demonstrated excellent performance with a capacity retention rate of 81%. This research was published in "Nature Energy" under the title "Designing an asymmetric ether-like lithium salt to enable fast-cycling high-energy lithium metal batteries."[55]

Harbin Institute of Technology

Founded in 1920, the Harbin Institute of Technology is a prestigious university in the fields of science and engineering. In accordance with the "one school, three districts" management policy, in addition to Harbin, there are also branch schools in Weihai, Shandong Province, and Shenzhen, Guangdong Province. In China, branch campuses are generally considered inferior to main campuses in terms of reputation and educational quality. However, the Harbin Institute of Technology is known for its high level of education and research capabilities on all three campuses.

Several research teams at the Harbin Institute of Technology, which are renowned for their development of electrochemical devices, are introduced below.

(1) School of Chemistry and Chemical Engineering[56], Harbin Institute of Technology

The School of Chemistry and Chemical Engineering was established in the 1930s and has a long history among the branches of the Harbin Institute of Technology. The department was upgraded to a graduate school in 2008. There were 160 faculty members (74 professors, 61 associate professors, and two academicians), 17 of whom were awardees of the National High-Level Talent Special Support Program

[54] https://mec.tsinghua.edu.cn/rd/lkktz1.htm
[55] https://www.nature.com/articles/s41560-023-01282-z
[56] https://chemeng.hit.edu.cn/

and 11 of whom were awardees of the National Distinguished Youth Science Fund. Thanks to the large number of outstanding faculty members in the school, 19 national science and technology funding projects and more than 90 provincial funding projects have been secured, and over 3,000 SCI papers have been published. Many companies have been established through the commercialization of scientific and technological achievements over the past five years, and their revenue has exceeded RMB 1.5 billion.

Xiaohong Wu's research team[57] has attracted attention for the development of high-capacity, low-cost, and long-life aqueous flow batteries. Liquid flow batteries play an important role in the storage and utilization of renewable energy sources such as solar and wind energy as large-scale energy storage technologies. Ferricyanide/ferrocyanide has a stable structure and is eco-friendly and inexpensive, making it an ideal redox-active material for liquid-flow batteries. However, their low solubility is a limiting factor for improving the energy density of liquid-flow batteries and has been a bottleneck in mass production. To solve the above problems, the research team improved on the existing research by applying a molecular design method based on intramolecular–intermolecular interactions. It succeeded in obtaining a highly soluble (solubility at room temperature of 2.32 mol/l), fast-acting, and stable active material of lithium ferrocyanide (Li4[Fe (CN)6]). This aqueous Zn/Fe flow battery has the characteristics of high capacity, low cost, and long life. The average capacity retention rate of half cells in neutral and alkaline conditions is nearly 100%, and the storage capacities of full cells are 61.64 AH/L and 56.28 AH/L, respectively, with a low overall chemical cost of US$11 per kWh.

Wang et al.[58] published a paper titled "Tailoring electronic-ionic local environment for solid-state Li-O2 battery by engineering crystal structure" in the journal "Science Advances." This paper provides insights into the design of new cathode structures and high-performance solid-air batteries and is regarded as having contributed to the development of solid-state batteries. Solid-state Li-O2 batteries (SSLOBs) are rechargeable batteries that offer high theoretical energy densities and low manufacturing costs, making them promising electrochemical energy storage devices. High-performance solid polymer fuel cells require not only excellent oxygen evolution and oxygen reduction performance but also excellent ion and electron transport and balance performance. However, it is extremely difficult to design solid-state cathodes (SSC) that satisfy all these requirements. The research team first conceived the idea of constructing a specially structured SSC target by tailoring the local electronic-ionic transport by adjusting the crystal phase structure. Amorphous ruthenium (A-Li-RuO) composite materials with a disordered long-range structure were prepared by low-temperature heat treatment, and it was discovered that this material could significantly improve electronic-ionic conduction dynamics. It was concluded that multidimensional diffusion in the amorphous structure contributed to electronic-ionic conduction transport.

(2) College of New Energy[59], Weihai, Harbin Institute of Technology

College of New Energy was established at the Weihai Campus in 2018 with the aim of developing integrated human resources in the field of new energy, in accordance with the Ministry of Education'

[57] http://homepage.hit.edu.cn/wuxiaohong?eqid=a71dfcce000661dc0000000364866dac
[58] https://m.163.com/dy/article/HN4INP0H0511BNSN.html
[59] https://newenergy.hitwh.edu.cn/xyjj/list.htm

s policy of developing "new engineering." In the two years since its establishment, the Department of Science and Process has been recognized as a first-class department in Shandong Province. It is well known for the high quality of its faculty and the high employment rate of its graduates. 25% of faculty members were professors, and the employment rate of students during their time exceeded 90%.

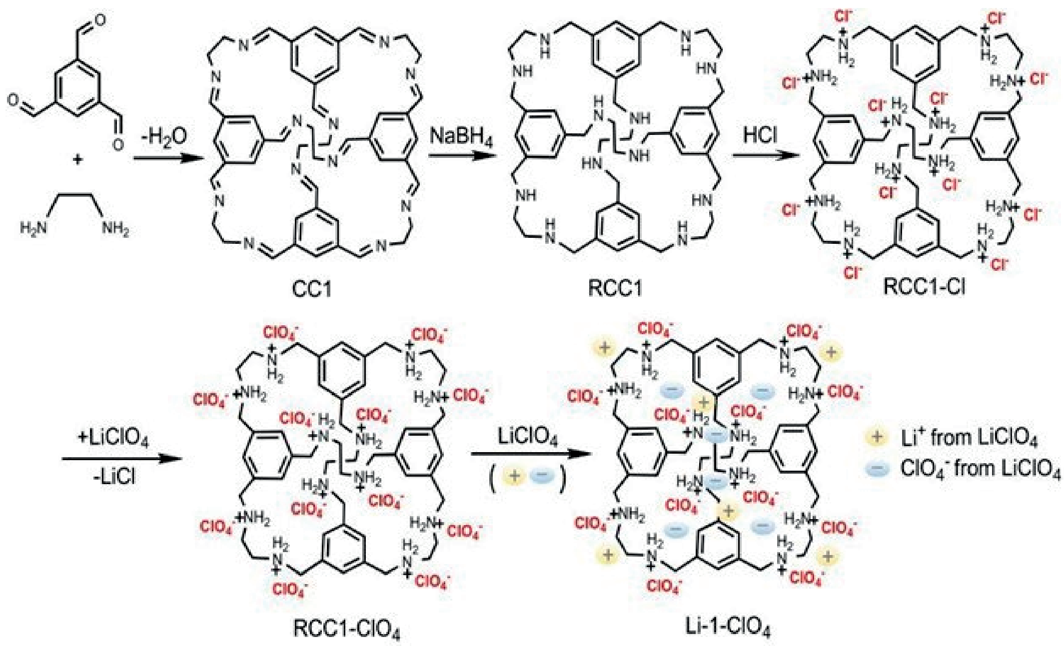
Su's research team[60] has succeeded in improving the low-temperature performance of lithium-ion batteries by changing their electrolyte composition. The technology developed by the research team not only succeeded in extending the life of lithium-ion batteries by 20%, but also limited the decrease in battery capacity to less than 20% even at -43° C. Lithium-ion batteries are characterized by their long life, high specific capacity, and lack of memory effect. They are widely used in home appliances, new energy vehicles, power tools, energy storage devices, and other fields. However, when used at low temperatures, problems such as capacity degradation, shortened cycle life, and difficulty in charging become apparent, so the operating temperature was limited to -20° C to -55° C. Xin et al. solved this problem by changing the electrolyte components. Details of related results are published in the journal "Advanced Energy Materials" under the title "Recent Advances in Conduction Mechanisms, Synthesis Methods, and Improvement Strategies for $Li_{1+x}Al\ xTi_{2-x}(PO_4)_3$ Solid Electrolyte for All-Solid-State Lithium Batteries."

(3) School of Materials Science and Engineering, Shenzhen, Harbin Institute of Technology

Established in 2002, the School of Materials Science and Engineering is a small but elite faculty with 42 members who have trained 72 PhDs and 649 master's degree holders. The main research areas are electronic packaging materials and device processing, quantum materials and quantum devices, biointelligent materials, special materials and additive manufacturing, materials genetic engineering and its applications, micro/nano-optoelectronic devices, and new energy materials and devices.

Qiu et al.[61] developed a new porous-organic-cage-based Li+ conductor. They used it as the cathode electrolyte in a solid-state battery, thereby developing a room-temperature all-solid-state battery with excellent cycle performance (Figure 3-1-10). The related results have been published in the Journal "Nature Communications" under the title "Room Temperature All-Solid-State Lithium Batteries Based on a Soluble Organic Cage Ionic Conductor." Solid lithium secondary batteries are expected to be the next-generation energy storage battery systems because they have a higher energy density and are safer than current liquid-based Li-ion batteries. However, ensuring lithium-ion conduction in the anodes of solid lithium secondary batteries is key to the development of solid lithium secondary batteries. Therefore, the research team proposed Li-RCC1-ClO_4, a porous soluble organic cage-based ionic Li-ion conductor, which was used for the first time. Anionic and cationic functional groups can provide an environment with highly effective dielectric screening, enabling the dissociation of lithium ions from lithium salts (e.g., $LiClO_4$) into mobile ions, as shown in the figure below.

[60] http://zsb.hitwh.edu.cn/home/article/details?id=1514
[61] http://kjc.hitsz.edu.cn/info/1008/2750.htm



Source: Science and Technology News, Shenzhen, Harbin Institute of Technology

Figure 3-1-10 New porous soluble organic cage-based ionic lithium-ion conductor

Leading Companies (Rechargeable battery)

Among rechargeable batteries, Chinese companies dominate the global lithium supply chain from upstream to downstream, especially lithium-ion batteries. In 2021, Chinese companies were reported to have accounted for approximately 80% of global lithium battery cell manufacturing[62]. Companies with a high market share or significant growth in the drive battery market are listed in Table 3-1-16.

[62] https://www.energy-storage.news/china-continues- to-dominate-lithium-battery-supply-chains-but-policy-support-gives-us-new-hope/

Table 3-1-16 Companies with a high market share in storage batteries

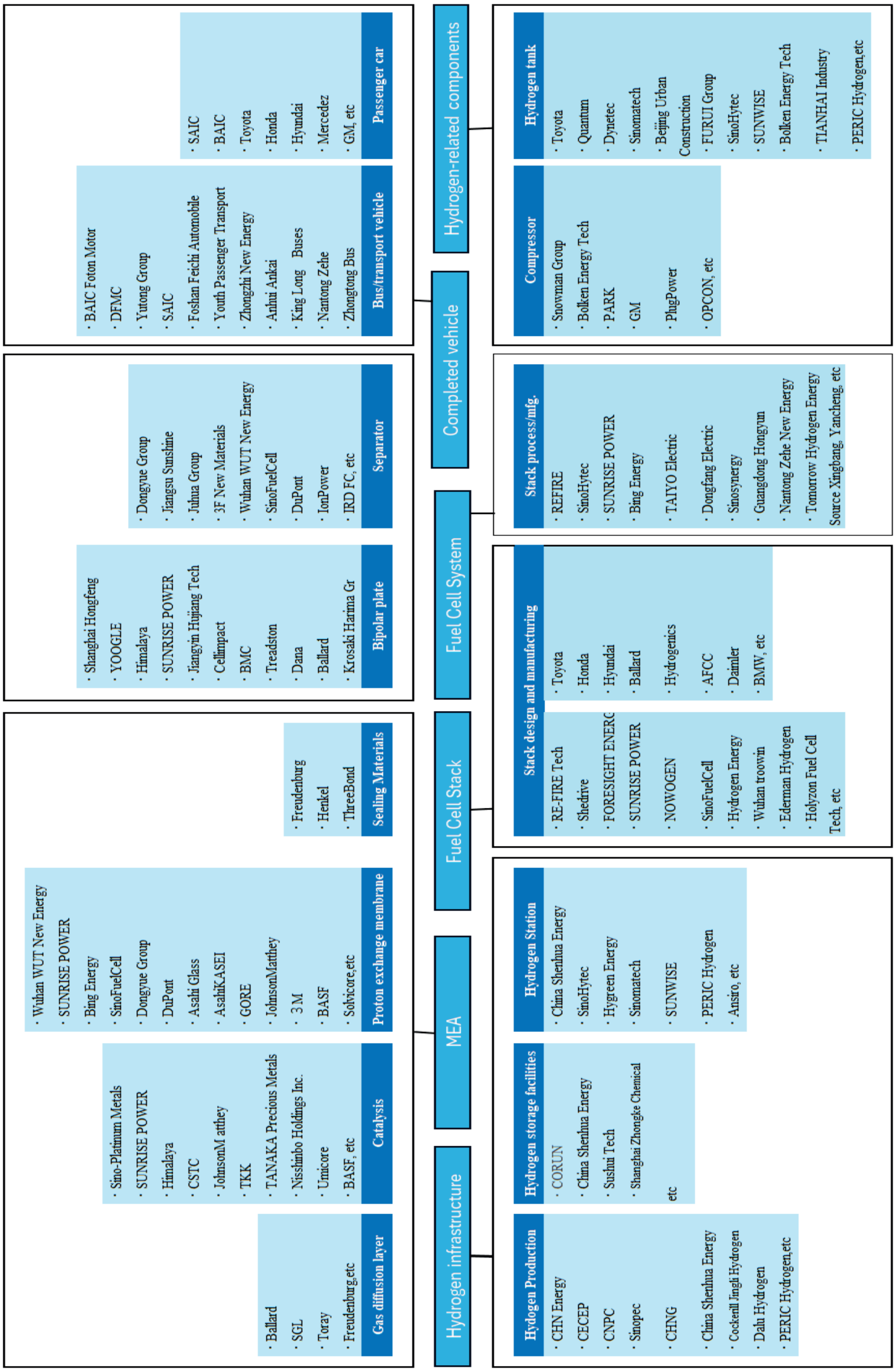
Company name	Major business	Key points
CATL (Contemporary Amperex Technology)	A privately owned mega battery manufacturer in China. Its main products are automotive batteries. The company operates in three divisions: drive battery business, battery materials business, and storage system business, which handle cells, modules, and battery management systems. It generates profits from the sale of power batteries, storage batteries, and battery materials. It is also actively involved in the raw materials for lithium batteries and the construction of storage systems.	In 2022, the installed capacity will be 142.02 GWh, accounting for 48.2% of the domestic market share for automotive drive batteries and 37% of the global market share, up 4 points from the previous year. It has boasted the top share in both the Chinese domestic and global markets for six consecutive years. The production capacity of the production base currently being planned independently will reach 600 GWh, and with joint production with FAW Group, Geely, GAC Group, and Dongfeng also within scope, it is expected to exceed 700 GWh by 2025.
BYD (Build Your Dreams)	The company is engaged in the secondary battery, mobile phone parts and assembly, and automobile businesses, and is a major manufacturer ranked third in the world in the manufacture of lithium-ion batteries (for EVs) and first in the world for mobile phones. Unlike other manufacturers whose main business is supplying products to other companies, the company adopts a policy of independent research and development design. Its major feature is to consistently develop and manufacture everything from EV batteries to EV bodies in-house, and also to promote its own brand. Passenger EVs are launched in the Japanese market on January 31, 2023.	The company has production bases in multiple regions of the country and has established and operates a factory in a joint venture with Chang'an Automobile. Currently, in addition to its own brand, it supplies FAW Group, Jin Kang, and Dongfeng. In 2022, it ranked second in the domestic market with an installed capacity of 69.1 GWh and a market share of 16.2%. BYD ranks third in the world with a 13.6% share of the global market for automotive drive batteries. An industrial park has been set up in Xiangyang, Hubei Province, and the company is also working on production projects for NEVs and parts.
CALB（China Aviation Lithium Battery）	Supplier of lithium-ion batteries, battery management systems, storage batteries, and related integrated products, and lithium battery materials.	The company has seven production bases in China, three of which are capable of mass production. Production capacity is approximately 16 GWh. Delivering to GAC Group and Chang'an Automobile. Ranked third in China's 2022 domestic ranking of drive battery assembly volume, accounting for 6.4%. By 2025, the company's production capacity is expected to exceed 500 GWh, with a target of 1 TWh per year by 2030.
Gotion (Guoxuan Hi-Tech)	A Chinese supplier that independently develops, manufactures, and sells lithium-ion batteries for new energy vehicles. Its main businesses are lithium batteries and power transmission and distribution equipment.	The company's lithium-ion battery business generated sales of RMB 18,481.74 million in the fiscal year ending December 2022, accounting for 80.18% of total sales. In 2022, the company's battery production volume was approximately 13.33 GWh, with a 4.52% share of the Chinese domestic market, a 66.2% increase from the previous year. Of these, the production volume of ternary power batteries was 1.43 GWh, with a market share of 1.30%. In comparison, the production volume of lithium iron phosphate power batteries was 11.89 GWh, with a market share of 6.47%.
EVE Energy (億緯鋰能)	A Chinese supplier engaged in the development, production, and sale of consumer batteries (lithium batteries, small lithium-ion batteries) and drive batteries (new energy vehicle batteries and battery systems, energy storage batteries).	The drive battery uses ternary materials or lithium iron phosphate as the cathode material. It is mainly used in the new energy vehicle field for passenger cars, commercial vehicles, machine tools, electric ships, and other applications. In 2022, it ranked sixth in terms of cumulative drive battery assembly in China, up two ranks from the previous year. In addition, the supply volume was 7.18 GWh, and the market share in China was 2.4%.

Source: Compiled by APRC based on various materials[63]

[63] LEADLEO" 2022 China Energy Storage System Battery Industry Overview" : KOTRA "Secondary Battery Global Market Trends Report" ; GOUSEN SECURITIES "Global Electrochemical Storage Market Outlook and Technological Innovation" , Marklines Website https://www.marklines.com/, SNE Research Website https://www.sneresearch.com/kr/insight/release_view/143/

Highlighted Companies (Hydrogen and Fuel Cells)

According to the "Trends in Research and Development Projects, Local Governments, and Companies in China's Hydrogen and Fuel Cell Industry" published by NEDO in 2020, a large number of companies are engaged in hydrogen and fuel cells in China, and Figure 3-1-11 summarizes them by industry chain and type.



Source: "Trends in Research and Development Projects, Local Governments, and Companies in China's Hydrogen and Fuel Cell Industry," published by NEDO in 2020

Figure 3-1-11 Hydrogen and fuel cell companies in China by industrial chain and type

As shown in Figure 3-1-11, there are many notable companies in the hydrogen and fuel cell fields, ranging from infrastructure to components; however, it is not possible to cover all of them here. Therefore, the following section highlights some representative companies among system manufacturers that research, develop, and manufacture fuel cell systems and some manufacturers of bipolar plates, catalysts, and proton exchange membranes, which are core materials for fuel cell membrane electrode assemblies (MEA).

(1) Bipolar plate manufacturer: Shanghai Hongfeng Industrial Co., Ltd[64]

Founded in 2007, Shanghai Hongfeng is the leading BP manufacturer of bipolar plates. Since its establishment, the company has focused on the development of graphite bipolar plates for fuel cells and has played an active role as a supplier of graphite bipolar plates for hydrogen fuel cell demonstration vehicles at the 2008 Olympics and 2010 Expo. The company has obtained one invention patent and nine utility model patents and has already realized mass production of graphite bipolar plates for hydrogen fuel cells, with an annual production volume reaching 2 million sets. In addition, through independent research, ultrathin graphite bipolar plates for hydrogen fuel cells with a thickness of less than 1.4 mm have been successfully developed and mass-produced. Bipolar plates are not only used domestically but also exported to the United States, Canada, Italy, South Korea, and other countries.

Currently, the company is conducting joint research with leading fuel cell companies such as Dongfang Electric, Shenzhen Yoda, SinoHytec, Reforming, and Gaocheng Green Energy. In 2021, the company shipped two million graphite bipolar plates, ranking first in terms of shipment volume and recording sales of 120 million yuan. In July 2022, it invested RMB 220 million in a "Hydrogen Fuel Cell Graphite Bipolar Plate Industrialization Project." The new artificial graphite bipolar plates to be manufactured as a result of this investment are expected to reach approximately eight million sets per year, which is equivalent to the amount used in 40,000 hydrogen forklifts and 5,000 hydrogen fuel-cell vehicles that are being rapidly commercialized.

(2) Catalyst manufacturer: Hymalaya[65]

Foreign companies, such as Johnson Matthey (UK), Umicore (Belgium), and TANAKA Precious Metals (Japan), are market leaders in catalysts, another key material in hydrogen and fuel cells. Among Chinese manufacturers, Himalaya is a notable exception.

Founded in Wuhan in 2008, the Himalayas relocated its headquarters to the Xianning National High-Tech Industrial Park in 2013 and signed a contract with Tsinghua University in 2015 regarding the transfer of research results. With this contract, the two parties jointly established the "Tsinghua Himalaya Hydrogen Fuel Cell Industrialization Base." After several years of research, they developed a long-lasting and stable

[64] For details, please refer to Website of Shanghai Hongfeng Industrial Co., Ltd https://www.shf.net.cn/index.php?c=content&a=list&catid=318 and "Fuel Cell Bipolar Plate Market", https://36kr.com/p/1987005298320393, "In-depth Analysis of the Fuel Cell Bipolar Plate Market" https://www.htech360.com/a/1037

[65] For details, Hymalaya Website, http://www.whxmly.com/, "Himalaya signs an agreement for hydrogen fuel cell and engine system production line project", https://baijiahao.baidu.com/s?id=1762839423556398170&wfr=spider&for=pc

nano-supported catalyst for fuel cells and succeeded in producing a continuous pipeline microwave with homogeneity. This catalyst is used in PEM electrolysis cells, membrane electrodes, and other devices. It is superior in quality to imported products, yet significantly cheaper, making it popular owing to its excellent cost performance. The Himalayas continue to expand their research and development of hydrogen energy applications. It already holds more than 100 independent intellectual property rights in the fuel-cell field, more than 50% of which are invention patents. In addition to the catalysts, the company has developed and manufactured core components for the entire hydrogen fuel cell system, including membrane electrodes, bipolar plates, electrical stacks, hydrogen fuel cells, and starting systems. In 2022, the company will successfully develop a third-generation fuel cell electric stack module, enabling it to offer products with a wide output range from 100 W to 130 kW and contributing significantly to the domestic production of key materials for hydrogen fuel cells.

(3) Proton exchange membrane manufacturer: Dongyue Group[66]

Proton exchange membranes are essential materials in the hydrogen and fuel cell industries, and Dongyue Group is arguably the most influential Chinese company in this field. Similar to catalyst manufacturers, Chinese domestic manufacturers are making great strides, with companies from the U.S., Japan, and Belgium leading the way.

The Dongyue Group was founded in 1987 and is headquartered in Jinan, Shandong Province. However, it was listed on the Hong Kong Stock Exchange in 2007. Through 25 years of dedicated efforts, the Dongyue Group has grown into Asia's largest production base for fluorosilicon materials, a leading enterprise in China's fluorosilicon industry, and the first industrial park (base) for fluorosilicon. Currently, the company is doing business with famous domestic and international companies, such as Daikin, Mitsubishi, Haier, Hisense, Greer, and Midea.

The Dongyue Group has many famous trademarks and brands in China for the manufacture of industrial materials, such as fluorosilicon materials; it has won numerous awards, including the National May 1st Labor Award, and has a proven track record of working on numerous national science and technology funding projects. In the 2000s, the company actively engaged in research on proton exchange membranes. In 2004, the Dongyue Group succeeded in developing a proton exchange membrane with a performance equivalent to that of commercially available membranes through joint research with Shanghai Jiao Tong University. After further research, by 2016, the lifespan of the proton exchange membrane increased from 800 hours to 6,000 hours, and the DF260 membrane, which maintains this lifespan at a commercial level, reached the mass production level. The Dongyue Group was able to reduce the thickness of the DF260 membrane to 10 μm, and through 6,000 hours of testing with AFCC in Canada, achieved durability of over 600 hours under open circuit voltage (OCV). The DF260 membrane also demonstrated excellent functionality and successfully completed more than 20,000 cycles under both wet and dry conditions. The

[66] For details, please refer to Top 15 Proton Exchange Membrane Suppliers
https://baijiahao.baidu.com/s?id=1768136005358015093&wfr=spider&for=pc;
For exchange membrane, https://zhuanlan.zhihu.com/p/526627378; For Proton Exchange Membrane Industry Report
https://baijiahao.baidu.com/s?id=1763594419564906257&wfr=spider&for=pc

Dongyue Group is currently working on a project to commercialize 1.5 million square meters of fuel cell membranes and auxiliary chemicals. It is also constructing a perfluorosulfonic acid resin ion membrane production plant with an annual production capacity of 50 tons.

(4) System Makers

Several major system manufacturers are introduced in Table 3-1-17.

Table 3-1-17 Major Fuel Cell system manufacturers

Company name	Major business	Key points
SinoHytec	A manufacturer that sells fuel cell systems. It is the first company in China to research and develop hydrogen and fuel cell drive systems. It is known as the "leading hydrogen energy brand."	In 2016, the company achieved mass production of fuel cell systems. Currently, the commercial operation of hydrogen fuel cell vehicles has been realized in multiple regions of China. In 2021, it became the industry leader with a 27.8% share of the Chinese market for automotive fuel cell systems. In 2021, it established Huafeng Fuel Cell Co., Ltd., a joint venture with Toyota and one of the suppliers of fuel cell vehicles for the 2022 Winter Olympics and Paralympics. As of December 2022, there are 1,083 hydrogen fuel cell vehicles equipped with SinoHytec engines.
SINOSYNERGY	A high-tech company focused on the research, development, production, and sale of hydrogen fuel cell stacks and hydrogen fuel cell systems.	In 2021, the Chinese hydrogen fuel cell market was approximately 522.3 MW, and SINOSYNERGY shipped 126 MW, accounting for 24.1% of the market share and ranking first in the industry. In 2022, NATURE magazine featured the company as a notable player in the hydrogen fuel cell industry in its article "A GREEN FUTURE OF HYDROGEN FUEL CELLS IN CHINA," generating significant buzz.
REFIRE	Engaged in research and development of fuel cell systems, stacks, MEA technology, and products.	By the end of 2022, 3,500 fuel cell vehicles will be deployed, with a total mileage of over 140 million km. Calculated using hydrogen produced from renewable energy, this will result in a reduction of 76,000 tons of carbon emissions. In 2022, the installed capacity of fuel cell systems was 89,575 kW. In December 2022, the company announced the PRISMA XXII fuel cell system with a rated output of 220 kW, which is being applied to heavy-duty vehicles.
TAIYO Electric	A major Chinese manufacturer that produces motors for construction and home appliances, starters and generators for automobiles, and electric drive systems for new energy vehicles.	On February 17, 2017, the company signed a framework agreement with Canadian hydrogen fuel cell technology supplier Ballard Power Systems, Inc. for a fuel cell module technology license agreement. The company announced the annual production capacity to be expanded over three years starting in 2019: 50,000 sets of electric drive systems for commercial vehicles (motors, controllers, reduction gears, or transmissions); 100,000 sets of electric drive systems for passenger cars (motors, controllers, reduction gears, or transmissions); 100,000 sets of drive systems for new energy vehicles (VCU: Vehicle Control Unit), high-voltage distribution systems, DCDC converters, etc.; and hydrogen fuel cells: 8,000 sets.

Source: Compiled by APRC based on various materials[67]

[67] NEDO "Trends in Hydrogen in China" : Each company's website: MarkLines website https://www.marklines.com/

3.1.6 Large-scale Research Infrastructure

There are more than 70 large-scale research infrastructures in China, including those operated by the central and provincial governments, which is an extremely large number. Below are some examples of representative research infrastructure.

In terms of measurement and evaluation infrastructure, China's pioneering first-generation synchrotron radiation facility, "Beijing Electron-Positron Collider (BEPC)"[68], is in operation in Beijing, and the third-generation synchrotron radiation facility, "Shanghai Synchrotron Radiation Facility (SSRF)"[69], is in operation in Shanghai. In addition, the "Beijing Electron Photon Source (HEPS)"[70], a fourth-generation synchrotron radiation facility, began operation in 2024, and construction has begun on another fourth-generation synchrotron radiation facility, "Hefei Advanced Light Source (HALF)."[71]

The following information about the computing infrastructure has been obtained from publicly available sources.

(1) Institute of Computing Technology, Chinese Academy of Sciences[72]

Established in 1956, this institute specializes in computational technology. It publishes outstanding research results every year, including "research on software systems that support the infrastructure of supercomputers" and "new models of deep learning processing system structures." The two achievements illustrated here are highly regarded domestically, winning the State Scientific and Technological Progress Award and the State Natural Science Award.

(2) National Supercomputing Center in Jinan[73]

Established in 2011, with the approval of the Ministry of Science and Technology, it is based in Jinan City, Shandong Province. Although it has a short history, it is famous as the research institute where Sunway Blue Light was born. It uses a proprietary Sunway CPU architecture and is the first example in China to exceed one petaflop (PF) with a system based on a unique architecture.

(3) National Supercomputing Center in Guangzhou[74]

The research institute was located at Zhongshan University. When it unveiled the Tianhe-2 in 2013, it ranked among the TOP500 list of the world's fastest supercomputers and received high praise. Launched on December 6, 2023, the next-generation domestic supercomputing system "Tianhe Xingyi," compared to "Tianhe-2," has doubled its capacities in many areas like computing power, networking capabilities,

68 https://spc.jst.go.jp/news/170104/topic_1_06.htm
69 https://spc.jst.go.jp/news/110603/topic_4_04.htm
70 https://spc.jst.go.jp/news/240401/topic_4_02.html
71 https://spc.jst.go.jp/news/230904/topic_3_02.html
72 Please refer to the website of the institute（http://www.ict.ac.cn/ky/kygk/ ）。Award-winning researches can be found at http://www.ict.ac.cn/ky/kjjl/gjj/.
73 https://www.nsccjn.cn/
74 http://www.nscc-gz.cn/

storage capacity, and application service capabilities, and is said to boast the highest specifications in China at present.

(4) National Supercomputer Tianjin Center[75]

It is China's first national supercomputer research center, which was approved in 2009 for its establishment by the Ministry of Science and Technology. "Tianhe-1," released in August 2010, ranked first in the 36th Supercomputer TOP500 in November 2010, attracting global attention. "Tianhe-1" has already been used by 1,600 companies and government agencies in fields such as oil and natural gas research, high-end manufacturing, pharmaceutical research, air pollution analysis, and weather information. Then, in 2018, it was reported that the "Tianhe-3 prototype E class supercomputer," which is more than 10 times more powerful than "Tianhe-2," had been developed and installed at the National Supercomputing Tianjin Center. If put into practical use, "Tianhe-3" is expected to become the world's fastest supercomputer.

3.2 South Korea

Lithium-ion batteries (LIBs) were first mass-produced by Sony in Japan in 1991 and have since been adopted in devices such as notebook computers and mobile phones. Following the rapid spread of LIBs, demand surged in South Korea and worldwide. However, at that time, notebook computers and mobile phone manufacturers, such as SAMSUNG and LG, relied entirely on imports for LIBs, making domestic production an urgent issue. In South Korea, small and medium-sized enterprises (SMEs) managed the battery manufacturing sector, and large corporations were not permitted to enter the market. However, expanding demand for secondary batteries led to the relaxation of these regulations.

Against this backdrop, major South Korean conglomerates, such as SAMSUNG, LG, and SK, anticipated rapid growth as they entered the secondary battery market and began research and development (R&D) aimed at mass production in the 2000s. In 2000, SAMSUNG SDI (formerly SAMSUNG Electro-Mechanics) established a mass-production line for secondary batteries and officially began large-scale production.

The South Korean government was also seeking a new growth engine to follow its traditional mainstays of semiconductors and displays and began focusing on secondary batteries. Thus, it formulated various policies (detailed below) and significantly increased investments to promote R&D in the electrochemistry field.

South Korea has demonstrated remarkable growth in even basic research. According to the number of papers indexed in the Web of Science (WoS) database, South Korea ranks among the top five countries globally in all three major device categories: batteries, fuel cells, and water electrolysis. In particular, the number of South Korean publications related to batteries has surged since 2010, placing the country third in the world in 2022, following China and the U.S. Furthermore, South Korea ranks fourth globally in the field of fuel cells, behind China (first), the U.S. (second), and Japan (third). South Korea ranks fifth in water electrolysis, followed by China, the U.S., Japan, and Germany. As discussed later, the country has recently

[75] https://www.nscc-tj.cn/

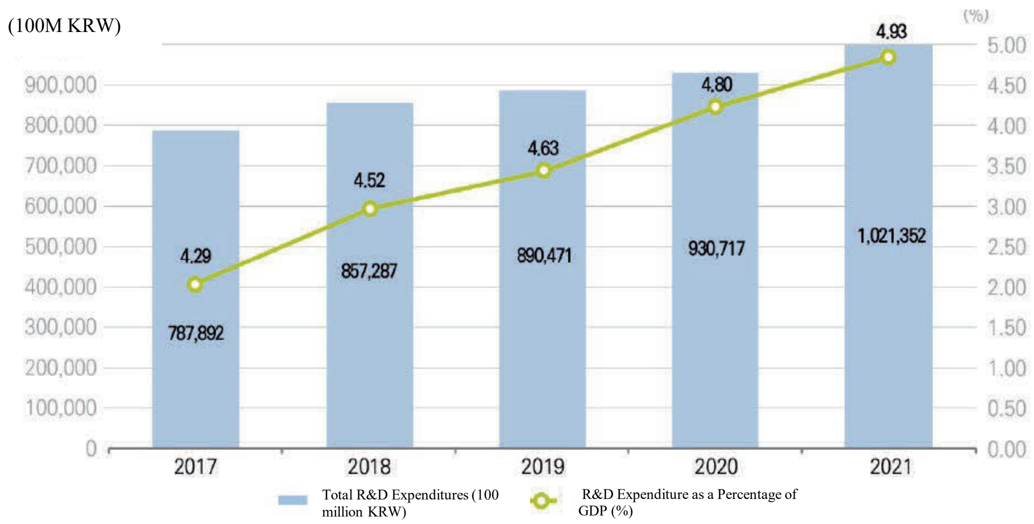
promoted several research programs focusing on next-generation secondary batteries for automotive applications.

Thus, South Korea has achieved rapid advancement in R&D in both academia and industry. In the early 2000s, Japan dominated the secondary battery market. However, South Korea has since enhanced its global competitiveness, along with Western countries and Japan.

3.2.1 Research Funding

(1) National R&D Expenditures

South Korea's R&D expenditures continue to increase annually. R&D spending surpassed the 100 trillion won mark for the first time in 2021, increasing from 78.7892 trillion won in 2017 (approximately 9.01 trillion yen, based on an exchange rate of 1 won = 0.11 yen, same hereafter) to 102.1352 trillion won (approximately 11.68 trillion yen) (Figure 3-2-1). In the same year, the ratio of R&D spending to gross domestic product (GDP) was 4.93%, ranking second worldwide.



Source: Korean National Statistics Portal.

Figure 3-2-1 Trends in R&D Expenditures in South Korea

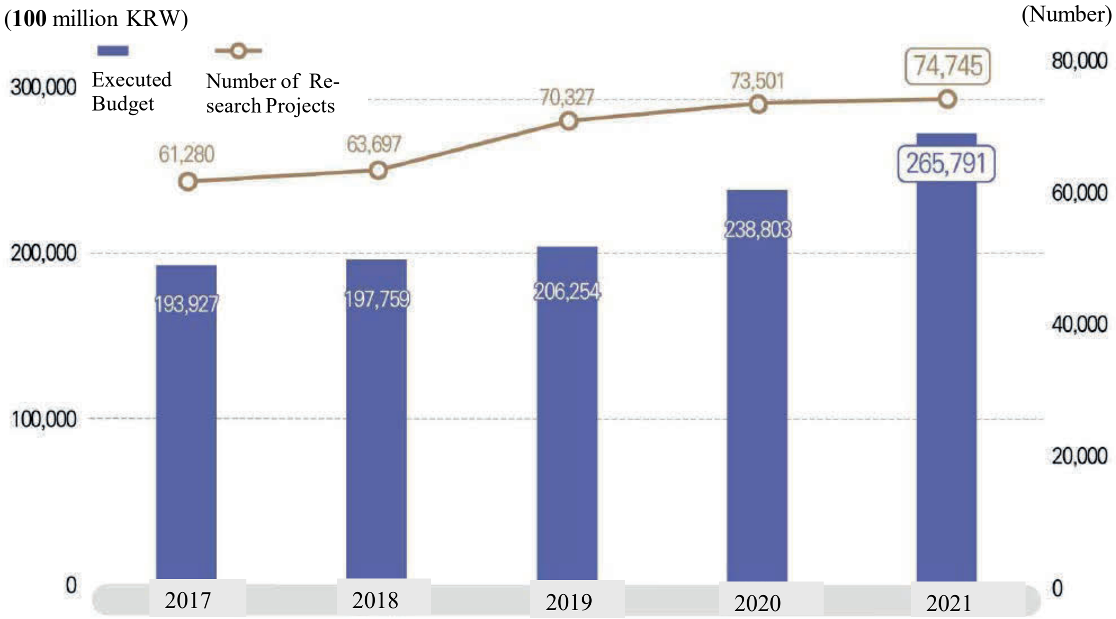
In 2021, based on funding sources, the government and public sector contributed 24.095 trillion won (23.6%, approximately 2.8509 trillion yen) to R&D spending, while the private and foreign sectors contributed 78.0403 trillion won (76.4%, approximately 8.9326 trillion yen), indicating a high proportion from private and foreign sources. Based on research entity, public research institutions accounted for 11.997 trillion won (11.7%, approximately 1.3733 trillion yen), universities for 9.3306 trillion won (9.1%, approximately 1.068 trillion yen), and companies for 80.8076 trillion won (79.1%, approximately 9.2475 trillion yen). Based on research stage, expenditures on basic R&D amounted to 15.1002 trillion won (14.8%, approximately 1.7282 trillion yen) and those on applied R&D to 21.4704 trillion won (21.0%, approximately 2.4572 trillion yen), while the highest proportion was allocated to development research at 65.5647 trillion won (64.2%, approximately 7.5037 trillion yen).

(2) Research Stage

Table 3-2-1 Breakdown of R&D Expenditures in South Korea by Research Stage

Research Stage	Research Entity	2018	2019	2020	2021
Total		**85,728,715**	**89,047,077**	**93,071,686**	**102,135,244**
Basic Research	Public Research Institutions	2,353,558	2,516,382	2,577,697	2,683,404
	University	2,533,534	2,937,469	3,132,145	3,639,259
	Company	7,293,375	7,608,451	7,738,257	8,777,507
Applied Research	Public Research Institutions	2,568,973	2,733,998	2,780,583	2,988,451
	University	2,302,552	2,166,220	2,568,756	2,906,057
	Company	13,953,189	15,139,925	14,729,290	15,575,855
Developme nt Research	Public Research Institutions	4,921,336	4,918,387	5,760,278	6,325,146
	University	2,214,330	2,267,959	2,652,450	2,785,298
	Company	47,587,868	48,758,286	51,132,231	56,454,265

(3) Electrochemistry Sector



Source: Korea Institute of S&T Evaluation and Planning (KISTEP).

Figure 3-2-2 Trends in South Korea's National R&D Expenditures

In 2021, South Korea's national R&D expenditure amounted to 26.5791 trillion won (approximately 3.0425 trillion yen). The number of research projects also increased annually, totaling 74,745 in 2021. R&D spending in the electrochemistry field has shown consistent growth over time. Specifically, in 2021, government expenditures were 16.8 billion won (approximately 1.9 billion yen) for basic research, 3.6 billion won (approximately 400 million yen) for applied research, 4.5 billion won (approximately 500 million yen) for development research, and 300 million won (approximately 34 million yen) for other purposes, totaling 25.1 billion won (approximately 280 million yen).

(4) Research Funding Flow

Table 3-2-2 outlines South Korea's major science and technology research programs and projects. Funding for electrochemical research is primarily managed and executed by two agencies: the National Research Foundation of Korea (NRF) under the Ministry of Science and ICT (MSIT) and the Korea Evaluation Institute of Industrial Technology (KEIT) under the Ministry of Trade, Industry and Energy (MOTIE). The NRF is primarily responsible for basic research, whereas the KEIT focuses on commercialization and development. Table 3-2-3 presents the basic research funding provided by the NRF.

Table 3-2-2 Major Electrochemical Research Programs and Projects in South Korea

Ministry	Funding Agency	Research Program / Project	Research Institution
Ministry of Science and ICT (MSIT)	National Research Council of Science & Technology (NST)	"Core Source Technologies for Next-Generation Secondary Batteries" (2017–2020), approx. 4.2 billion KRW (approx. ¥460 million)	KIER (Laboratory for Separation and Conversion Materials)
	NST	Creative Convergence Research Project: "Development of Convergent Solutions for Materials and Processes for High-Energy-Density Carbon-Neutral Batteries" (2022–2027), approx. 11.4 billion KRW (approx. ¥ 1.25 billion)	Korea Electrotechnology Research Institute (KIER), Korea Institute of Materials Science, Korea Institute of Science and Technology (KIST), Yunsung F&C Co., Hanwha / Hanwha Machinery, Gyeongsang National University, Ulsan National Institute of Science and Technology (UNIST)
	NRF	Technology Development for Climate Change: "Core Source Technologies for Next-Generation Lithium Metal Secondary Batteries for EVs" (Phase 1/2, 2018.7–2020.12), approx. 2.4 billion KRW (approx. ¥260 million)	Korea Electrotechnology Research Institute (Next-Generation Battery Center), Green Science, SK NeclariS, SK Innovation, Dong-A University, University of Colorado, Seoul National University, ROSTECH, DGIST, etc.
Ministry of Trade, Industry and Energy (MOTIE)	Korea Institute of Energy Research (KIER)	Energy Talent Development Program: "GET-Future Lab for Next-Generation LIBs"	Kayang University
		"Development of Manufacturing Technologies for Cathode Materials, Electrolytes, and Cells of High-Performance Lithium Iron Phosphate Batteries" (2023–2026), total 23.3 billion KRW (gov't: 16.4B, private: 6.9B; approx. ¥ 2.56 billion)	• Battery: SAMSUNG SDI, SWEMEKA (cathode), EcoPro BM (electrolyte), Dongwha Electrolyte, CIS (equipment), etc. •Universities: Kyonggi University, Sogang University, SeoulTech, Sungkyunkwan University, Ajou University, Hanyang University, Dong-A University, Korea Institute of Ceramic Engineering and Technology, Korea Testing Laboratory (KTL), Korea Research Institute of Chemical Technology, etc.
		Commercialization Technology Development for Mid- to Large-Scale Secondary Batteries: "Development of High-Energy-Density (300 Wh/kg) Lithium Secondary Batteries for EVs" (2016–2020), approx. 5.7 billion KRW (approx. ¥620 million)	Korea Automotive Technology Institute, LG Energy Solution, Hyundai Motor Company, Bexel, RAON TECH, Hanyang University–Industry Cooperation Foundation
	KEIT	World Premier Materials (WPM) Program: "Core Technologies for Lithium-Air Secondary Batteries; Electrode Materials for Lithium Secondary Batteries and Application Technologies" (2010–2019), approx. 33 billion KRW (approx. ¥3.63 billion)	SAMSUNG SDI, MK Electronics, Aekyung Petrochemical, Aekyung Chemical, Seoul National University (Prof. Kang Kisuk), Korea Electronics Technology Institute

Ministry of Education	NRF	Brain Korea 21 (BK 21) Plus Project: "Future Convergent Energy Leaders Program" (Basic Research) (2013–2020) BK21 FOUR: "Innovative Talent Development for Emerging Industries" (2020–2027)	Department of Energy Engineering of Hanyang University

Table 3-2-3 Major Basic Research Programs in South Korea

＊ Unit: Million KRW

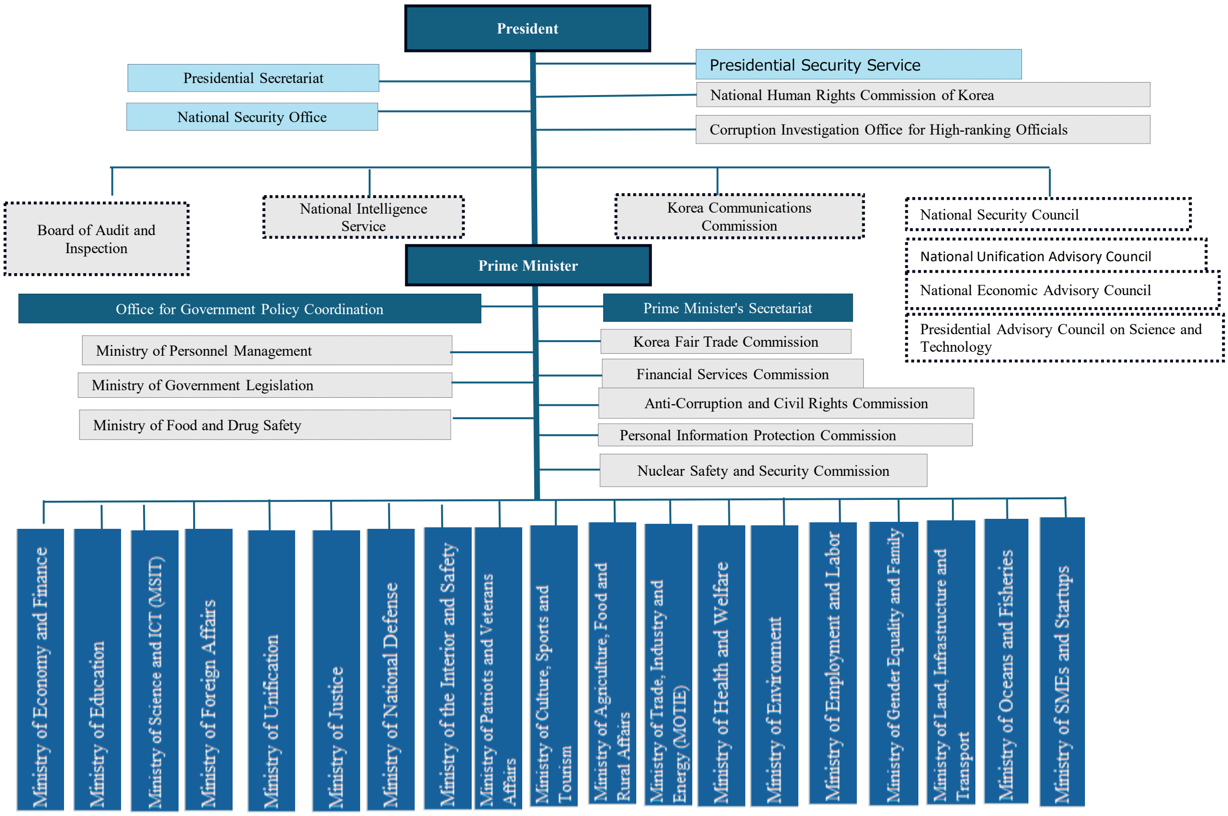
Program	Subprogram	Detail work	Content	Total Budget (2023)	New Budget (2023)	Ministry
Basic Rsearch Promotion	Basic Research Support	Individual Research	Leader Research	77,892	4,595	MSIT
			Mid-career Research	996,319	221,108	MSIT
			Young Researcher Program	310411	72,981	MSIT
			General Research	216,873	46,297	MSIT
			First Research in Life	35,533	4,500	MSIT
		Group Research	Basic Research Lab Support Program	178,555	50,625	MSIT
			Leading Research Center Support Program	234,841	47,890	MSIT
	Basic Research Infrastructure	Basic research and infrastructure program	Specialized Research Utilization Program	1,950		MSIT
			Global Hub for Basic Research Experimental Data	3,020		MSIT
			Collaboration with CERN (European Organization for Nuclear Research)	7,094		MSIT
			Support for Utilization of Large-scale Overseas Research Facilities	791	501	Huge Public Research Policy
			Multi-purpose Synchrotron Accelerator			MGIT
		Radiation Accelerator Joint Utilization Research	Synchrotron Accelerator Joint Research Support Project	61,449		MSIT
			Core Technology Development for Accelerator Project	1,000		MSIT
			Technology Development of Core Equipment for Radiation Photo-accelerator			MSIT

Source: NRF.

3.2.2 Research Promotion Framework

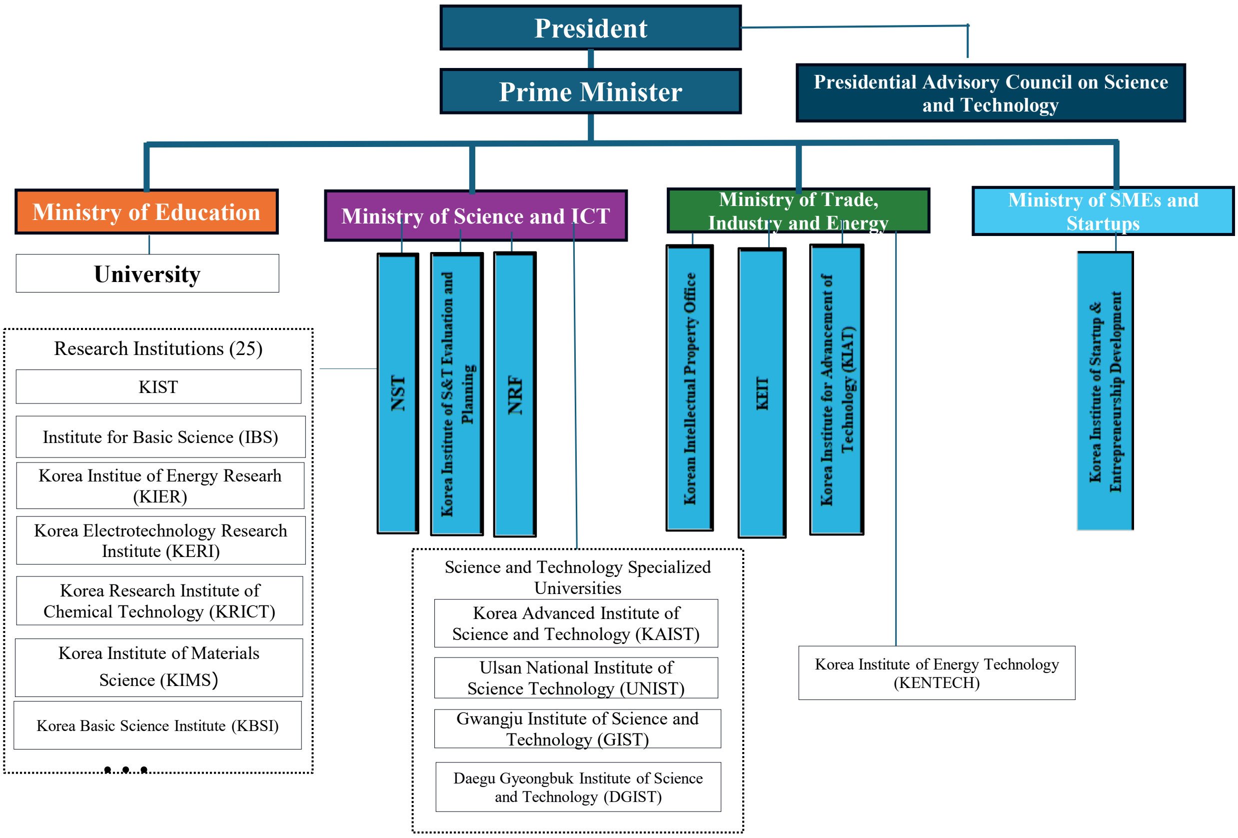
The structure of South Korea's government organizations has changed with each administration. The Yoon Suk-yeol administration began in May 2022, and as of 2023, the government included the President as the head of state, the Prime Minister, appointed by the President and responsible for directing and supervising the heads of central administrative agencies, and the Deputy Prime Minister, who handles tasks delegated by the Prime Minister. The government comprises 19 ministries, 3 offices, and 19 agencies (Figure 3-2-3).

The agencies involved in science and technology policy include the MSIT (as the principal authority), Ministry of Education, MOTIE, and Ministry of SMEs and Startups. With each change in administration, ministry names and jurisdictions have been adjusted. In particular, the current configurations of the ministries related to science, technology, information and communication, and education are the result of mergers and reorganizations (Figure 3-2-4).



Source: "Government 24" (South Korea).

Figure 3-2-3 Korean Government Organization Structure



Source: Compiled by APRC.

Figure 3-2-4 Departments Involved in Science and Technology Policy and their Affiliated Research Institutions in South Korea

In South Korea, national R&D projects are those supported by the government budget or funds in accordance with the laws and regulations of central administrative agencies[76]. In practice, any project categorized as related to R&D during the budget formulation process and funded by the national budget or public funds is considered a national R&D project. Implementing these national R&D projects requires designating specialized R&D agencies to conduct all or some of the tasks on behalf of central administrative bodies. Key specialized agencies include the NRF, which handles academic research under the MSIT and Ministry of Education; the Institute for Information & Communications Technology Planning & Evaluation (IITP) under the MSIT; KEIT, Korea Institute for Advancement of Technology (KIAT), and Korea Institute of Energy Technology Evaluation and Planning (KETEP) under the MOTIE; and Korea Technology and Information Promotion Agency for SMEs (TIPA) under the Ministry of SMEs and Startups. These agencies are responsible for planning R&D programs and managing research projects, including evaluation and outcome management, as well as tasks such as international cooperation and human resource development. Figure 3-2-5 summarizes the institutional transitions of the ministry currently known as the MSIT.

[76] National Research and Development Innovation Act of Korea

Source: Compiled by APRC.

Figure 3-2-5 Evolution of Science and Technology Ministries in South Korea

3.2.3 Related Key Policies

The South Korean government has designated secondary batteries as a national strategic technology and announced a series of related policies. Secondary batteries are becoming increasingly important core components in a wide range of industries, including smartphones, electric vehicles (EVs), and energy storage systems (ESS). Although South Korea has strong global competitiveness in this field now, recent challenges, such as supply chain disruptions and intensified competition over leadership in the next-generation secondary battery market, have made strategic responses essential.

The Yoon administration began in May 2022, and in October of the same year, following a resolution by the National Science and Technology Advisory Council, it announced the "National Strategy for Fostering Strategic Technologies" identifying 12 key national strategic technologies, including secondary batteries. Based on this strategy, the government also formulated the "R&D Strategy for Securing Ultra-Gap Competitiveness in Three Core Technologies," focusing on securing future core technologies, such as next-generation batteries, semiconductors, and displays.

Furthermore, in February 2023, the government released the "Strategy for Securing Critical Minerals" aimed at transforming South Korea into a global advanced industry powerhouse. This strategy targets 10 priority strategic minerals selected from a wider list of 33 critical minerals designated as key national resources. These 10 strategic minerals include battery-related materials, such as lithium, nickel, cobalt, manganese, and graphite. The goals include reducing import dependency on any single country for these minerals to 50% or less and raising the recycling rate to 20% by 2030.

In March 2023, South Korea enacted the Special Act on the Promotion of National Strategic Technologies, establishing an institutional foundation for fostering strategic technologies, including secondary batteries. In April of the same year, the National Strategic Technology Special Committee designated the development of next-generation secondary batteries as a key national strategic technology project that required focused support. Furthermore, aiming to achieve the world's first commercialization of all-solid-state batteries, the government announced the National Strategy for Strengthening Competitiveness in the Secondary Battery Industry, a plan to invest 20 trillion won (approximately 2.3 trillion yen) through public–private partnerships by 2030.

In May 2023, the government released a five-year plan (2023–2027) outlining the current status and strategies for fostering and protecting key industries such as semiconductors, displays, and biotechnology. This plan also revealed that over 39 trillion won (approximately 4.5 trillion yen) in private investment would be directed toward secondary batteries by 2026. In July, Cheongju, Pohang, Saemangeum, and Ulsan were selected as specialized complexes for advanced strategic industries related to secondary batteries. In August, the government published the Strategic Roadmap, the highest-level technical strategy for secondary batteries, highlighting detailed priority areas, such as LIBs and core materials, next-generation secondary batteries, modules and systems, and reuse and recycling.

Table 3-2-5 Major Science and Technology Policies Related to Electrochemistry in South Korea

Date	Policy / Strategy	Summary	Responsible Ministry
2022.10	National Strategy for Fostering Strategic Technologies	Adopted 12 major national strategic technologies that included secondary batteries at the National Science and Technology Advisory Council	MSIT
2023.2	Strategy for Nurturing Talent in Advanced Fields	Announced human resource development strategies in five core areas: aerospace & future mobility, bio-health, advanced components/materials (e.g., semiconductors and batteries), digital, and environment & energy	Ministry of Education
2023.4	Public-Private Joint Strategy for Post-IRA Battery Industry Development	Announced KRW 7 trillion support over 5 years for North American expansion, and KRW 50 billion (approx. ¥5.7 billion) investment in lithium iron phosphate (LFP) battery R&D	MOTIE
2023.4	National Strategy for Strengthening Competitiveness in the Secondary Battery Industry	Targeting the first commercialization of all-solid-state next-generation batteries by 2030 through public–private investment of KRW 20 trillion (approx. ¥2.3 trillion)	MOTIE
2023.5	1st Basic Plan for Nurturing and Protecting National Strategic High-Tech Industries	Five-year plan (2023–2027) for semiconductors, displays, batteries, and bio-industries. Over KRW 39 trillion (approx. ¥4.5 trillion) in private investment for next-generation secondary batteries by 2026	MOTIE
2023.7	Designation of Specialized Complexes for National Strategic High-Tech Industries – Secondary Batteries	Designated Cheongju, Pohang, Saemangeum, and Ulsan as specialized complexes for secondary batteries	MOTIE
2023.8	Strategy Roadmap (I) Focused on National Strategic Technology Missions – Tech Hegemony Fields	The National Science and Technology Advisory Council deliberated on and approved strategic roadmaps for three fields: secondary batteries, semiconductors/displays, and advanced mobility	MSIT

Source: Compiled by APRC.

3.2.4 Research Funds and Research Programs

South Korea's major research funding agencies in the electrochemistry field include the NRF under the MSIT and the KEIT under the MOTIE. When examining the top institutions by the number of published research papers across the three device categories (Table 3-2-6), the trends by funding agency are as follows: for batteries, the top contributors are the NRF, followed by the former MSIT and Future Planning and Ministry of Education, Science and Technology; for fuel cells, the leading agencies are the NRF, MOTIE, and Ministry of Education, Science and Technology; and for water electrolysis, the top agencies are the NRF, former MSIT and Future Planning, and current MSIT.

Table 3-2-6 Major Research Funding Agencies for Electrochemistry in South Korea

Research Funding Agency	Secondary Battery	Fuel Cell	Water Electrolysi
National Research Foundation of Korea（NRF）	5,278	2,091	537
Ministry of Science ICT Future Planning, Republic of Korea (2013–2017)	1,274	440	145
Ministry of Education, Science and Technology (MEST) Republic of Korea (dissolved in 2013 reorganization)	1,038	469	44
Ministry of Trade, Industry,and Energy (MOTIE) Republic of Korea	982	493	96
Korean Government	816	337	30
Ministry of Science and ICT (MSIT), Republic of Korea	740	221	114

Source: Compiled by APRC.

Table 3-2-7 summarizes recent major research programs and projects in the field of electrochemistry. Notable efforts include research projects aimed at improving energy density for carbon neutrality and developing LFP battery manufacturing technologies, of which China currently holds the dominant global share, and next-generation secondary batteries for EVs.

At the KIER, R&D is led by a comprehensive project focused on developing integrated solutions for material and process innovation aimed at high-energy-density carbon-neutral batteries. The KIER is engaged in research and the dissemination of results in the energy technology sector. Its research divisions include the Hydrogen Energy Institute, Renewable Energy Research Institute, Energy Efficiency Research Division, and Climate Change Research Division.

Mr. Kim Jin-Soo of the Ulsan Next-Generation Battery Research Center at the KIER serves as the project leader. This project is advancing the demonstration-level development of foundational materials and equipment aimed at realizing a new dry electrode manufacturing process that eliminates the solvents used in the conventional wet process for LIB electrodes. By developing an integrated solution that innovates both materials and processes for dry electrode manufacturing, this project is expected to contribute to achieving carbon neutrality in South Korea by 2050 and secure the country's global competitiveness in the battery material, component, and equipment industries by 2030.

Table 3-2-7 Major Research Programs, Projects, and Principal Investigators

Project	Project Leader	Research Objectives	Participating Institutions
Development of Converged Solutions for Materials and Process Innovation for Carbon Neutral High-Energy-Density Batteries (2022–2027)	Kim Jin-Soo (KIER), Ulsan Next-Gen Battery Center) Total Budget: KRW 11.4 billion (approx. JPY 1.3 billion)	- Conceptual design of a new solvent-free dry process to replace conventional wet-process electrode manufacturing for LIBs, and demonstration-level development of the necessary foundational materials and equipment. - Realization of a LIB with approximately 60% higher energy density (around 400 Wh/kg)	KIER, KERI, KIMS, KIST, Yunsung F&C Co., Hanwha/Machinery, Gyeongsang National University, (UNIST)
Development of Cathode Materials, Electrolytes, and Cell Manufacturing Technologies for High-Performance LFP Batteries (2023–2026)	EcoPro BM, Dongwha Electrolyte, CIS Total Budget: KRW 23.3 billion (approx. JPY 2.67 billion)	Development of the world's highest-performance LFP Batteries ① Localization of cathode material production ② Development of manufacturing technology for the world's highest-performance LFP cells, targeting an energy density of 200 Wh/kg (currently 160 Wh/kg).	Cathode Materials: EcoPro BM, KRICT, Kyonggi University, Sungkyunkwan University Electrolytes: Dongwha Electrolyte, Ecopro HN, Korea Testing Laboratory (KTL), Hanyang University, Ajou University, Sogang University Electrodes: CIS, SWEMEKA, Korea Institute of Ceramic Engineering and Technology (KICET), Hanyang University, SeoulTech, Dong-A University Demand-side Company: SAMSUNG SDI
Core Source Technology for Next-Generation Batteries (2018–2023)	Lee Sang-Min (KERI) Total Budget: KRW 24.3 billion (approx. JPY 2.78 billion)	Development of Core Source Technology for lithium-metal secondary batteries for EVs	KERI, Korea Institute of Industrial Technology (KITECH), KIST, Korea Electronics Technology Institute (KETI)
Development of Energy Materials and Improvement of Energy Demand Management Efficiency _Core Source Technology for Next-Generation Secondary Batteries (2017–2022)	Jang Bo-Yoon (KIER) Total Budget: KRW 4.2 billion (approx. JPY 0.48 billion)	Development of high-rate high-capacity non-lithium energy materials for EVs, which are highly integrated 3D-stacked power supply systems tailored to user needs	KIER
Basic Source Technology Development Project for Climate Change Response_ Development of Core Element Technologies for Next-Generation Lithium-Air Secondary Batteries (2020–2022)	Park Jeong-Gi (KAIST) Total Budget: KRW 2.52 billion (approx. JPY 0.29 billion)	Development of stabilizing additives for Li-metal/electrolyte interfaces and introduction of first-principles computational methods for catalyst design and elucidation of reaction mechanisms in lithium–air batteries	KAIST, Seoul National University, Inha University, Kyonggi University
Nano and Materials Technology Development – National Core Materials Research Group (Platform-Based Materials Innovation Leading Project) _ Development of Core Materials for Next-Generation Secondary Batteries with High Capacity and Safety (2020–2024)	Seok Jong-Dong (KRICT) Total Budget: KRW 14.0 billion (approx. JPY 1.6 billion)	Development of integrated organic-inorganic electrolytes/separators for next-generation secondary batteries, heat-resistant nano-material separators, performance enhancement of multi-functional electrolytes and additives for Lithium-ion secondary battery	KRICT, UNIST, LG Electronics, ENCHEM Co., Korea Electronics and Telecommunications Research Institute (ETRI), KITECH, Seoul National University, Konkuk University, DGIST, etc.

Source: Compiled by APRC; participating institutions with research leaders are underlined.

3.2.5 Major Research Institutions and Major Companies

Major Research Institutions

Based on a search of the WoS database, Table 3-2-8 lists the top South Korean research institutions involved in electrochemical device development. In terms of the total number of publications across the three device categories, leading institutions include Seoul-based universities[77] such as Seoul National University, Hanyang University, Korea University, Sungkyunkwan University, and Yonsei University. The major contributors include science and technology-focused universities centered on engineering and scientific research, such as the KAIST, UNIST, and Pohang University of Science and Technology (POSTECH); regional national universities, such as Chonnam National University, Chonbuk National University, and Pusan National University; the KIST as a public research institution; and the University of Science and Technology (UST), a graduate school jointly established by government-funded research institutes. SAMSUNG ranks prominently among private companies.

Table 3-2-8 Leading Research Institutions in Electrochemistry in South Korea

Research Institution	Secondary Battery	Fuel Cell	Water Electrolysis
Seoul National University	1,614	581	118
Hanyang University	1,329	423	78
KAIST	1,246	519	102
Korea University	1,126	479	118
Sungkyunkwan University	1,059		
KIST	958	718	159
UNIST	956	287	97
Yonsei University	772	358	94
Chonnam National University	740		
SAMSUNG	691		
KIER		464	129
Jeonbuk National University		340	
Pusan National University		310	
POSTECH			83
UST			83

Source: Compiled by APRC.

An overview of the major top-level research institutions in South Korea and their related research activities is provided below.

[77] The area encompassing Seoul Metropolitan City and the surrounding Gyeonggi Province.

(1) Seoul National University

Seoul National University, founded in 1946 and based in Seoul, is a comprehensive national university. With approximately 29,000 students enrolled in undergraduate and graduate programs, it is widely recognized as South Korea's most prestigious and leading institution.

Electrochemistry research is primarily conducted by the School of Chemical and Biological Engineering and Department of Materials Science and Engineering. The School of Chemical and Biological Engineering at Seoul National University was selected for the BK21 program in chemistry and engineering, which aims to foster globally competitive research talent. Professor Jang Wook Choi, who leads the Multiscale Energy Science Laboratory, was selected as a Highly Cited Researcher (HCR) by Clarivate, ranking in the top 1% of citations worldwide for six consecutive years from 2017 to 2022.

Collaboration among industry, academia, and related companies is also progressing. In 2021, Seoul National University signed a Memorandum of Understanding (MOU) with SAMSUNG SDI to operate the "Seoul National University–SAMSUNG SDI Battery Talent Development Track (SSBT)" aimed at nurturing outstanding talent in the battery field. From the 2022 academic year through the 2031 academic year, the SSBT will select 10 graduate students annually, totaling over 100 scholarship recipients over a 10-year period, and provide them with battery-related education. In addition to specialized academic coursework, the program offers various educational initiatives, including overseas training programs, employment opportunities at SAMSUNG SDI, and competitions for innovative battery technology ideas. The SSBT chair is Professor Kang Kisuk from the Department of Materials Science and Engineering, who also serves as the head of the Next-Generation Secondary Battery Center. Professor Choi is a member of the program's steering committee. Furthermore, Professor Kang is a research fellow at the Nanoparticle Research Center of the Institute for Basic Science (IBS), Korea's premier institution for basic science research. Clarivate selected him as an HCR for five consecutive years, from 2018 to 2022, placing him in the top 1% of researchers worldwide in terms of citations.

In January 2023, an MOU was signed with LG Energy Solution to establish an industry–academia cooperation center. The focus going forward will be on identifying collaborative research topics and conducting studies on materials for sulfide-based all-solid-state and lithium-sulfur batteries.

In July 2023, the Hyundai Motor Group–Seoul National University Joint Battery Research Center opened at Seoul National University. Professor Choi heads the center, which comprises seven laboratories dedicated to battery development, analysis, measurement, and processing. The center focuses exclusively on EV batteries and is pursuing 22 joint research projects across four key areas: lithium metal, all-solid-state batteries, battery management systems (BMS), and battery process technologies. A total of 21 professors, as well as master's and doctoral researchers from institutions such as KAIST, UNIST, DGIST, Hanyang University, Sungkyunkwan University, and Chungnam National University, are participating in this initiative.

(2) Hanyang University

Hanyang University is a comprehensive private university with a strong engineering focus. In December 2008, the Department of Energy Engineering was established as part of the "World Class University" project initiated by the Ministry of Education, Science and Technology (the predecessor of the MSIT). Since September 2013, the department has been selected for the "BK21 Plus (BK21 Program for Leading Universities & Students)" global talent development project. It was selected for the "Phase 4 BK21 Innovative Talent Development Project (New Industry Fields)" in September 2020 and continues to pursue R&D. The head of the educational research group for this project, titled 'Educational Research Group for Energy New Industry Engineering Talent,' is Professor Sun Yang-Kook of the Department of Energy Engineering.

Professor Sun leads the Energy Storage and Conversion Materials Laboratory and was selected as an HCR for seven consecutive years, from 2016 to 2022. He is conducting research on LIBs and next-generation batteries, and in 2022, he transferred technology to LG Chem for the highest sum in South Korean history. Professor Sun has been engaged in battery R&D for EVs since the early stages, and South Korean automakers have adopted his technologies. He has also participated in joint international research projects with global automobile manufacturers.

In response to the growing demand for skilled personnel in the highly competitive battery industry, Professor Sun requested the establishment of a graduate program in Battery Engineering. Unlike contract-based departments at other universities, Hanyang University's Battery Engineering program operates as an industry–academia cooperative course rather than being tied to employment at a specific company. Students in this program are selected through a screening process by companies such as LG Energy Solution, SK On, POSCO Future M, and LG Chem. Separately from this program, LG Chem has established an industry–academia cooperation center at Hanyang University, where it engages in joint research on next-generation cathode materials and works to improve their capacity, output, and charging performance.

(3) KAIST

The KAIST was established in 1971 as a research-oriented university to foster scientific and technological talent and conduct science and technology research driven by national policy. Based in Daejeon in central South Korea, KAIST comprises colleges such as the College of Natural Sciences, College of Life Science and Bioengineering, College of Engineering, College of Liberal Arts and Convergence Science, and College of Business. It has approximately 11,000 undergraduate and graduate students and 660 faculty members.

Active research in the field of electrochemical devices is being conducted in the Departments of Chemical and Biomolecular Engineering and Materials Science and Engineering. Professor Kim Bumjoon of the Department of Chemical and Biomolecular Engineering leads the Polymer Nanoelectronics Laboratory. In 2018, he was appointed as an Endowed Chair Professor, a title awarded to distinguished researchers with outstanding academic achievements. Professor Kim conducts research on soft electronics and polymer hybrid materials and has achieved significant results, such as the development of elastomer-based solid electrolytes for high-energy-density all-solid-state batteries.

Industry–academia collaboration is also progressing. The LG Energy Solution–KAIST Battery Research Center was established to promote R&D related to next-generation batteries. In January 2023, SK On, a major battery manufacturer, signed an agreement to launch the industry–academia cooperative education program "SKBEP" aimed at fostering talent in the battery sector. Starting in the fall of 2023, the program was introduced in nine fields related to batteries: biological and chemical engineering, chemistry, advanced materials, electrical and electronic engineering, computer science, and AI. The program targets master's and doctoral students who will receive job offers from SK On upon graduation.

(4) Korea University

Professor Kang Yun-Chan leads the Nano-Energy Materials Laboratory in the Department of Materials Science and Engineering. He has an outstanding research record in the fields of functional nanomaterials and battery materials. In 2022, he was appointed as a Distinguished Professor, an honor awarded to faculty members who have made exceptional contributions in their respective fields and demonstrated leadership, in recognition of his achievements.

Korea University has operated the "Battery–Smart Factory Department" since 2022 in collaboration with LG Energy Solution to foster talent in the field of next-generation batteries. The program focuses on research related to next-generation batteries, such as lithium-metal, lithium-sulfur, all-solid-state, and sodium-ion batteries.

These efforts include Professor Kang's research at the Energy Storage & Conversion Materials Lab on the synthesis and analysis of next-generation secondary battery materials based on aerosol and liquid-phase processes. Furthermore, Professor Yu Seung-Ho's Electrochemical Energy Lab is working on the commercialization of next-generation batteries by using real-time X-ray imaging analysis to elucidate charge-discharge mechanisms at the electrode level.

In collaboration with the KIST, Korea University has introduced a joint faculty system and established the KU (Korea University)–KIST Graduate School of Energy and Environment. Korea University and KIST are also working together to cultivate interdisciplinary talent in fields that integrate medical technology, biotechnology, IT, and nanotechnology.

(5) Sungkyunkwan University

Sungkyunkwan University is a comprehensive university based in Seoul with more than 34,000 students across its undergraduate and graduate programs. The university has operated with the participation of the SAMSUNG Foundation since November 1996.

Sungkyunkwan University was selected for the Korean Ministry of Education's "Phase 4 BK21 Project" (September 2020 to August 2027), which aims to foster world-class research-oriented universities. In the electrochemistry field, the Education and Research Group for Innovation in Renewable Energy Integrated Systems was launched under the BK21 program to train specialized professionals. Professor Yoon Won-Sub, the head of this research group, has been conducting research on the design and synthesis of cathode and anode materials for next-generation LIBs.

In November 2022, Sungkyunkwan University signed an agreement with SAMSUNG SDI to launch the "Sungkyunkwan University–SAMSUNG SDI Battery Talent Development Program," which aims to develop next-generation secondary battery technologies. This program focuses on nurturing talent in the fields of battery materials, cells, and systems. Between the academic years of 2023 and 2032, 100 master's and doctoral students will be selected as scholarship recipients. The selected students will take battery-related courses, engage in relevant research, and participate in training programs and competitions organized by SAMSUNG SDI. Upon graduation, they will receive job offers from SAMSUNG SDI.

(6) KIST

The KIST was established in 1966 as South Korea's first government-funded research institute. It conducts R&D using a wide range of future technologies, including energy, brain science, next-generation semiconductors, AI, and robotics. Electrochemistry research is conducted under the Clean Energy and Advanced Materials Research Division, which includes the Clean Energy Research Center, Next-Generation Solar Cell Research Center, Energy Materials Research Center, Energy Storage Research Center, and Hydrogen & Fuel Cell Research Center. The KIST is a leading institution in South Korea for research on fuel cells and water electrolysis.

The Hydrogen & Fuel Cell Research Center was established in 1987 to promote the commercialization of fuel cells and is currently led by Director Jang Jong Hyun. This center conducts research aimed at securing core technologies for renewable-energy-linked hydrogen production (water electrolysis), chemical hydrogen storage, and hydrogen utilization (fuel cells). Recently, the center developed a new component structure that significantly reduces the use of platinum and iridium in the electrode-protective layers of polymer electrolyte membrane (PEM) water electrolysis systems.

Director Jang's current research focus is on fuel cells and water electrolysis, with a particular emphasis on solid polymer electrolyte membranes[78]. In the short term, the center aims to develop PCEC (Proton-Conducting Electrochemical Cells) technology, and in the mid-to-long term, AEM (Anion Exchange Membrane) technology. Until recently, Korea's hydrogen technology was still in the catch-up stage and the prevailing view was that hydrogen production would occur overseas. Consequently, R&D focused on building supply chains to import hydrogen from other countries. However, more recently, the establishment of domestic hydrogen production bases has been discussed [c4]. Collaborating with companies for R&D, as seen in the battery sector, is ideal. However, because no leading water electrolysis companies are currently in South Korea, national efforts are regarded as catching up with technological developments.

As mentioned above, the KIST runs a joint graduate program at Korea University called the KU–KIST Graduate School of Energy and Environment. KIST researchers participate in graduate-level education as visiting professors and conduct research on foundational technologies for clean power generation systems, focusing on solar and fuel cells.

(7) UNIST

The UNIST is a research-oriented university that focuses on advanced materials, biotechnology, and next-generation energy. Established in 2009, the university comprises 15 departments within the Schools of Engineering, Information-Bio Convergence, Natural Sciences, and Schools of Humanities and Business Administration.

The Department of Energy and Chemical Engineering houses several specialized research centers, including the Advanced Battery Research Center, Secondary Battery Research Center, Next-Generation Hydrogen Convergence Technology Research Institute, Seawater Resources Technology Research Center, and Perovskitronics Research Center. These centers conduct research in fields related to

[78] Initially, it is referred to as PEM (Proton Exchange Membrane). See the appendix for reference.

electrochemistry. In 2017, the Industry–University Research Center for Secondary Batteries was established, featuring facilities for fabrication, analysis, and testing, and has since developed a strong reputation in secondary battery research.

Professor Jaephil Cho, Director of the Secondary Battery Research Center and a faculty member of the Department of Energy and Chemical Engineering, was selected as an HCR in the top 1% of citations on WoS for seven years, from 2016 to 2022.

Professor Hyun-Wook Lee, also from the Department of Energy and Chemical Engineering, was selected as an HCR in the top 1% of citations from 2019 to 2022. Professor Lee has an extensive research track record for elucidating the mechanisms underlying the degradation and reduced lifespan of secondary battery materials using transmission electron microscopy (TEM). Furthermore, he emphasizes that understanding the fundamental principles of materials is essential for analysis. He is actively engaged in research on battery materials, including cathodes, anodes, and all-solid-state components, with a particular focus on Prussian blue-type compounds. Regarding future prospects, Professor Lee commented that, "In Korea, all-solid-state batteries are receiving the most attention as next-generation batteries. Whether it's sodium-based or solid-state, while there are some differences, the systems are similar to lithium-based batteries, and I believe more diverse research is needed." [c9] [c10]

The UNIST also operates a contract-based master's program in the Department of Energy and Chemical Engineering in collaboration with SK On to cultivate talent in battery technology at an early stage.

Major Companies and Key Startups

In the electrochemistry field, notable Korean companies can be broadly categorized into LIB and material manufacturers. Among LIB manufacturers, LG Energy Solution, SK On, and SAMSUNG SDI are ranked among the top 10 globally and recognized as Korea's "Big Three" battery makers. In addition, SMLAB, a startup recognized by the government as a "pre-unicorn" company, is gaining attention. The key players among material manufacturers include LG Chem, EcoPro BM, L&F, POSCO Future M, Nano New Materials, and Daejoo Electronic Materials.

Table 3-2-9 Notable Companies and Startups in Electrochemistry in South Korea

Category	Company Name	Company Overview	Key Products
Battery Manufacturers	LG Energy Solution	Established in 2020 Sales: KRW 25.6 trillion (approx. JPY 2.9 trillion) R&D Investment: KRW 876 billion (approx. JPY 100.0 billion)	EV batteries, small batteries, ESS batteries
	SK On	Established in October 2021 Sales: KRW 7.6178 trillion (approx. JPY 871.7 billion) R&D Investment: KRW 234.6 billion (approx. JPY 26.8 billion)	Development and mass production of high-energy-density EV batteries: NCM622 (2014), NCM811 (2018), NCM9½½ (2022)
	SAMSUNG SDI	Established in 1970 (renamed in 1999) Sales: KRW 20.1241 trillion (approx. JPY 2.3 trillion) R&D Investment: KRW 1.0763 trillion (approx. JPY 123.2 billion)	EV batteries, small batteries, ESS, electronic materials
Material Manufacturers	LG Chem	Established in 1947 Sales: KRW 51.8649 trillion (approx. JPY 5.9 trillion) R&D Investment: KRW 1.778 trillion (approx. JPY 203.0 billion)	Separators, cathode materials, binders for anodes
	EcoPro BM	Spun off from EcoPro in 2016 Sales: KRW 5.3576 trillion (approx. JPY 613.1 billion) R&D Investment: KRW 50.9 billion (approx. JPY 5.8 billion)	Cathode active materials, precursors
	POSCO Future M	Established in 1963 Renamed from POSCO Chemical in March 2023 Sales: KRW 3.3019 trillion R&D Investment: KRW 50.9 billion	Korea's only producer of both cathode and anode materials; precursor materials
	L&F	Established in 2000 Sales: KRW 3.8862 trillion R&D Investment: KRW 33.6 billion	Cathode active materials for secondary batteries, precursors
	Hansol Chemical	Established in 1980 Sales: KRW 2.449.55 million	Anode binders, separator binders, silicon anode materials, CNT dispersants
	Nano New Materials	Established in 2000 Sales: KRW 77.6 billion	CNT slurry
	Daejoo Electronic Materials	Established in 1981 Sales: KRW 174.1 billion	Silicon anode active materials
	SKC	Established in 1976 Sales: KRW 3.1389 trillion	Anode materials for EV lithium batteries, SiC (silicon-carbon composite) anode materials for LIBs
Startups	SMLAB	Founded in July 2018 by Prof. Cho Jae-pil (UNIST)	Manufactures single-crystal cathode materials via dry processes for secondary batteries; supports NCM, NCA, NCMA, LMR with over 90% Ni content; certified as a "Preliminary Unicorn" by the government
	LiBEST	Founded in 2016 by a KAIST graduate student; KAIST spin-off	Develops flexible secondary batteries with antifreeze and flame-retardant properties; selected among top "Super-Gap Startup 1000+" by government

Note: Sales and R&D investment figures are as of 2022.

3.2.6 International Co-authorship and International Cooperations

Based on a survey of the literature on WoS, Table 3-2-10 shows the countries with the highest number of international co-authored publications with Korea on the development of electrochemical devices. In all three research fields, the ranking order of the U.S., China, India, and Japan remains unchanged. India and Saudi Arabia stand out among the top 10 countries. Regarding India, this can be attributed to the Korea–India Cooperation Center at the KIST, which promotes research collaboration in fields such as physics, chemistry, materials science, and computer engineering with institutions including IISc, IIT Bombay, IIT Bhubaneswar, and JNCASR. As for Saudi Arabia, long-standing cooperation in the energy sector, along with recent increases in investment and collaboration in areas such as renewable energy, hydrogen, CCUS, and EVs, has led to active joint research on electrochemical devices.

Table 3-2-10 Top International Co-authoring Countries in Electrochemistry Research in South Korea

Battery Storage	Fuel cell	Water Electrolysis
U.S. (1,973)	U.S. (696)	U.S. (129)
China (1,066)	China (391)	China (106)
India (713)	India (339)	India (78)
Japan (377)	Japan (175)	Japan (35)
Australia (308)	Saudi Arabia (129)	Pakistan (33)
Germany (269)	United Kingdom (109)	Germany (32)
United Kingdom (240)	Egypt (102)	Vietnam (31)
Pakistan (212)	Germany (102)	Saudi Arabia(28)
Saudi Arabia (204)	Vietnam (82)	Malaysia (27)
Singapore (151)	Malaysia ｛81)	Australia (22)

From the perspectives of competition and protection in R&D, we next discuss the positioning of electrochemical devices as strategic technologies and their treatment in terms of research security.

In June 2023, the MOTIE enacted the "Notice on the Designation of National Strategic Technologies," designating 17 technologies in the fields of semiconductors, displays, secondary batteries, and bioindustry as National Strategic Technologies.

Among them, the following three technologies related to secondary batteries were designated:

1. Design, processing, manufacturing, and evaluation technologies for high-energy-density lithium batteries (pouch-type batteries with an energy density over 280 Wh/kg, prismatic batteries over 252 Wh/kg, cylindrical batteries with a diameter of 21 mm or less over 280 Wh/kg, and cylindrical batteries with a diameter greater than 21 mm over 260 Wh/kg);
2. Design, manufacturing, and processing technologies for high-capacity lithium secondary battery cathode materials (Nickel content exceeding 80%); and
3. Design, processing, manufacturing, and evaluation technologies for ultra-high-performance electrodes (over 600 mAh/g, such as silicon-graphite composite anodes, sulfur cathodes, and lithium metal anodes)

or next-generation lithium secondary batteries (all-solid-state batteries, lithium-sulfur batteries, and lithium-metal batteries).

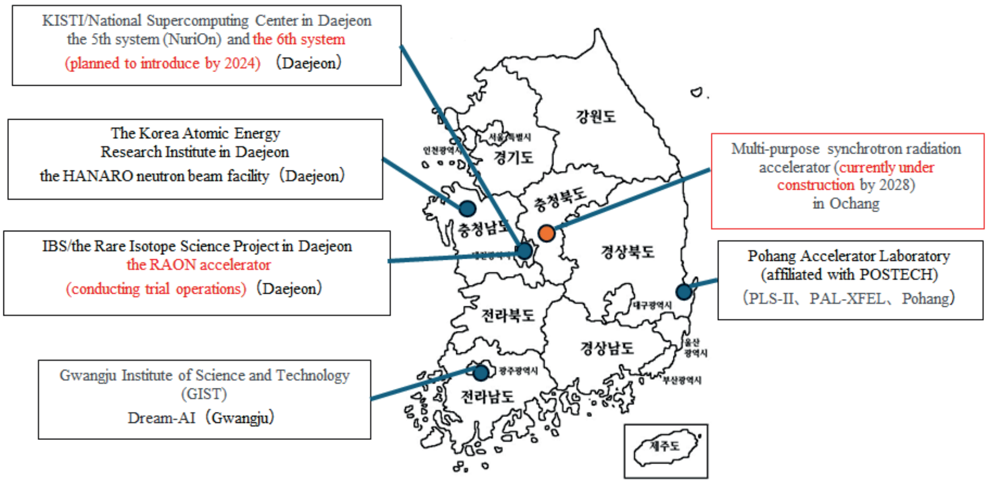
On September 26, 2023, the National Science and Technology Advisory Council approved a proposal titled, "Measures to Operationalize a Research Security System for Building a Reliable Research Ecosystem." The rationale behind this resolution is to establish a research security framework that aligns with the global trend of technological hegemony, systematically protect national research assets, and enhance research security regulations in accordance with the National R&D Innovation Act. The goal is to create a research environment in which researchers engaged in national R&D projects can work with peace of mind.

The proposed implementation directions are as follows:

- Establishment of Legal Frameworks for Researchers and Research Assets: building a management system for information critical to research security, systematizing inter-ministerial security regulations, and streamlining research security frameworks at the institutional level;
- Enhancement of Security Task Management for National Core Research: developing a more detailed classification of security levels and systematizing classification standards, supporting the protection and utilization of research outcomes in sensitive and security-related projects, and standardizing the management of security-related tasks within information systems; and
- Establishment of a Research Security Support System for Sustainable Research: developing a support system staffed by dedicated personnel and fostering experts in research security, systematizing the management of foreign researchers and critical personnel, and raising awareness of research security through expanded guidelines and incentives.

3.2.7 Large-Scale Research Infrastructure

The Korea Basic Science Institute (KBSI) supports research facilities, equipment, and analytical services to promote basic science and serves as the foundation for national science and technology R&D. As part of its large-scale research infrastructure, Korea has eight supercomputers and ranks ninth globally. The National Supercomputing Center at the Korea Institute of Science and Technology Information (KISTI) operates "NuriOn," which ranks 49th globally, and planned to introduce its sixth system by 2024. Two synchrotron radiation accelerators (third- and fourth-generation accelerators) are currently in operation at POSTECH. In addition, a new multipurpose synchrotron radiation accelerator is under construction in Ochang and is scheduled to begin operation by 2028 (Figure 3-2-7).

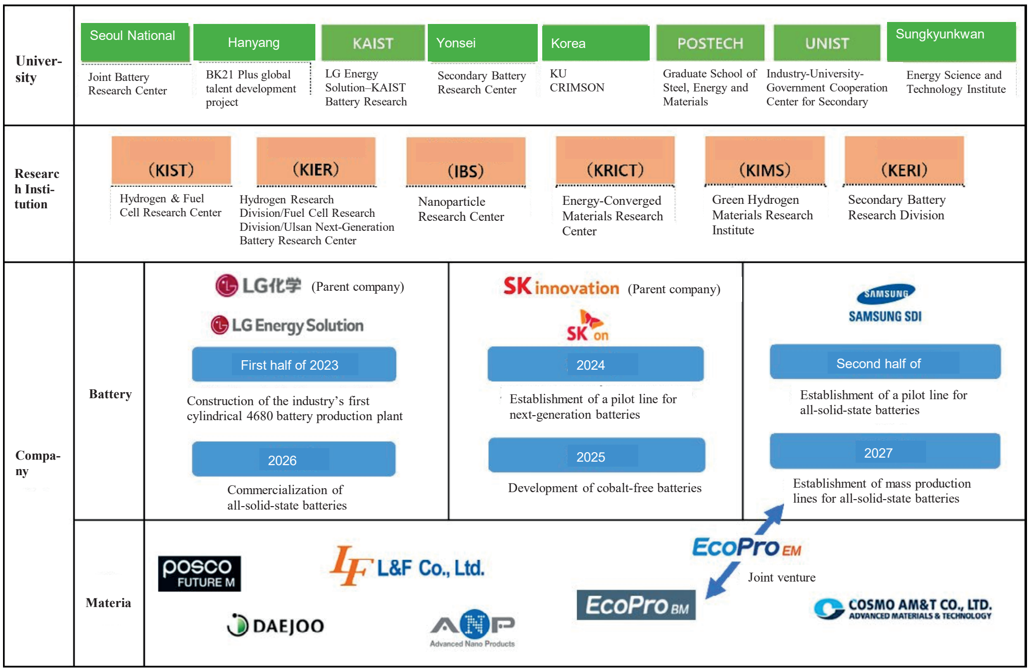


Source: Compiled by APRC.

Figure 3-2-7 Map of Large-Scale Research Facilities in South Korea

3.2.8 Key Players

The trends in R&D in South Korea's electrochemical field have been outlined based on the number of WoS publications, focusing on the three main device categories. Figure 3-2-8 summarizes the major players across industry, academia, and government research institutes. In South Korea, R&D is actively promoted through collaboration among industry, academia, and government research institutions, in line with the government's strategic priorities. In particular, the three major battery conglomerates with global competitiveness are forming partnerships with universities and public research institutions, not only to conduct joint research but also to develop top talent. Through a strategy focused on selection and concentration, they are enhancing their technological research capabilities.



Source: Compiled by APRC based on data from the MOTIE, South Korea

Figure 3-2-8 Major Players in Industry–Academia Research in the Field of Electrochemistry in South Korea

3.3 Taiwan

Recently, Taiwan has achieved remarkable development by playing an important role in the global semiconductor supply chain. Since taking office in 2016, the Tsai Ing-wen administration has prioritized the development of green energy technology industries as a pillar of national economic policy. The battery industry, which is essential to electric vehicles, has been identified as an innovative technology that will drive economic transformation in Taiwan, following the semiconductor industry. The government aims to build an ecosystem that integrates academia and industry around the green energy technology science city constructed in Shalun, Tainan, in 2020.

The central project in Taiwan's research and development of electrochemical fields, including rechargeable batteries and fuel cells, is the "Development of the Shalun Smart Green Energy Science City," conceived in 2016. The government plans to establish a science city in Shalun, Tainan, by 2020. This city includes a joint research center and demonstration area. The government plans to create an ecosystem involving local universities, public research institutions, and related industries. Investment in the "battery storage" field is also progressing. Major companies such as Hon Hai, Taiwan Plastic Group, and Taiwan Cement are entering the midstream battery cell sector, which requires significant initial investments. These companies aimed to develop a one-stop Taiwanese battery industry. Hon Hai, which produces electric vehicles (EVs) in Taiwan, established a battery storage research and development hub in Kaohsiung. The company has launched an industry-academia collaboration project with six major universities to advance the development of "all-solid-state lithium batteries" centered around Professor Huang Bing-Chao of National Taiwan University of Science and Technology, a leading expert in battery storage research in Taiwan. Additionally, the Advanced Battery Materials Industry Alliance, established by the National Cheng Kung University and the National University of Tainan, facilitates industry–academia collaboration and international cooperation.

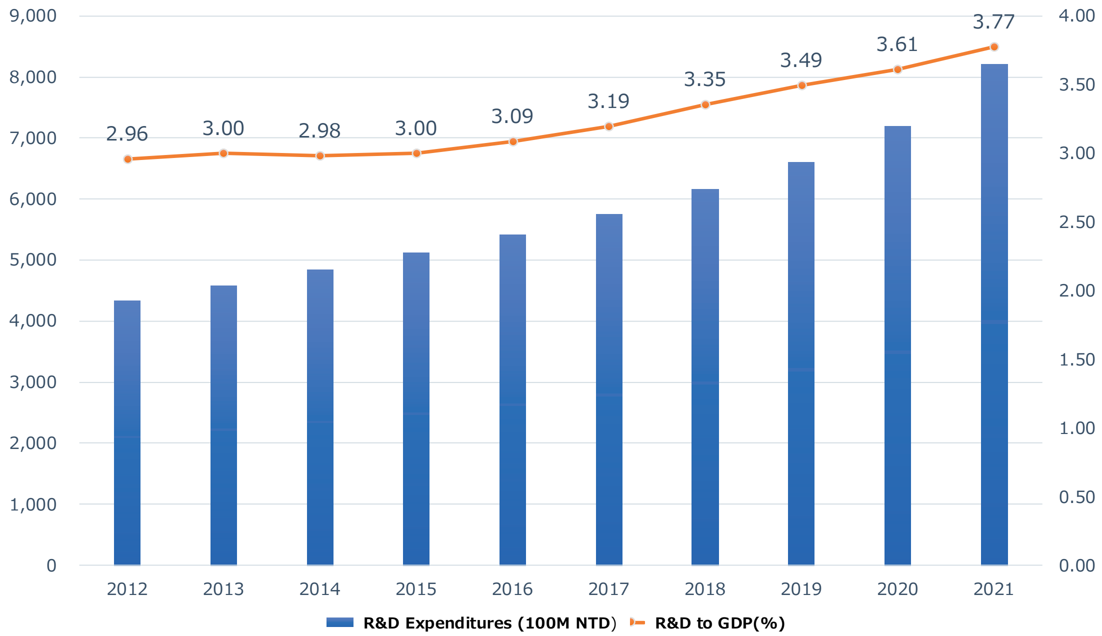
Fuel cells are part of the international supply chain. Taiwanese companies supply raw materials and parts to major foreign companies. Although there is less R&D activity in this sector than in the battery sector, the National Communications Commission and Energy Administration of the Ministry of Economic Affairs have supported R&D aimed at establishing a domestic infrastructure for polymer electrolyte fuel cells (PEFCs) as backup power sources. Recently, efforts have been made to introduce PEFCs into vehicles, such as buses, scooters, and ships.

Additionally, although hydrogen energy development and utilization have achieved practical applications in certain areas, such as fuel cells, the large-scale practical application of products other than fuel cells is still in its infancy. "Hydrogen energy" has been identified as one of the 12 key strategic areas for achieving the 2050 net-zero emissions target. The focus is on developing low-cost, high-performance technologies for producing and storing hydrogen as well as generating power from hydrogen and ammonia. Since 2022, Yuan Ze University has been implementing the "Electrolyzer Energy Storage Technology and Green Hydrogen Application Service Industry Consortium" project with support from the National Science and Technology Council (NSTC). Through industrial collaboration, this project aims to advance the research and development of proton exchange membrane (PEM) technology, complete the PEFC industry chain, and cultivate talent.

Efforts to promote fuel cell and hydrogen energy production are expected to accelerate.

3.3.1 Research Funding

(1) Research and development expenditure



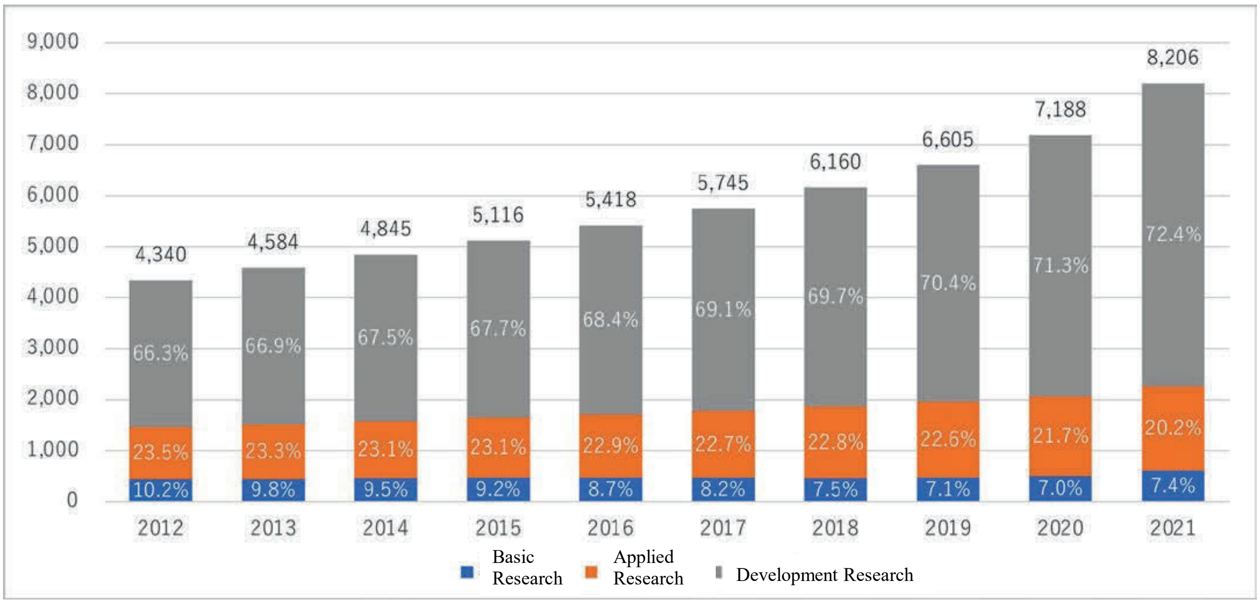
Source: Taiwan "Statistical Abstract of Science and Technology," prepared by APRC.

Figure 3-3-1 R&D Expenditures and Ratio to GDP (Unit: 100 million NTD)

From 2012 to 2021, Taiwan's R&D expenditures will increase from 434 billion NTD (2.0832 trillion JPY at an exchange rate of 1NTD = 4.8 JPY, unless otherwise stated) to 820.6 billion NTD (3.939 trillion JPY). Additionally, the R&D expenditure-to-GDP ratio rose from 2.96% in 2012 to 3.77% in 2021. Since 2016, when the Tsai Ing-wen administration took office, the increase in this ratio has been particularly significant. This reflects the administration's emphasis on science and technology innovation policies as well as the efforts of Taiwanese companies to invest in R&D.

(2) Total research funding and breakdown by research stage

When broken down by research stage, development research increased steadily from 66.3% in 2012 to 72.4% in 2021. On the other hand, although the amount of applied and basic research has increased, their respective ratios have decreased. Applied research will decrease from 23.5% in 2012 to 20.2% in 2021, and basic research will decrease from 10.2% to 7.4%. These findings suggest that development research, which is centered on companies and focuses on practical applications, has been a major driving force behind R&D in Taiwan.



Source: "OECD Main Science and Technology Indicators," prepared by APRC.

Figure 3-3-2 Percentage of each research stage (Unit: 100 million NTD)

Table 3-3-1 Breakdown of Research Funds by Research Stage and Research Entity (Unit: 1 million NTD)

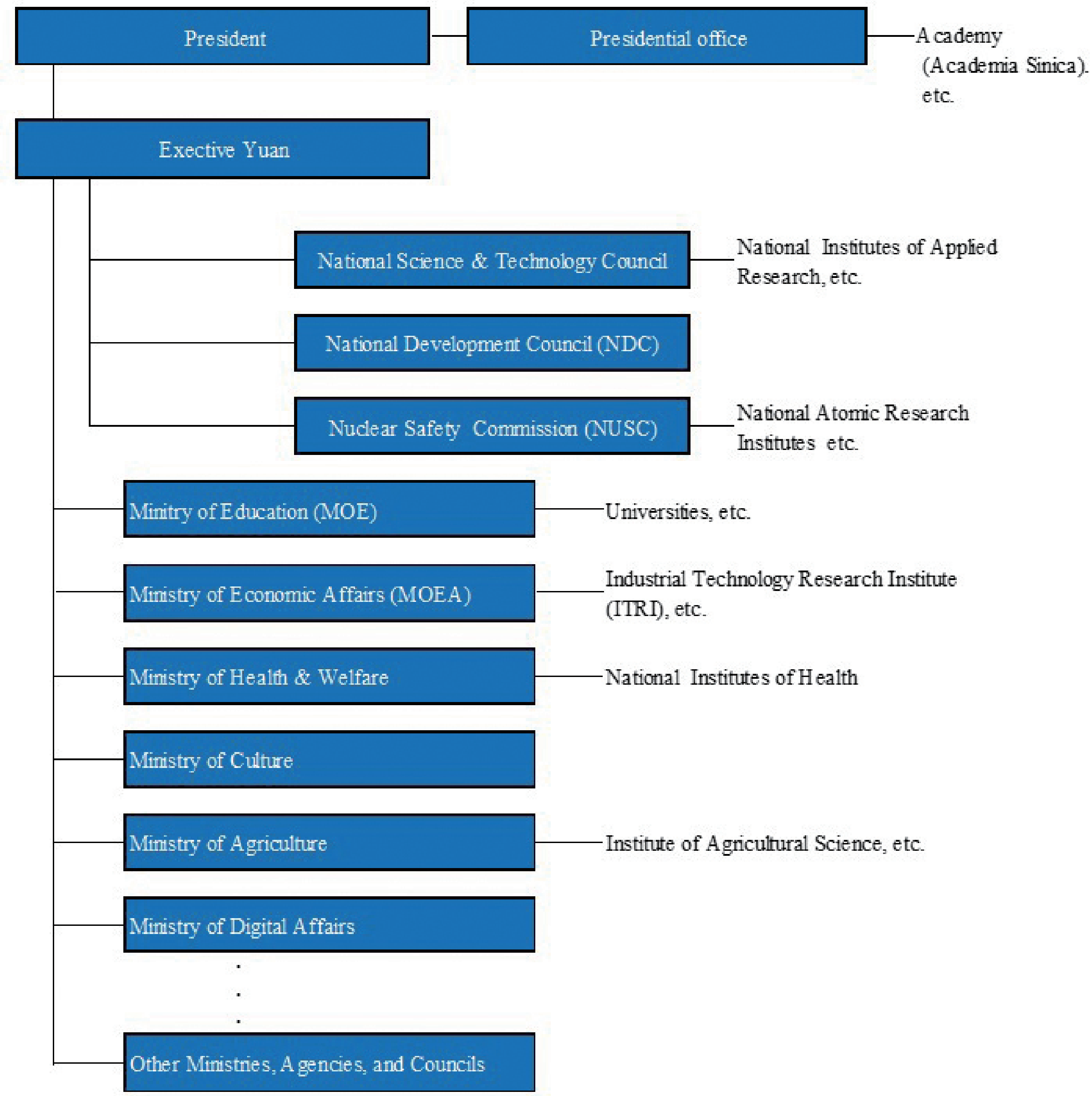
Subject of research	Research Stage	2018	2019	2020	2021
Whole		615,986	660,511	718,791	820,631
Company		494,707	534,587	593,354	691,589
	Basic	1%	1%	1%	1%
	Applied	19%	19%	19%	19%
	Development	80%	80%	80%	80%
University		54,758	55,302	55,830	56,338
	Basic	43%.	42%	50%	62%
	Applied	42%	43%	37%	28%
	Development	15%	15%	13%	10%
Public research institution		65,740	69,753	68,692	71,855
	Basic	27%	26%.	27%	26%
	Applied	31%.	29%	30%	29%
	Development	42%	44%	43%	45%
Nonprofit organization		781	869	915	849
	Basic	25%	22%	17%	19%
	Applied	67%	69%	77%	73%
	Development	8%	8%	6%	8%

Source: "OECD Main Science and Technology Indicators," prepared by APRC.

In 2021, approximately 80% of the total R&D expenditure will be spent on research conducted by companies. Of this, approximately 80% was spent on developmental research, whereas 20% was spent on applied research. Universities and public research institutions primarily conduct basic research. Recently, there has been a noticeable shift toward basic research at universities, away from applied and developmental research.

3.3.2 Research Promotion System

(1) Science and technology-related ministries



Source: Based on the Science and Technology White Paper (2021-2024) and other sources, prepared by APRC.

Figure 3-3-3 Diagram of Major Relevant Ministries and Agencies

National Science and Technology Council

In 2022, the National Science and Technology Council (NSTC) was reorganized by the Ministry of Science and Technology to strengthen the integration and promotion of science and technology-related policies across ministries and agencies, and enhance science and technology governance. Previously, the Ministry of Science and Technology provided subsidies for academic research and managed the national science and technology budget. The Science and Technology Report Office, part of the Executive Yuan, was responsible for allocating science and technology budgets across the Taiwanese government. This office also integrated science and technology development tasks across ministries, including the Ministry of Science and Technology, and coordinated nationwide science and technology policies. However, as science and technology advance, many policy objectives can no longer be addressed by a single ministry or department. There is an increasing need for R&D spanning multiple ministries and fields. Thus, to integrate and promote science and technology development across ministries and to strengthen the management system for implementing science and technology policies, the Science and Technology Council was reorganized into the National Science and Technology Council. The NSTC inherited the functions of the Science and Technology Council and the Science and Technology Bureau and is responsible for formulating and coordinating the overall science and technology policy, allocating the overall science and technology budget, formulating science and technology development plans, and executing budgets within the scope of the budget allocated to the Council.

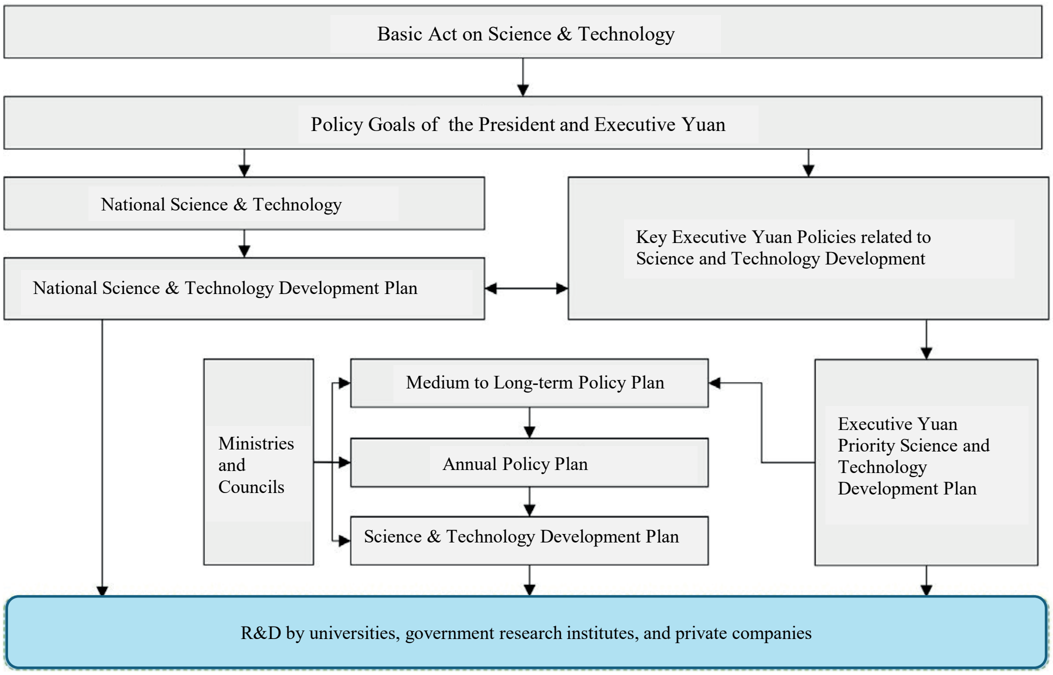
According to the Organizational Act of the National Science and Technology Council[79], members of a council should consist of the heads of relevant government agencies, research institution heads, and experts. The main government agencies related to science and technology in Taiwan are the chair of the National Development Council; the Ministry of Economic Affairs, Education, Agriculture, Health and Welfare, Culture, and Digital Affairs; and the President of the Control Yuan.

(2) Mechanism for Formulating Science and Technology Policy

In Taiwan, the Fundamental Science and Technology Act[80] forms the foundation for science- and technology-related policies. Based on this law, the Executive Yuan holds a National Science and Technology Conference every four years. At this conference, experts from industry, the government, and academia shared their opinions on the development of science and technology over the next four years. The Executive Yuan compiled and approved the National Science and Technology Development Plan, which announced important policy guidelines and promoted the implementation of the development plan. In addition, each ministry and agency formulates science and technology development plans corresponding to the higher-level plans. These plans were developed in accordance with central government policies and the agencies' respective responsibilities. These plans promote R&D activities at universities, research institutions, and companies (Figure 3-3-4).

79 National Laws and Regulations Archive National Science and Technology Commission Organization Act https://law.moj.gov.tw/LawClass/LawAll.aspx?pcode=H0000139

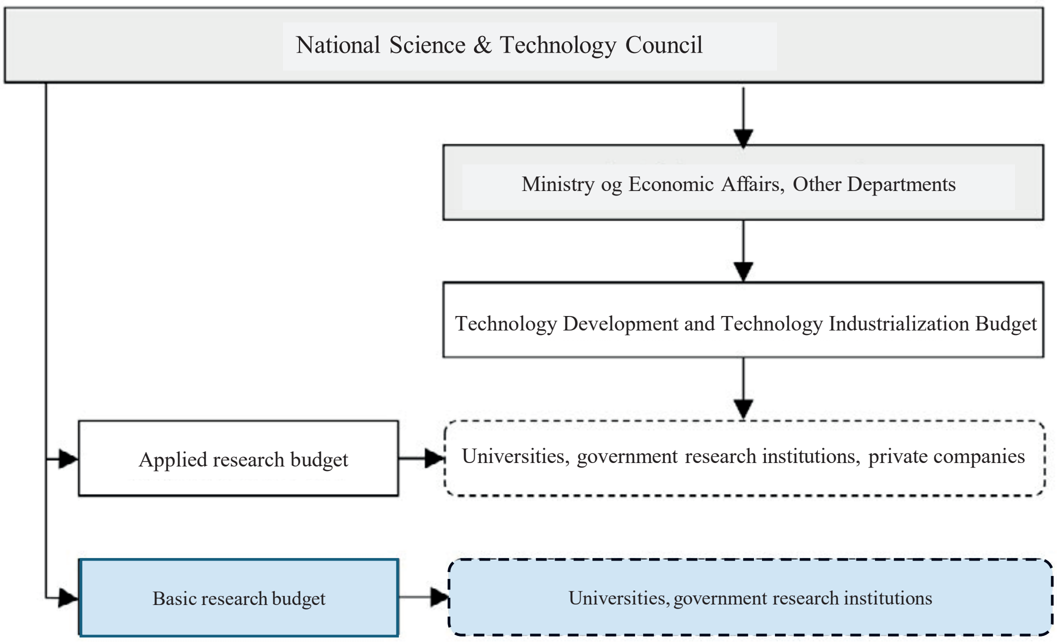
80 National Legal Reference Library Basic Law of Science and Technology https://law.moj.gov.tw/LawClass/LawAll.aspx?pcode=H0160028



Source: Prepared by APRC based on JST/APRC research report "Taiwan's Science and Technology Capability."

Figure 3-3-4 Mechanisms of Taiwan's Science and Technology Policy Formation

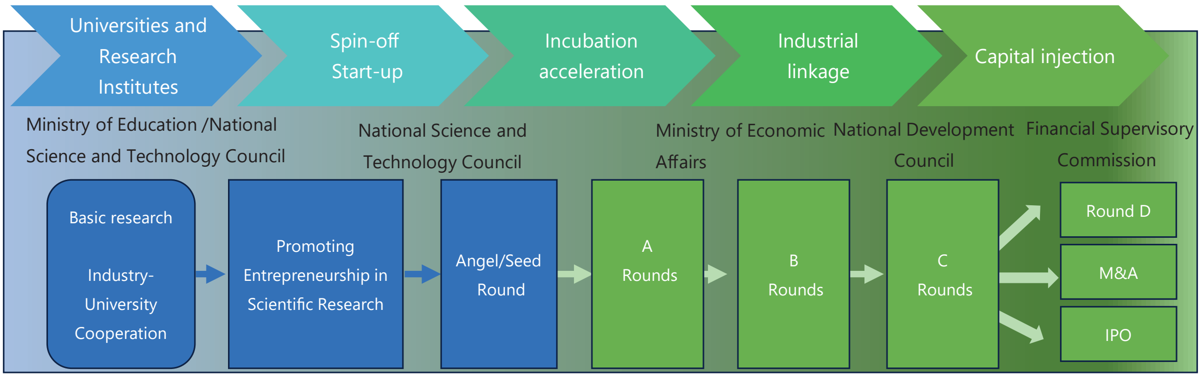
(3) Research Funds Flow



Source: Prepared by APRC based on JST/APRC research report "Taiwan's Science and Technology Capability."

Figure 3-3-5 Taiwanese Government Science and Technology Funding Allocation Process

The Taiwanese government's science and technology research and development budget is divided into three categories: "basic research," "applied research," and "technology development and industrialization." Funds for basic and applied research are primarily allocated from the National Science and Technology Council (NSTC) budget. In contrast, funds for technology development and industrialization are allocated from the budgets of other science and technology-related agencies, such as the Ministry of Economic Affairs. The basic research budget is not available to companies. The NSTC is positioned at the top of Taiwan's innovation ecosystem, providing support from basic research at universities through the transition to the start-up and initial incubation stages. To ensure that support continues through commercialization, the NSTC can introduce follow-up resources from the Ministry of Economic Affairs, the National Development Council, and the Financial Supervisory Commission at each stage.



Source: Prepared by APRC based on NSTC website.

Figure 3-3-6 Government Support Structure in Taiwan's Innovation Ecosystem

3.3.3 Related Key Policies

In 2016, when Tsai Ing-wen took office, the Taiwanese government established the "5+2 Innovative Industries Plan" as its national economic policy. In 2020, during its second term, the government formulated the "Program for Promoting Six Core Strategic Industries," an extension of the former plan. The promotion of green and renewable energy is a key component of both plans.

(1) "5+2 Innovative Industries Plan" (2016) [81]

In light of the global shift toward the Fourth Industrial Revolution, which focuses on digitalization, automation, and the adoption of artificial intelligence, the Executive Yuan of Taiwan established the "5+2 Innovative Industries Plan" in September 2016. This program aims to accelerate the transformation and upgrading of Taiwan's industries. It is based on three strategic pillars: "Connecting with the Future," "Connecting with the World," and "Connecting with the Region." The program targets seven key industries: "Asia's Silicon Valley," "Smart Machinery Industry," "Green Energy Technology Industry," "Biomedical Industry," "Defense Industry," "New Agriculture," and "Circular Economy."

In response, the former Ministry of Science and Technology proposed the Green Energy Technology

[81] National Development Council 5+2 Industrial Innovation Plan
https://www.ndc.gov.tw/Content_List.aspx?n=9D024A4424DC36B9

Industry Innovation and Promotion Plan[82], a research and development plan for green energy technology industries, approved by the Executive Yuan in October of that year. The plan aims to promote science and technology industries based on the pillars of "energy conservation," "energy creation," "energy storage," and "system integration," with the goal of achieving a 20% share of renewable energy by 2025. In the area of "energy storage," research and development will focus on fuel cells, including lithium batteries and solid oxide fuel cells (SOFC), as well as large-scale energy storage systems. A notable aspect of the plan is the construction of a smart green energy science city in Shalun, Tainan. In 2019, the former Ministry of Science and Technology established a joint research area for green energy technologies, aiming to advance the R&D of future-oriented technologies and promote collaboration between industry and academia. The Ministry of Economy plans to complete a demonstration test area in 2020 and take charge of the practical development research. In the future, this area will attract industries such as lithium batteries, fuel cells, smart grids, and smart motors. The goal is to establish a commercial area that will attract these industries and form a large-scale green industrial ecosystem involving academia, industry, and government.

(2) "Forward-looking Infrastructure Development Program" (2017)[83]

The Forward-looking Infrastructure Development Program is Taiwan's most recent large-scale infrastructure investment plan. This corresponds to the 10 Major Construction Projects of the 1970s and the New 10 Major Construction Projects of the 2000s. Launched by President Tsai Ing-wen in 2017, the program aims to develop the infrastructure necessary for national and industrial development over the next 30 years. The programme is divided into eight categories and will be implemented by 2024. These categories include "railway infrastructure," "water environment infrastructure," "green energy infrastructure," "digital infrastructure," "urban and rural infrastructure," "infrastructure for measures against declining birthrates and childcare support," "food safety infrastructure," and "infrastructure for human resource development and employment promotion." The budget is divided into four phases: Phase 1 (2017–2018): 107 billion NTD (513.6 billion JPY); Phase 2 (2019–2020): 223 billion NTD (1.07 trillion JPY); Phase 3 (2021–2022): 229.9 billion NTD (1.104 trillion JPY); and Phase 4 (2023–2024): 209.8 billion NTD (1.007 trillion JPY). The total budget is approximately 769.7 billion NTD (3.695 trillion JPY).

The "Green Energy Infrastructure" initiative is one of these projects. It aims to strengthen energy security, promote a green economy, and establish Taiwan as a key hub for the development of the green energy industry in Asia. A total of 39.8 billion NTD (191 billion JPY) was allocated to the project's four phases, focusing on developing the "Shalun Smart Green Energy Science City."

(3) "Program for Promoting Six Core Strategic Industries" (May 2021)[84]

On May 20, 2020, President Tsai Ing-wen announced the promotion of six core strategic industries as an extension of the "5+2 Innovative Industries Program," which she promoted during her first term and

[82] NSTC Green Energy Technology and Industry Innovation Promotion Plan https://www.ey.gov.tw/File/E6BF582F5C257C8D?A=C
[83] National Development Commission Infrastructure Construction Plan for the Future https://fi.ndc.gov.tw/index.php
[84] National Development Commission Six Core Strategic Industry Promotion Plan https://www.ndc.gov.tw/Content_List.aspx?n=9614A7C859796FFA

will continue to promote during her second term, ending in 2024. These industries include information and digital technologies, information security, medical and health technologies, green power and renewable energy, defense technologies, and civil and emergency response technologies. The following year, on May 21, 2021, the Executive Yuan approved the "Program for Promoting Six Core Strategic Industries."

This plan aims to promote the "Green Energy Technology Industry Innovation and Promotion Action Plan" and, as the next step, establish an Asian hub for the green energy industry, the Asia-Pacific Green Energy Center. The plan also aims to promote a green power and renewable energy industry, centered on wind and solar power generation. Additionally, in light of increasing economic security risks, it seeks to strengthen the independent development of key components for major industries that will determine the country's future, such as automotive batteries.

Taiwan is home to the electric motorcycle start-up Gogoro and has extensive experience with motorcycle batteries. However, the country lacks the experience and competitiveness in terms of high-output, high-capacity batteries for four-wheeled vehicles. To address this issue, plans have been proposed to enhance the international competitiveness of two-wheel electric batteries. For four-wheeled applications, the country plans to collaborate with electric bus operators through the "Smart Electric Bus DMIT Project" to advance the research and development of high-voltage, high-energy-density, fast-charging batteries. The goal was to strengthen domestic battery manufacturers for domestic production.

(4) "National Science and Technology Development Plan" (2021–2024) (December 2020)

The National Science and Technology Development Plan (2021–2024) was formulated following the 11th National Science and Technology Council meeting held in December 2020. The plan has four goals. Goal 1 is to improve the environment for human resource development and create a competitive advantage. Goal 2 aims to improve scientific research systems and promote future-oriented science and technology. Goal 3 creates fertile ground for economic growth and innovation. Goal 4 aims to enhance smart living and achieve a peaceful society. Under Goal 2, the plan outlines measures to enhance basic research capabilities and promote innovation by strengthening collaboration between academia, industry, and the government. Goal 3 highlights the expansion of renewable sources. Specifically, the plan proposes the establishment of an Asia-Pacific Green Energy Center to facilitate green energy development. This center focuses on advancing vanadium redox battery (VRB) technology for large-scale storage facilities.

(5) "Taiwan's 2050 Net-zero Policy" (from 2021)

Fossil fuels account for approximately 80% of Taiwan's power supply. As countries worldwide move toward net-zero emissions by 2050, Taiwan's Tsai Ing-wen administration declared the same goal in April 2021. In March 2022, the government released "Taiwan's Pathway to Net-Zero Emissions in 2050[85]," which outlines specific measures and initiatives to achieve carbon neutrality by 2050. In December of that year, the government announced its "12 Key Strategic Action Plans[86]." As a result, Taiwan's energy supply will

[85] National Development Council, "Taiwan 2050 Net Zero Emissions Roadmap," https://www.ndc.gov.tw/Content_List.aspx?n=DEE68AAD8B38BD76

[86] National Development Commission, "12 Key Strategic Action Plans" https://www.ndc.gov.tw/Content_List.aspx?n=6BA5CC3D71A1BF6F

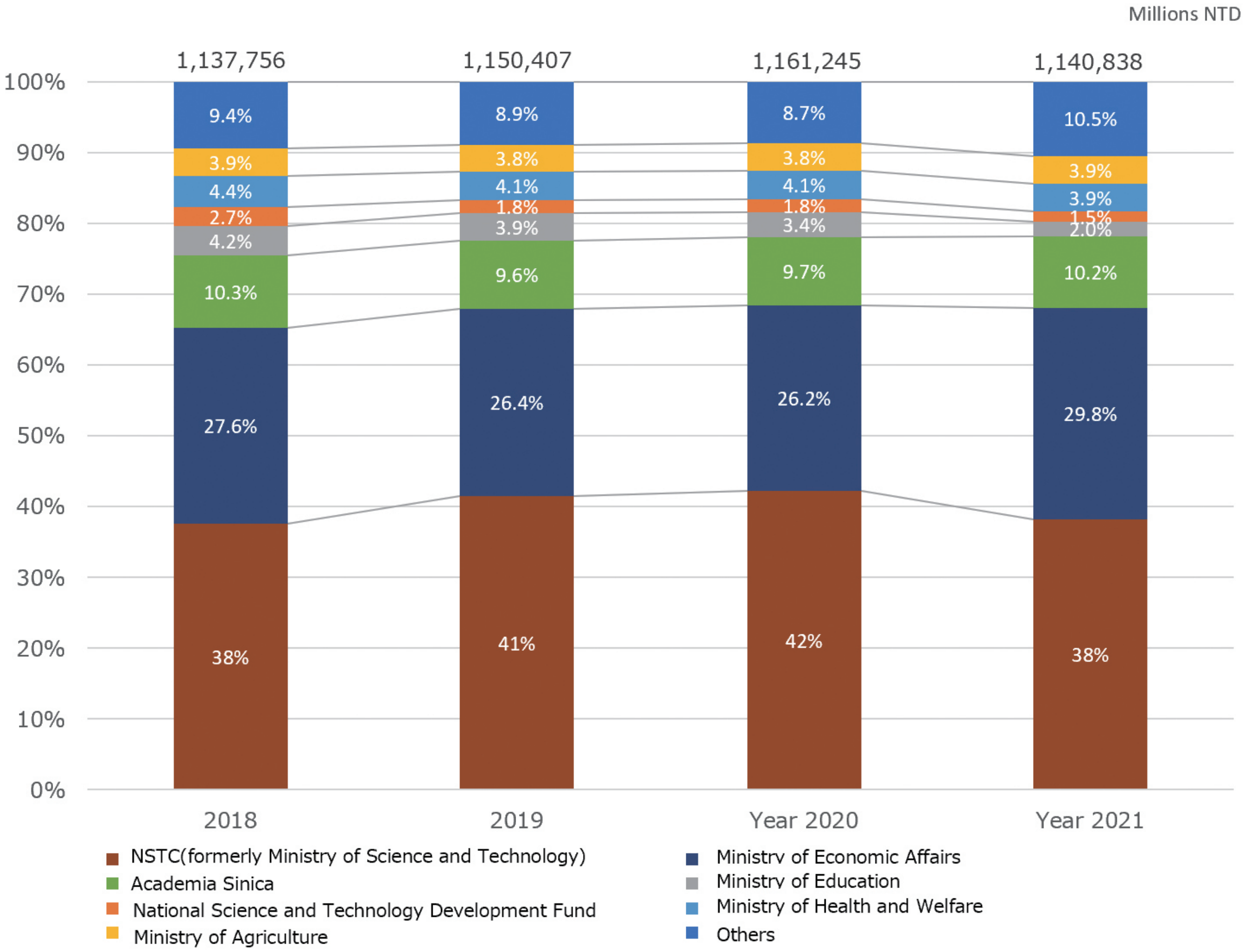
consist of 60–70% renewable energy, including 9–12% hydrogen energy, by 2050.

The pathway consists of four major transitions: the Transition to Safe and Secure Energy, the Transition of Industrial Structure to Enhance Competitiveness, the Transition to Sustainable Lifestyles, and the Transition to a Resilient Society. These transitions are supported by two foundational pillars: "Development of related technologies" and "Establishment of related legal and institutional frameworks," which include introducing carbon footprints and carbon taxes.

The 12 priority strategic areas include wind and solar power generation, hydrogen energy, future energy sources such as geothermal and ocean power generation, power systems and energy storage, and carbon dioxide capture. Of developd investment of 900 billion NTD (4.32 trillion JPY) between 2022 and 2030, 210.7 billion NTD (1.11 trillion JPY) will be allocated to develop renewable and hydrogen energy technologies, and 207.8 billion NTD (997.4 billion JPY) will be allocated to develop power grids and energy storage systems. Regarding batteries, efforts have been focused on improving the energy density and charge/discharge rates, reducing the cost of lithium solid-state batteries, developing safer materials, and advancing recycling technologies for rare elements. Regarding hydrogen energy, anticipated developments include low-cost, high-performance hydrogen production and storage technologies, as well as hydrogen and ammonia power generation technologies.

3.3.4 Research Funds and Programs

Approximately 40% of the government's science and technology budget is allocated to the National Science and Technology Council (NSTC). The Ministry of Economic Affairs receives 30% and Academia Sinica receives 10%. These three agencies account for approximately 80% of the total budget. According to budget allocations by the agency, the "basic research" budget is exclusively allocated to the NSTC and Academia Sinica. The NSTC receives approximately 65%, while Academia Sinica receives the majority of research funds. The Ministry of Economic Affairs, meanwhile, has the largest budget allocation for initiatives related to Taiwan's key government policies, such as the "5+2 Innovative Industries Plan" and the "Program for Promoting Six Core Strategic Industries."



Source: Taiwan "Science and Technology White Paper," prepared by the APRC.

Figure 3-3-7 Annual Allocation of the Government's Science and Technology Budget by Ministry

Table 3-3-2 Fiscal Year 2021 Budget Allocations by Category for Each Government Agency (Unit: millions NTD)

Department	Basic research	General Science and Technology Administration	Policy Priorities	Future-Oriented Infrastructure	Core Metrology Total	Agency Total
National Science and Technology Council	28,535	5,518	5,577	3,430	525	43,584
Ministry of Economic Affairs		8,157	15,329	8,516	1,992	33,993
Academia Sinica	10,773	274	533	93	0	11,673
Ministry of Health and Welfare		2,464	1,607	150	274	4,495
Ministry of Agriculture		2,762	1,364	191	175	4,492
Ministry of Education		226	1,104	892	22	2,243
Ministry of Transportation and Communications		549	601	1,071	0	2,221
Other		2,602	3,097	5,587	96	11,383
Total	39,308	22,551	29,213	19,929	3,083	114,084

Source: "2021 Central Government Science and Technology Development Achievements Summary," prepared by the APRC.

Table 3-3-3 lists the primary R&D funds of the National Science and Technology Council (NSTC) and the Ministry of Economic Affairs. The government has promoted various policies to strengthen Taiwan' s industrial competitiveness. Many Taiwanese companies are small to medium-sized enterprises (SMEs), and it is difficult for them to expand their business activities to include basic research. Consequently, industry-academia collaboration programs that develop research personnel tailored to companies' needs and transfer R&D results from universities and public research institutions are prominent.

Table 3-3-3 Main Funding Programs of NSTC and the Ministry of Economic Affairs

NSTC	General Specialized Subject Research Program	This program supports individual researchers at universities and academic research institutions. Support amount: 1 million NTD (4.8 million JPY)
NSTC	Academic Research Project Program	This program supports promising basic and applied research conducted by teams. Support amount: 40 million NTD (192 million JPY) per year. Support period: 5 years
NSTC	2030 Cross-Generation Young Scholars Program	This program develops young, talented individuals with potential. Support amount: 5 million～10 million NTD/year (24 million～ 48 million JPY/year) Duration of support: 4 years.

NSTC	Industry-University Cooperative Research Program	This program bridges research results in academia to companies and aims for practical application. Matching funds with companies (minimum 250,000 NTD [1.2 million JPY] contribution)
NSTC	Industry-University Cooperative Research Program for Future-oriented Technology	This program promotes industry-academia collaboration in research and development in important technological fields, as well as the training of personnel in these fields. Support amount: 5 million to 40 million NTD per year (24 million to 192 million JPY). Support period: 1 to 3 years. The program is divided into three types based on the scale and duration of support. The largest type, the “Future-Oriented Technology R&D Type,” involves the National Science and Technology Council (NSTC) supporting academic researchers. In contrast, the Ministry of Economic Affairs supports companies through “Industrial Technology Projects.”
NSTC	Scientific Research and Entrepreneurial Program	This program provides one year of support for commercializing research results from academic institutions and establishing spin-off companies. There are two types of support. Type 1 provides up to 8 million NTD (38.4 million JPY) for verifying market needs and developing prototypes of promising research results with potential for future commercialization. Type 2 provides up to 15 million NTD (72 million JPY) for start-up support for projects that have successfully completed Type 1.
Ministry of Economic Affairs	Academic, Scientific, and Technical Projects	This program supports academic departments and promotes and nurtures new businesses based on their achievements. 20 to 30 million NTD (96 million to 144 million JPY) will be provided for 1 year.
Ministry of Economic Affairs	Industrial, Scientific, and Technological Projects (A+ Corporate R&D Innovation Enhancement Plan)	This program provides subsidies to companies investing in research and development of innovative and advanced technologies, with the aim of strengthening international competitiveness through the establishment of industrial ecosystems. It includes forward-looking technology research and development plans, global R&D partnership programs, and more.
Ministry of Economic Affairs	Corporate and Scientific Projects	This program will provide grants to twenty research institutions, including seven major organizations such as the Industrial Technology Research Institute (ITRI). These grants will fund research and development projects that will lead to the creation of advanced and key industrial technologies, improve research infrastructure, and promote international and interdisciplinary cooperation.

Source: NSTC and Ministry of Economic Affairs, prepared by APRC.

Tables 3-3-4, 3-3-5, and 3-3-6 list the top research funding agencies mentioned in Taiwanese papers on rechargeable batteries, fuel cells, and water electrolysis from 2013 to 2023. The agencies are ranked by the number of times they’re mentioned. In addition to domestic institutions, the tables list support agencies from countries presumed to be international research collaboration partners, such as China, the United States, India, and Germany[87]. The Japanese Ministry of Education, Culture, Sports, Science, and

[87] The support by the Spanish Government shown in Table 3 cannot be confirmed in the original paper and appears to be a registration error in the database

Technology (MEXT) is also involved in the field of water electrolysis. The former Ministry of Science and Technology (MOST, now NSTC) accounts for approximately half of the total, whereas the Ministry of Education (MOE) accounts for 1–3%. The Ministry of Economic Affairs (MOEA) accounted for 1% of battery storage and fuel cell research but did not appear among the top agencies in water electrolysis research. As shown in Table 3-3-2, the R&D expenditure ratio between the NSTC and the MOEA is approximately 4:3. Thus, the number of studies reporting MOEA funding outcomes is very low. This is likely because the Ministry of Economic Affairs primarily supports these companies.

Table 3-3-4 Main Research Funding Agencies (Storage Batteries)

Grant Providing Organizations	Number	Percentage (%)
MOST	2009	46.4
NSFC	242	5.6
Spanish Government	199	4.6
MOEA	65	1.5
Academia Sinica Taiwan	57	1.3
MOE	47	1.1
DOE of USA	44	1.0
Fundamental Research Funds for The Central Universities	43	1.0
National Tsing Hua University	43	1.0
NSF of USA	38	0.9
National Taiwan University	36	0.8
DOST of India	32	0.7
BMBF	30	0.7
ARC of Australia	26	0.6
National Health Research Institute, Taiwan	26	0.6

Table 3-3-5 Main Research Funding Agencies (Fuel Cells)

Grant Providing Organizations	Number	Percentage (%)
MOST	1093	55.2
NSFC	117	5.9
Spanish Government	67	3.4
MOE	62	3.1
DOE of USA	25	1.3
Chang Gung Memorial Hospital	20	1.0
DOST of India	20	1.0
MOEA	20	1.0
National Taiwan University	20	1.0
Fundamental Research Funds For The Central Universities	18	0.9
NSF of USA	15	0.8
Academia Sinica Taiwan	14	0.7
National Natural Science Foundation Of Guangdong Province	13	0.7
King Saud University	10	0.5
ARC of Australia	9	0.5

Table 3-3-6 Major Research Funding Agencies (Water Electrolysis)

Grant Providing Organizations	Number	Percentage (%)
MOST	179	47.6
NSFC	49	13.0
Academia Sinica Taiwan	10	2.7
National Key Research and Development Program of China	10	2.7
Spanish Government	9	2.4
DOE of USA	9	2.4
China Postdoctoral Science Foundation	8	2.1
National Taiwan University	7	1.9
Fundamental Research Funds For The Central Universities	6	1.6
MEXT	6	1.6
MOE of Singapore	6	1.6
MOE	6	1.6
Harbin Institute Of Technology	5	1.3
Max Planck Postech Hsinchu Center For Complex Phase Materials	5	1.3
NSF of USA	5	1.3

Source: Clarivate Web of Science, prepared by the APRC.

Note: Blue indicates support organizations in Taiwan.

3.3.5 Major Research Institutions and Major Companies

Major Research Institutions

Table 3-3-7 shows the number of publications per research institution in the fields of "storage batteries," "fuel cells," and "water electrolysis" from 2013 to 2022. Fuel cells account for approximately half of the storage battery field, whereas water electrolysis accounts for approximately one-tenth.

National Taiwan University, National Cheng Kung University, and National Taiwan University of Science and Technology excel in electrochemical research across all three fields. Conversely, Academia Sinica, the most renowned academic research institution in Taiwan, has not appeared in the electrochemical field. The Industrial Technology Research Institute (ITRI) of the Ministry of Economic Affairs, which aims to contribute to Taiwan's industrial development through advanced technological research and development, appears only in the field of batteries.

Table 3-3-7 Taiwan's Top Research Institutions in Electrochemistry by Number of Publications (2013-2022)

Storage Battery Field

Research Institutions	Number	(%)
National Taiwan University	553	12.8
National Taiwan University of Science and Technology	513	11.9
National Cheng Kung University	462	10.7
National Tsing Hua University	459	10.6
National Yang Ming Chiao Tung University	359	8.3
National Taipei University of Technology	290	6.7
National Synchrotron Radiation Research Center	253	5.8
Industrial Technology Research Institute (ITRI)	193	4.5
Ming Chi University of Technology	191	4.4
National Central University	187	4.3

Fuel Cell Field

Research Institutions	Number	(%)
National Taiwan University	239	12.1
National Cheng Kung University	232	11.7
National Taipei University of Technology	209	10.6
National Taiwan University of Science and Technology	179	9.0
National Tsing Hua University	162	8.2
Yuan Ze University	158	8.0
National Central University	129	6.5
National Ilan University	117	5.9
National Kaohsiung University of Science and	97	4.9
National Yunlin University of Science and Technology	91	4.6

Water Electrolysis Field

Research Institutions	Number	(%)
National Taiwan University	54	14.4
National Cheng Kung University	45	12.0
National Yang Ming Chiao Tung University	39	10.4
National Synchrotron Radiation Research Center	30	8.0
National Tsing Hua University	30	8.0
National Taiwan University of Science and Technology	29	7.7
Chinese Academy of Sciences	26	6.9
National Central University	25	6.6
National Sun Yat-sen University	23	6.1
National Taipei University of Technology	22	5.9

Source: "Clarivate Web of Science," prepared by APRC.

The following is a list of major research institutions in the field of electrochemistry, compiled from literature databases on leading research institutions and researchers, collaboration with industries in areas such as venture incubation, and various publicly available research activities.

(1) Industrial Technology Research Institute (ITRI)

ITRI is Taiwan's largest industrial technology R&D organization, operating under the Ministry of Economic Affairs. With over 6,000 researchers, the ITRI's mission is to promote social welfare by creating industrial development and economic value through scientific and technological R&D. To date, ITRI has nurtured 273 venture companies, including global corporations such as TSMC and UMC. ITRI's Green Energy Research Institute fuel cell team is engaged in the research and development of solid polymer electrolyte fuel cells (PEFCs). In Taiwan, where natural gas is widely used, a stationary cogeneration-type natural gas fuel cell system with an electrical capacity exceeding 5 kW has been developed. The team also fabricated a portable fuel cell with a capacity of 1 kW.

Additionally, the Fuel Cell Team at ITRI's Materials and Chemical Engineering Research Laboratories has been engaged in the technological development of membrane electrode assemblies, fuel cell stacks, and power generation system integration for PEFCs and direct methanol fuel cells (DMFCs) for many years. The team developed DMFC products and introduced them to power applications for field-monitoring systems. Furthermore, lightweight high-output PEFCs have been incorporated into unmanned aerial vehicles (UAVs) to provide a long-duration flight power supply. For the same weight, the flight time is two to three times longer than that of lithium batteries. This team's high-efficiency hybrid power control integration technology also enables adjustment of the output between fuel cells and lithium batteries, achieving long-term stable UAV flight.

Various technologies have been developed in the field of battery development, creating business opportunities for industries both in Taiwan and overseas.

The development of lithium batteries began in 1993, and by 1996, lithium batteries using lithium cobalt oxide were developed and established a production line in collaboration with another company. In 2000, prismatic lithium–manganese dioxide battery technology was developed and transferred to a company that contributed to mass production in Taiwan. STOBA, a functional polymer material with a nanosized tree-like structure, was developed in 2009. This material forms a protective layer during abnormal heating, inhibits lithium-ion movement, and safely stops the batteries. This technology was transferred to domestic and international manufacturers, enabling them to enter the international battery supply chain and stimulate growth in Taiwan's battery industry.

Since 2010, ITRI has developed numerous batteries and related materials. These include the ChemSEI-Linker, a Nanoscale thin film for cathode materials that extend battery durability and life; URABat, an aluminum battery capable of high-speed charging and discharging, which was developed in collaboration with Stanford University; network amide epoxy polymer electrolyte (NAEPE) used in solid lithium-ion batteries to improve the safety of lithium batteries; and a battery array system that utilizes waste batteries. These innovations have been successfully applied in the industry.

(2) National Taiwan University of Science and Technology

The National Taiwan University of Science and Technology specializes in science and technology, and is located in Taipei City, Taiwan. Originally established as the National Taiwan Institute of Technology, the university was founded to cultivate specialized technical personnel and managers necessary for Taiwan's economic and industrial development. Reorganized as a university in 1997, it now has five campuses, including a main campus in the Taipei area and additional campuses in Tucheng, Keelung, Gongguan, and Zhubei, and six colleges offering programs in engineering, electrical and computer engineering, business administration, design, liberal arts and social sciences, and applied sciences. It comprises approximately 10,000 undergraduate and graduate students.

The "Sustainable Electrochemical Energy Development Center (SEED)[88]," led by Professor Bing-Joe

[88] See also the base website for more information. https://seed.ntust.edu.tw/index.php

Huang, one of Taiwan's most renowned experts in electrochemistry and a National Lecturer, focuses on two core development areas: "battery technology" and "hydrogen energy conversion technology" for industrial applications. These are combined with two foundational technologies – "advanced materials analysis technology" and "theoretical calculation and simulation technology" – to pursue research and development in the following areas: (1) batteries for electric vehicles, (2) batteries for extreme environments, (3) sustainable energy storage batteries, (4) P2X electrolysis technology[89], (5) thin film technology, and (6) hydrogen energy applications. The center has established cooperative relationships with research institutions in Germany, Sweden, the United States, and Russia. It is conducting joint research with Japanese research institutions, including Kyoto University, Tokyo Institute of Technology, Hokkaido University, and NIMS. In particular, the center has a long-standing cooperative relationship with the University of Münster in Germany. It has been conducting a project (LiBEST) on the development of high-efficiency, high-safety lithium-ion battery technology for more than five years under a bilateral joint research program between Taiwan and Germany. We are also jointly implementing the M.ERA-NET project (Achillies) to develop a new type of lithium-silicon sulfide high-energy battery with a stable cycle. Furthermore, under Horizon Europe's "Battery 2030+" initiative, the university is collaborating with Uppsala University to develop and utilize field scanning electron microscopy (SEM) and field transmission electron microscopy (TEM) technology to directly observe lithium precipitation and dendrite growth through an anode-free cell structure, and combined this with X-ray electron spectroscopy techniques to investigate the composition of the SEI interphase membrane (solid electrolyte interphase membrane). SEED has actively engaged in industry-academia collaborations and implemented over 130 projects in the past five years.

(3) National Taipei University of Technology

Established in 1912, National Taipei University of Technology is one of the oldest universities in Taiwan. It competes with the National Taiwan University of Science and Technology for the title of top industrial university in Taiwan. More than 10% of Taiwanese corporate founders, board members, and CEOs are said to be alums of this university, which comprises seven colleges, 19 departments, and 56 programs (34 master's and 22 doctoral programs). More than 13,000 students are currently enrolled. University places equal emphasis on research and practical applications. In 2022, it established the Frontier Institute of Research for Science and Technology to develop cutting-edge technologies and cultivate talent through close collaboration with industry.

The "R&D Center for Nano-Optoelectronic Magnetic Materials," led by Professor Sea-Fue Wang, who is ranked first in Taiwan for SOFC-related literature, focuses on researching materials such as ceramics, functional nanopowders, nanodiamond materials, nanocatalysts, and the optoelectronic applications of organic polymers. The center engages in research and development, industry-academia collaboration, technical training, and evaluation services, specifically focusing on intermediate-temperature Solid Oxide

[89] Conversion of electricity into other energy and other forms of energy. There is P2H (Power to Heat), which converts to heat such as hot water and ice making, and P2G (Power to Gas), which converts to gaseous fuels such as hydrogen and methane by using electrolysis of water (water electrolysis). (Maru Wakari Denryoku Digital Revolution Keyword 250, published by the Newspaper Department of the Japan Electric Association)

Fuel Cells (IT-SOFC). This center is involved in developing new electrolytes and cathode materials, designing and manufacturing large-area IT-SOFC unit cells and stacks, and evaluating the life and failure mechanisms of IT-SOFC stacks. The university participates in the Taiwan Hydrogen Fuel Cell Partnership alongside the National Cheng Kung University, which aims to promote the industrialization of hydrogen and fuel cells. Additionally, in 2009, the university signed a memorandum of understanding (MOU) with NIMS regarding research collaboration on fuel cells.[90]

(4) National Taiwan University

The National Taiwan University is headquartered in Taipei City, Taiwan. Established in 1928 during the Japanese colonial period at Taipei Imperial University, it was renamed the National Taiwan University after the World War II. In the 2024 QS World University Rankings, National Taiwan University was the only Taiwanese university ranked within the top 100 globally, at 69th. This makes it Taiwan's top university. The university comprises 16 colleges, three professional schools (dentistry, veterinary medicine, and pharmacy), and 58 undergraduate programs, including 56 departments and two dual-degree programs. It also has 146 research institutions and 35,000 undergraduate and graduate students, making it a large institution.

The Department of Chemistry consists of 33 full-time faculty members, five part-time faculty members, and eight visiting professors who specialize in analytical chemistry, organic chemistry, inorganic chemistry, physical chemistry, and chemical biology. Professor Ru-Shi Liu, one of the top researchers in lithium-air battery-related literature, is affiliated with this department, which has approximately 600 students enrolled in undergraduate and graduate programs. Additionally, the Department of Chemical Engineering at the College of Engineering, led by Professor Nae-Lih Wu, conducts research on battery-related technologies, including studies on metal oxide electrode materials.

(5) National Cheng Kung University

The "Hierarchical Green Energy Materials Research Center (Hi-GEM)[91]," established in 2018 with funding from the Ministry of Education and the National Science and Technology Council (NSTC), is primarily responsible for related research. Hi-GEM is led by faculty members from the Departments of Materials Science and Engineering and Chemical Engineering. Hi-GEM research focuses on energy storage (solid batteries, secondary batteries, and supercapacitors) and energy conversion (solar and fuel cells). Notable achievements include the development of high-performance gel-like solid electrolytes compatible with liquid electrolyte production lines, high-performance silicon-carbon anode materials, low-resistance nanocomposite cathode materials for low-temperature solid oxide fuel cells, and high-ion-conductive composite electrolytes. Hi-GEM includes faculty members from the National Taiwan University, National Tainan University, National Tsing Hua University, National Yang Ming Chiao Tung University, National Taiwan University of Science and Technology, and Yuan Ze University.

Hi-GEM also conducts joint research with institutions in the United States, Japan, Germany, the United

[90] See NIMS website. https://archive.nims.go.jp/news/archive/2009/12/vk3rak000000t0uk.html
[91] See location websites. http://higem.ncku.edu.tw/index.php?lang=cht

Kingdom, and France. The Hi-GEM facilities are located in the central areas of Shalun Smart Green Energy Science City, Tainan Technology Industrial Park, and Southern Taiwan Science Park. They have also been established by several major green-energy manufacturers. The goal is to establish a green energy R&D hub in southern Taiwan. Additionally, Hi-GEM launched an advanced battery materials industry alliance with the National Tainan University Lithium Battery Research and Development Center and is promoting regional and corporate collaboration.

(6) National Yang Ming Chiao Tung University

It was founded in 1975 at National Yang Ming Medical College. In 1994, it was upgraded to the National Yang Ming University, becoming Taiwan's first comprehensive university with a medical school. On February 1, 2021, the university merged with National Chiao Tung University, which is renowned for its electronics engineering program. This merger resulted in the formation of a comprehensive university. In 2019, the university established the Smart Science and Green Energy College within Shalun Smart Green Energy Science City. This made the university an important partner in the industry-academia research community in the Tainan region.

For over 12 years, Professor Jeng-Kuei Chang's team in the Department of Materials Science and Engineering has conducted research in energy storage materials with support from the National Science and Technology Council's Long-Term Special Research Program and the Taiwan-Germany Joint Research Program. The team has achieved significant technological advancements, including the development of ion–liquid electrolyte materials for lithium batteries that are safe, flame-resistant, and tolerant to high temperatures and voltages. The team also promoted industrial applications by collaborating with domestic manufacturers.

Through unique research on the structural design of anions and cations in ionic liquids, formulation of lithium salts, and selection of cosolvents and additives, universities have made significant contributions to improving the stability and safety of lithium-ion batteries under high-voltage conditions. The university conducts joint research on electrolytes at Kyushu University and the Herz-Helmholtz Institute in Germany. The university is engaged in a wide range of R&D activities related to energy storage materials and technologies. These activities include synthesizing cathode and anode materials for lithium batteries, developing solid electrolytes, and researching high-charge and high-voltage charging and discharge power supercapacitors, sodium batteries, aluminum batteries, and magnesium batteries. The university achieved concrete results in these areas.

(7) Chang Gung University

Chang Gung University is a private university located in Taoyuan, Taiwan. It was founded in 1987 as the "Chang Gung Medical College by Yung-ching Wang and Yung-tsai Wang, founders of the Taiwan Plastic Group." The university later expanded to include engineering and management colleges to support national economic development. In 1997, it was renamed "Chang Gung University." This university is renowned as a College of Medicine. Currently, approximately 7,300 students are enrolled in this study.

In October 2007, the university established a "Green Technology Research Center" to address the growing demand for R&D in green energy and environmental protection technologies. The center's key research themes include (1) battery and energy storage technologies, (2) carbon and nitrogen fixation and hydrogen energy technologies, (3) renewable and new energy technologies, and (4) circular economy and green process technologies. Chang Gung University is among the Taiwanese universities with the highest number of publications related to PEFCs. The university has active industry-academia collaborations with the Taiwan Plastic Group and the Ming Chi University of Technology, both of which were established by the same group. Chang Gung University researchers are involved with the "Center for Environmental Sustainability and Human Health" at Ming Chi University of Technology. They collaborated on PEFC research based on membrane processing research developed through studies on water treatment and resource sustainability.

(8) Yuan Ze University

Yuan Ze University is a private university founded in 1989 by the Far East Group, a leading Taiwanese conglomerate in Taoyuan City. The university has five departments: Engineering, Informatics, Management, Humanities and Social Sciences, and Electrical and Communication Engineering. More than 9,000 students were enrolled in undergraduate and graduate programs. Although Yuan Ze University is relatively new, it was the first and only university in Taiwan to receive a National Quality Award from the Executive Yuan in 2003. In 2005, the university received the Ministry of Education's Excellence in Education Award. Yuan Ze University is one of Taiwan's top 12 universities and has achieved the highest honors in education, research, and administration, leading the way in Taiwan's higher education sector.

Professor Guobin Zhong, a frequent contributor to top-ranked literature on water electrolysis, serves as deputy director of the "Fuel Cell Center[92]." Founded in 2000, with the support of the Energy Technology Research and Development Program from the Ministry of Economic Affairs (MOEA), Taiwan became its first interdisciplinary fuel cell center. With continued support from the MOEA, the center is engaged in developing key technologies for high-efficiency, low-cost fuel cells and key components for high-temperature solid polymer fuel cells. The center also conducts collaborative research with other government agencies, including the National Science and Technology Council, National Chung-Shan Institute of Science and Technology, and National Atomic Research Institute. In 2006, the center was selected for the "Top University Program" by the Ministry of Education, and upgraded to a national fuel cell center for international research and development. The center is located within Yuan Ze MicroScience Park in Zhongli City, Taiwan. Its research and development projects include key electrolyte membrane materials, nanostructured membrane electrodes, catalyst technology, gas diffusion layer and runner design, alternative materials for bipolar plates, water management and simulation, single-cell and battery stack technology, and electronic power and battery system integration. In addition to technological development, the center cultivates scientific and technological talent essential for the growth of Taiwan's fuel cell industry.

Since 2022, Professor Guobin Zhong has led the "Electrolyte Energy Storage Technology and Green Hydrogen Application Service Industry Consortium" project with the support of NSTC[93]. This project

[92] https://www.fuelcells.org.tw/
[93] For more information on the project, see the following website: https://www.mech.yzu.edu.tw/index.php?do=edm&id=298

aims to advance the research and development of proton exchange membrane (PEM) technology through an industry-academia consortium while striving to complete and strengthen the PEFC industrial chain. The project seeks to establish a "net-zero emissions" industrial chain by integrating upstream, midstream, and downstream energy-related industries. The PEM electrolysis technology, which produces hydrogen, oxygen, and ozone, can be used to cultivate talent in the application and conversion of green hydrogen and low-carbon ozone technologies for use in energy storage, engine purification, semiconductors, green pharmaceuticals, and other fields.

Major Companies

Similar to the semiconductor supply chain, battery technology is expected to be innovative and will lead to economic transformations in Taiwan. It is also considered a key component of the EV industry and is at the center of active research and development in Taiwan's electrochemistry industrial sector. This section summarizes the major company trends in Taiwan based on various publicly available materials.

(1) Battery Manufacturers

As the demand for electric vehicles and energy-storage facilities increases, so does the global production of lithium-ion batteries. In Taiwan, many companies have recently invested in raw battery materials, cells, and modules. Taiwan Cement Corporation (TCC), the largest cement manufacturer, Hon Hai Precision Industry Co., Ltd. (Foxconn), Formosa Plastics Group (Formosa), and CPC Co. (CPC) invested 43 billion NTD (206.4 billion JPY) in this sector.

Taiwan's battery supply chain can be divided into three categories: upstream materials, midstream batteries (i.e., battery cells), and downstream battery modules. Upstream raw battery materials account for over 60% of manufacturing costs and are critical. Taiwan's domestic supply of cathode materials is less than 30%, whereas that of anode materials is only 15%. Nearly all raw materials for battery cells are imported, primarily from Japan and South Korea, except for conductive carbon, electrode materials, and insulating films. Mechema Chemicals International Corp. and CoreMax Corp. supply cobalt sulfate and nickel sulfate for Nickel Cobalt Aluminum (NCA) ternary batteries, and Advanced Lithium Electrochemistry (Cayman) Co. (Aleees) supplies cathode materials for lithium iron phosphate (LFP) batteries. China Steel Co. (CSC) and Long Time Technology Co., Ltd. were used as anodes. RPC Corp. and BenQ Materials Corp. handled the electrolyte and separator film development, respectively.

In terms of battery cell development, local manufacturers in Taiwan are still in the early stages of mass production and lag significantly behind their Japanese and South Korean counterparts. Battery cells are a core component of electric vehicles and require substantial initial investments; thus, major companies have entered the market. These include Hon Hai Precision Industry Co., Ltd., Taiwan Plastic Group (a leading petrochemical company), and E-One Moli Energy Corp. (Taiwan's largest lithium-ion battery manufacturer and subsidiary of the Taiwan Cement Corporation). These companies produce LFP and ternary system batteries. Additionally, GUS Technology, a start-up founded by former researchers at the Central Research Institute, manufactures lithium titanate battery cells. These four companies have constructed manufacturing facilities with a combined capacity exceeding 1 GWh by the 2023 fiscal year, and other companies, such as Amita and ProLogium, are also investing in this sector. Hon Hai aimed to produce electric vehicles and launched the MIH (Mobility in Harmony) Consortium, an open platform with over 2,500 global participants.

Taiwan has a strong competitive advantage in downstream battery modules and assemblies. Taiwan accounts for 40% of the global battery module production. Shin-Etsu Polymer (SMP), with annual sales exceeding 90 billion NTD (432 billion JPY), is a leading manufacturer in this sector.

Table 3-3-8 Summary of Major Taiwanese Companies in the "Storage Battery Sector"

	Company Name	Outline/Features
Cathode material	**Mechema Chemicals International Corp. (Mechema)**	The company primarily produces ternary cathode materials made from cobalt sulfate and nickel sulfate. It also extracts precious metals using metal recovery technology. Ten years ago, the company partnered with Toda Kogyo Corp. of Japan. As a result, its products are now used in Panasonic batteries and Tesla electric vehicles.
	Advanced Lithium Electrochemistry (Cayman) Co., Ltd. (Aleees)	Founded in 2005, it is the oldest LFP battery company in Taiwan. It is one of the few companies outside China with manufacturing technology and patents for LFP battery cathode materials. Its products are used in Panasonic batteries and Tesla electric vehicles.
	CoreMax Taiwan Corporation	With the support of the Ministry of Economic Affairs, the company entered the research, development, and production of battery materials in collaboration with ITRI in 2000. The company produces cobalt products. In 2010, the company began producing nickel sulfate. Currently, the company produces cobalt sulfate and nickel sulfate, both of which are used in ternary cathode materials. The company is building a new factory in Vietnam and plans to start mass production in 2025.
Anode material	**China Steel Chemical Corporation (CSCC)**	It is a subsidiary of the China Steel Group and the only coal chemical manufacturer in Taiwan. Using coal tar pitch as a raw material, it manufactures meso-phase carbon powder , which is used as a negative electrode material for lithium-ion batteries. The company is also engaged in developing high-capacity negative electrode materials.
	Long Time Technology Co., Ltd.	The company is the only specialized manufacturer that researches and produces three types of graphite materials (natural graphite, synthetic graphite, and mesocarbon microbeads) that are used as anode materials for lithium batteries. The company derives approximately 70% of its profits from these materials (14% from natural graphite, 48% from synthetic graphite, and 8% from mesocarbon microbeads). It collaborates with National Taiwan University and the Chung-Shan Institute of Science and Technology and has a technical partnership with Talga Group, an anode material manufacturer in Australia.
Electrolyte	**RPC Corporation**	The company is located in Taipei and develops and manufactures rechargeable batteries, including lithium-ion polymer, nickel-cadmium, and nickel-metal hydride batteries.
Insulator film	**BenQ Materials Corp.**	The company manufactures functional materials, such as polarizing plates and battery separators. It ranks fourth in the world in polarizing plates for televisions and notebook PCs. In 2010, the company established a joint venture with Chery Automobile in China and began researching and developing separators.

Cell	**Hon Hai Precision Industry Co., Ltd. (Foxconn)**	• Aiming to build an EV ecosystem, the company will construct the "Taiwan Battery Cell R&D and Pilot Production Center " in Kaohsiung. The company plans to begin producing 1 GWh-scale lithium iron phosphate (LFP) batteries in June 2024. Additionally, the company is investing 35 million NTD (approximately 168 million JPY) to collaborate with six domestic universities (National Taiwan University, National Taiwan University of Science and Technology, National Tsing Hua University, National Yang Ming Chiao Tung University, National Cheng Kung University, and National Tainan University) and ITRI. Together, they will conduct research and development on battery components, including solid-state batteries, and cultivate talent in this field. • To advance EV development, the company is promoting the MIH (Mobility in Harmony) consortium, an open platform with 2,300 participating companies (as of February 2023), aiming to accelerate Taiwan's electric vehicle industry. • The company is also collaborating with the electric motorcycle start-up Gogoro and the Indonesian government to jointly develop battery swapping technology.
	Formosa Smart Energy Tech Corp.	Taiwan Plastic Group subsidiary Taiyo New Intelligent Technology was established in 2022. The company plans to invest approximately 6 billion NTD (28.8 billion JPY) in the first phase at the Zhangbin Industrial Zone to construct a 2.1 GWh LFP battery cell factory and a 2.1 GWh LFP battery module factory, with completion scheduled for 2024. In the second phase, the company will invest approximately 10 billion NTD (48 billion JPY) to construct a battery cell factory with a capacity of 2.9 GWh and a battery module factory with a capacity of 2.9 GWh, with completion scheduled for 2027. The Taiwan Plastic Group can source over 70% of its battery materials from within its own group, including Formosa Lithium Iron Oxide Corporation (cathode materials), Formosa Mitsui Advanced Chemicals Co., Ltd. (electrolyte), and Nan Ya Plastics Corp. (copper foil), aiming for one-stop manufacturing of batteries. The company began developing lithium mines in 2021. Additionally, to reduce lithium procurement, it is collaborating with Ming Chi University of Technology to develop technology for recovering and reusing lithium from used lithium batteries. In September 2023, the company announced a 220 million NTD (1.056 billion JPY) investment to establish an industry-academia collaboration (2023–2027) with the Ming Chi University of Technology's Battery Research Center of Green Energy, aiming to construct a "solid-state lithium battery prototype production line[94]." The company is also implementing scholarships for doctoral students to secure talent.
	E-One Moli Energy Corp.	This company, a subsidiary of Taiwan Cement, is Taiwan's largest lithium-ion battery manufacturer. It specializes in ternary-system batteries based on cell technology from the Canadian company Molicel. The company has 25 years of experience developing batteries and currently has a production capacity of 1.5 GWh. It plans to build a 1.8 GWh production plant in Kaohsiung Xiaogang by 2023 and a 2.8 GWh plant in Canada by 2027. Its products include electric off-road motorcycles, electric wakeboards, electric vertical takeoff and landing (eVTOL) aircraft known as "flying cars", and the world's fastest electric vehicle (EV) hypercar, the "Rimac Nevera ." Its customers include the British appliance manufacturer Dyson.
	Amita Technologies Inc.	The company manufactures ternary, LFP, and lithium titanate batteries for electric boats. It is also developing hybrid solid-state batteries jointly with ITRI. In 2017, the company received an investment from Energy Absolute Public Company Limited (EA), a major Thai energy company. It began operating a battery cell factory in Thailand with a 1 GWh production capacity for ternary batteries. The company plans to increase the factory's battery production capacity to 2 GWh by the end of 2023.

94 https://www.fpg.com.tw/esg/tw/news/media/89

Cell	**ProLogium Technology Co., Ltd.**	Founded in 2006, the company was one of the first in Taiwan to enter the field of developing all-solid-state batteries. Through a technical partnership with Mercedes-Benz, the company developed and released oxide-based solid-state batteries that use ceramic solid electrolytes. In collaboration with the venture company Gogoro, the company developed solid-state batteries for motorcycles. The company has announced plans to invest 5.2 billion euros (approximately 878.8 billion JPY) in Dunkirk, France , to build its first overseas solid-state battery mega-plant.
	GUS TECHNOLOGY, CO., Ltd.	Founded in 2015 by Zhongile Zhang , a former Central Research Institute researcher, and other materials researchers, this emerging company has been operating for eight years. It is constructing a 1 GWh battery factory in the Zhongli Industrial Park in Taoyuan, which is scheduled for completion in April 2023. The company manufactures lithium titanate battery cells and will become the fourth GWh-class battery cell manufacturer in Taiwan, supplying batteries to Japanese companies such as Toshiba and Kaneka. The company received the "Taiwan SMEs Innovation Award 2022 " from the Ministry of Economic Affairs in 2022.
	Phoenix Battery Corporation	The company is the only manufacturer that produces 100% domestically sourced LFP battery cells and packs. It has also received technology transfer from ITRI and is conducting joint research and development on 4680-type hybrid solid-state batteries.
Module	**Simplo Technology, Co., Ltd.**	The company primarily manufactures and sells lithium battery packs. Its products include battery packs for laptops, tablets, smartphones, wearable electronics, industrial computers, lightweight power batteries, portable power supplies, enterprise server battery packs, and home appliance batteries.

Source: Prepared by APRC based on various public documents

(2) Fuel Cell Manufacturers

In Taiwan, the development of hydrogen energy is in its infancy, and most products are still in the demonstration or R&D stages. Hydrogen fuel-cell-related products are the main commercial products. Taiwan has developed a mature fuel cell industry capable of supplying all necessary materials, components, peripheral products, and end-use battery systems. The total output of Taiwan's fuel-cell industry is projected to reach approximately 4 billion NTD (19.2 billion JPY) by 2023. In response to the growing policy push toward transitioning from fossil fuels to green energy, the government set a policy target in the "2016 Energy Industry Technology White Paper" of "increasing fuel cell device capacity to 60 MW by 2025" and has implemented various measures to promote the adoption of fuel cells.

Since 2017, the National Communications Commission (NCC) has implemented a subsidy program under the "Disaster Power Supply Enhancement Plan for Mobile Communication Base Stations." The program provides backup power for a set period in areas with poor communication infrastructure in the event of a disaster. As part of this initiative, fuel cells were installed at 18 locations, including communication hubs and railway signal systems. In 2018, the Energy Administration of the MOEA implemented a " subsidy allocation for stationary fuel-cell power generation systems." This program provides subsidies of up to 70,000 NTD (336,000 JPY) per kilowatt (kW) for installing fuel cells with capacities ranging from one to 500 kW at private companies, schools, medical institutions, and other facilities. As of 2021, 48 fuel cells have been installed under this program. Recently, projects have been underway to integrate fuel cells into vehicles such as buses, scooters, and ships. Additionally, smart communities, such as the Shalun Smart Green Energy Science City, are being integrated into a smart grid system that serves as a single power supply network equipped with fuel cell-based backup power.

KAORI Heat Treatment Co., Ltd., CHEM, Toplus Energy Corp., and hiPower Green Tech provided the systems for the installation of stationary fuel cell power generation systems. The APFCT supplies systems for scooters, and the YC Synergy provides systems for ships. However, most fuel cell applications in Taiwan are limited to backup power sources, and most markets are located outside Taiwan. High-quality fuel cell products and their related key components are supplied to international manufacturers at competitive prices. For example, Bloom Energy, a major U.S. fuel cell manufacturer, receives hot boxes for SOFCs from the High-Power Heat Treatment Industry in Taiwan, as well as interconnect plates and their coatings from Taiwanese manufacturers.

Table 3-3-9 Major Taiwanese Companies in "Fuel Cell Field" and "Water Electrolysis Field"

Sort	Company Name	Outline/Features
System	Chung Hsin Electric & Machinery Manufacturing Corporation (CHEM)	The company's main products are insulated switchgear, generators, and power automation systems. In 2008, however, the company established a New Energy Research and Development Center and began developing hydrogen energy technology and fuel cells. Leveraging the strengths of industry, academia, and research, the company successfully applied for numerous technical patents and National Demonstration Verification Programs (NDPs), becoming the first Taiwanese manufacturer to officially enter the fuel cell operation business.
	hiPower Green Tech	The company has developed hydrogen energy technologies, including methanol-fueled hydrogen generators, hydrogen-rich tail gas recovery and purification systems, and microgrid power sources. It has also provided fuel cells that use methanol as fuel.
	M-FIELD Energy LTD.	For over 10 years, the company has been investing in fuel cell technology, primarily focusing on stationary fuel cell systems. It provides fuel cell solutions that utilize hydrogen and sodium borohydride.
	Toplus Energy Corporation	The company was established in 2008. Its core is the fuel cell team at the ITRI Green Energy Research Laboratory. The company designs and manufactures fuel cell stacks in-house. Its stationary polymer electrolyte membrane (PEM) fuel cell systems supply power ranging from 5 to 100 kilowatts and have been used successfully as standby power supplies for various industries, including communications, railways, and fire inspection.
	YC SYNERGY CO., LTD.	The company is one of the few high-output fuel cell system manufacturers in Taiwan. It serves the large-scale power generation system market (15 kW to several MW) with products for power plants, commercial fuel cell vehicles, ships, and other applications. The company is partnering with the German fuel cell company EKPO to promote the PEMFC (proton exchange membrane fuel cell) market.
	Asia Pacific Fuel Cell Technologies, Ltd . (APFCT)	The company develops hydrogen energy environmental solutions, including solid polymer fuel cell systems for light electric vehicles, such as scooters and carts. The company also develops hydrogen storage and refueling systems. With over 20 years of experience developing fuel cells, the company collaborates closely with world-renowned companies to provide reliable, stable, and efficient components.

Sort	Company Name	Outline/Features
System	KAORI HEAT TREATMENT CO., LTD.	Through its pursuit of innovative heat treatment technologies and continuous research and development, the company has successfully developed key components and system equipment for many industries, including plate heat exchangers and rollers. The company supplies hot boxes to Bloom Energy , a U.S. fuel cell manufacturer, and provides PEMFCs and hydrogen generators that use methanol and natural gas as fuel. These products are manufactured in-house.
	Delta Electronics, Inc.	Founded in 1971, the company specializes in charging devices and EV transmission systems. The company has entered into a technology transfer and licensing agreement with a subsidiary of the British fuel cell manufacturer Ceres Power regarding solid oxide electrolyte cell (SOEC) and solid oxide fuel cell (SOFC) technologies. Production is scheduled to begin at the end of 2026.
Components	Yangtze Energy Technologies, Inc.	The company specializes in manufacturing membrane-electrode assemblies (MEAs) for PEMFCs by providing water-electrolyte membrane-electrode assemblies (WE-MEAs). Its products are supplied to countries around the world, including Japan, China, and South Korea.

Source: Prepared by APRC based on various public documents

Main Research Topics

The Tsai Ing-wen administration's green energy technology policy is based on four pillars: "energy storage," which includes storage batteries, fuel cells, and water electrolysis; "energy conservation," "energy creation," and "system integration." Energy storage systems can be broadly divided into fixed and mobile types. Fixed energy storage is intended for large-scale power plants and as a backup power source for businesses. Fuel cells are being introduced for disaster response information and communication centers, as well as railways. Grid-connected demonstration projects using redox flow batteries are also underway. At the Shalun Smart Green Energy Science City demonstration site, the design and verification of a hybrid energy storage system that combines a vanadium flow battery system and a microgrid is also progressing.

Conversely, mobile energy storage systems using PEM fuel cells have been introduced in small trams and scooters. The research and development of batteries for four-wheeled EVs is an important challenge because these vehicles are expected to drive the future development of Taiwan's electric vehicle industry. With a focus on all-solid-state lithium batteries, research and development are being conducted on innovative materials and designs for cathodes, anodes, and electrolytes. The emphasis was on high energy density, rapid charging capability, safety, and economic viability.

Various related projects are being implemented under the "Green Energy Technology Joint Research and Development Program" using both top-down and bottom-up approaches. Representative research outcomes are presented herein.

(1) Rechargeable Batteries

According to the annual "Overview of Central Government Research and Development" compiled by the National Science and Technology Council (NSTC), the following summarizes recent research and development achievements related to rechargeable batteries.

With regard to lithium-battery development, efforts have been focused on creating highly efficient and safe solid-state lithium batteries. In 2020, the Industrial Technology Research Institute (ITRI) developed a nonflammable, low-cost solid electrolyte called "Networked Amide Epoxy Polymer Electrolyte" (NAEPE) as an alternative to flammable electrolytes. Lithium solid batteries using NAEPE have been verified to possess the high ion conductivity of liquid electrolytes and the safety of solid electrolytes, and this technology won the R&D 100 Award from the U.S. industrial technology journal R&D in the same year. The development and verification of mass production and industrialization are progressing with the cooperation of various companies. In 2021, the company developed a high-performance lithium-metal solid-state battery with an energy density of 350 Wh/kg and a lifespan of 400 cycles. This battery utilizes low-reactivity lithium metal electrolytes, lithium metal protection, ceramic separation, and solid electrolyte technologies. In 2022, the company will develop a lithium metal battery with an energy density exceeding 350 Wh/kg, which will pass safety tests. Practical tests are conducted on electric motorcycles. Additionally, numerous domestic battery cell manufacturers, including Amita Technologies, Inc., J. S. POWER Co., Ltd., and Phoenix Battery Corporation, have adopted NAEPE, successfully upgrading their products and advancing them toward practical applications.

A team led by Professor Jeng-yu Lin of Tatung University developed a synthesis technology for mass-producing layered lithium-rich manganese-based cathode materials for all-solid-state lithium batteries. They also used ion doping technology to stabilize the crystal structure of the cathode material, enhance the ion conductivity, and improve the stability and capacity of the battery. A team led by Professor Chih Chen at National Chio Tung University (now National Yang Ming Chiao Tung University) used an electroplated bicrystalline copper foil as a substrate for Si-based anode materials. They formed lithium-ion batteries with nickel-rich oxide cathodes, thereby increasing the energy density. Professor Chun-Chen Yang's team at the Ming Chi University of Technology developed an oxide solid electrolyte. They applied this material to NCM811 cathode materials in button and soft-pack batteries. A team led by Professor Fu-Ming Wang at the National Taiwan University of Science and Technology (NTUST) developed a solid electrolyte. It is environmentally friendly, water-soluble, inexpensive, and involves a green production process. This effectively improves solid-solid interface issues. They have also enabled the fabrication of high-capacity, lightweight, and high-performance secondary batteries. Additionally, the National Cheng Kung University and National Taiwan University are engaged in electrolyte-related research.

(2) Water Electrolysis

In terms of hydrogen energy development, the field of water electrolysis is still in its infancy, with most products still in the demonstration, research, and development stages. These products focus on the development of low-cost, high-performance hydrogen production technologies. A team led by Professor Ta-Jen Yen of National Tsing Hua University successfully increased the hydrogen production efficiency by nearly 30 times. They achieved this by combining plasmonic nanoantennas with molybdenum disulfide, a catalyst for water electrolysis.

A team, led by Professor Kuan-Wen Wang of National Central University, developed an efficient, stable, and low-cost dual-effect hydrogen production system.

Meanwhile, a team led by Professor Jyh-Cheng Jeng at the National Taipei University of Technology is working on the development of low-cost, highly stable, and highly efficient electrode materials for medium-temperature solid oxide fuel cells, as well as a new type of ammonia decomposition catalyst technology that significantly improves the reaction rates. A team led by Professor Hsiharng Yang at National Chung Hsing University developed non-precious metal catalysts for water electrolysis, reduced device costs, and developed anion exchange membranes and membrane electrodes to effectively improve efficiency. A team led by Professor Tzong-Lin Jay Shieh at the National Taiwan University used solar cell materials for electrolytic hydrogen production, achieving a competitive solar cell-hydrogen efficiency level of 10–15%. Professor Chien-Chieh Hu of the National Taiwan University of Science and Technology developed a composite membrane with high porosity and structural stability suitable for hydrogen separation. During hydrogen storage, a team led by Associate Professor Tsan-Yao Chen and Professor Fan-Gang Tseng of National Tsing Hua University synthesized nanocarbon spheres via zero-template hydrothermal carbonization. It enhanced the hydrogen adsorption efficiency through the hydrogen spillover effect.

(3) Fuel Cells

The fuel cell industry is well-established, and the National Atomic Research Institute of the Atomic Energy Council has a long history of research in this area. Dr. Jun-Liang Chang's team has developed a mass production technology for metal-supported solid oxide fuel cells using atmospheric-pressure plasma spray coating, and the team led by Associate Researcher Ching-Tsung Yu has utilized a new hydrogen production technology combined with carbon dioxide recovery technology to significantly reduce production costs. Another team led by researcher Jui-Yi Li, developed a solid oxide fuel cell that converts fuels, such as hydrogen and natural gas, into electricity while reusing waste heat. This technology achieves high energy-conversion efficiency. Professor Sheng-Wei Li's team at National Central University has developed a ceramic fuel cell that can operate at medium to high temperatures ranging from 400 to 700° C.

3.3.6 International Cooperations

To date, the NSTC has signed 134 cooperation agreements with 43 countries and organizations to promote bilateral and multilateral scientific and technological exchanges. The following are examples of cooperation in the field of electrochemistry between Germany and Sweden. In 2017, Taiwan's Ministry of Science and Technology and German Federal Ministry of Education and Research (BMBF) implemented the Taiwan-Germany Battery Joint Research Program, which aims to improve the performance and safety of lithium-ion batteries. Taiwan has a foundation in core materials for lithium-ion batteries, battery assembly, and battery system testing. In contrast, Germany has strengths in terms of practicality, rigor, and safety of its technology. This collaboration aims to strengthen R&D by integrating the technologies of the two countries to improve the performance and reliability of lithium-ion batteries and promote their application in the battery industry. In October of that year, three joint research projects were launched: "LiBest: Lithium-ion Batteries with High Electrochemical Performance and Safety Technology" (National Taiwan University of Science and Technology, Professor Bing-Joe Huang); "HighSafe: Sustainable, Environmentally Friendly, Safe, and High-Energy-Density Lithium Batteries (Materials, Cells, and Models) (National Tsing Hua University, Professor Chi-Chang Hu); and "EVABATT: Evaluation of an Advanced

All-Solid-State Battery Concept Achieving High Safety and Performance." From 2017 to 2020, NSTC and BMBF provided annual funding ranging from 1 to 1.5 million EUR. All projects target the development of new lithium-ion batteries with high energy densities and efficiencies. They focused on four key cell materials: electrodes, electrolytes, additives, and separators. This collaboration extends beyond the universities. Taiwanese research teams work with industry to facilitate business exchanges between Taiwanese and German battery cell material manufacturers. The BMBF conducted a second call for lithium-ion battery proposals in 2020. They selected the LiBest and HighSafe projects and launched a new project: "Adambatt: Advanced Applied Materials for Solid-State Batteries" at National Cheng Kung University with Professor Hsi-Sheng Teng.

Regarding cooperation with Sweden, the former Ministry of Science and Technology signed a "Memorandum of Understanding on Science and Technology Cooperation" with the Swedish Foundation for Strategic Research (SSF) in August 2019. They also launched a call for proposals for the "Sweden-Taiwan Joint Research Program," which targets information and communications technology, biotechnology, and materials research. Six joint research projects were selected out of 49 applications, including the "Solid Anode-Less Lithium Battery" project in the field of batteries (National Taiwan University of Science and Technology, Professor Bin-Joe Hwang). The SSF will provide 60 million SEK (approximately 840 million JPY) over five years. Up to 25% of the project funds from the SSF may be transferred to the Taiwanese research team. In addition, Taiwan will provide 50 million NTD (approximately 240 million JPY) in support.

3.3.7 Large-Scale Research Infrastructure

(1) Shalun Smart Green Energy Science City

The largest policy initiative related to electrochemistry in Taiwan is the development of Shalun Smart Green Energy Science City. Conceived in 2016 when the Tsai Ing-wen administration took office, it continuously developed through various policies. This project aims to strengthen energy security, promote a green economy, and establish Taiwan as a key hub for green energy industry development in Asia. As mentioned earlier, the "Forward-looking Infrastructure Development Program" allocates a total budget of 39.8 billion NTD (191 billion JPY) over four phases for green energy research and development, including the development of Shalun. MOEA, Ministry of Science and Technology (MOST), and Tainan City Government are collaborating to implement projects such as the construction of the Greater Tainan Convention and Exhibition Center, Academia Sinica Southern Campus, green energy demonstration site, green energy technology joint research center, and autonomous driving laboratory. Additionally, numerous electrochemistry-related projects have been conducted, as listed in Table 3-3-10.

A green energy demonstration site and green energy joint research center were opened in 2020. The occupancy rate at the demonstration site was 94%. For example, Truewin Technology Co., Ltd., an energy storage solution provider, completed the construction of a lithium battery cell performance testing room, battery management system laboratory, and lithium battery assembly research and development pilot production facility.

Table 3-3-10 Electrochemical Projects in the "Forward-looking Infrastructure Development Program"

Public Construction Plan to Enhance Flexibility in Power System Operation (administered by the Ministry of Economic Affairs) 6.88 billion NTD (33.0 billion JPY) The project involves establishing energy storage infrastructure and related operational models to ensure stable power system operation and introducing energy storage facilities in remote villages, hamlets, and islands.
The Regional Energy Storage Facility Technology Demonstration (administered by Academia Sinica) 260 million NTD (1.248 billion JPY) The project is developing an advanced energy management system for large-scale energy storage and establishing the practical demonstration and widespread adoption of MW-scale and residential energy storage systems. The project will also conduct fundamental research on next-generation all-solid-state batteries, develop high-capacity and high-security composite electrodes, and establish battery material identification technology to secure a leading international position in the field. Additionally, the project is aligning with the domestic industrial chain to establish the research, development, and mass production of next-generation all-solid-state batteries domestically.
Development of a Lithium-Ion Energy Storage System and Research and Development of Next-Generation All-Solid-State Battery Materials at the Academia Sinica's Southern Campus (administered by Academia Sinica): 125 million NTD (600 million JPY). The project integrates basic research and battery energy storage system development. It enhances domestic production capacity for materials and equipment.
Intelligent Electric Bus DMIT Project (Administered by the Ministry of Economic Affairs and the Ministry of Transportation and Communications) 1.625 billion NTD (7.8 billion JPY) The project supports the development of electric buses and their core components. The project also establishes a pilot production process environment and facilities for reliable solid-state batteries, guiding domestic battery manufacturers toward next-generation solid-state battery technology.
Low-Carbon Smart Environmental Infrastructure in a Science City (administered by NSTC) 245 million NTD (1.176 billion JPY) The project consists of nine subprojects, one of which is the "Development of a Low-Carbon Transportation System" in Shalun Smart Green Energy Science City. This subproject will establish a transportation system for low-carbon vehicles, such as electric cars and motorcycles. In collaboration with domestic companies, the project will develop key components for electric buses, including electric motors, lithium-ion batteries, power controllers, and fuel cell packs. Following successful research and development, these components will be introduced to the international market. Additionally, the project will develop a large-scale energy storage system with regional distribution capabilities, as well as the necessary battery materials for this system.

The Green Energy Technology Joint Research and Development Program (administered by NSTC)
1.661 billion NTD (7.973 billion JPY)
Scheduled to run until 2024, this plan focuses on energy creation, conservation, storage, and system integration. The plan consists of developing innovative technologies through a bottom-up approach and developing important applied technologies that meet industrial needs through a top-down approach. Additionally, the program aims to accelerate commercialization by developing human resources and leveraging the Shalun Smart Green Energy Science City ecosystem.
The top-down themes in the energy storage field are as follows:
i) Advanced secondary batteries
The establishment of advanced lithium batteries and supercapacitor technologies with high safety and efficiency. This includes high-energy silicon carbide (SiC) anodes, ternary nickel-rich cobalt-free cathodes, gel electrolytes, solid electrolytes, high-quality adhesives, and high-performance solid electrolyte interfaces, as well as lithium-ion supercapacitors.
ii) Advanced hydrogen storage:
The development of key materials and technologies for hydrogen production, storage, transportation, and applications in the hydrogen energy sector aims to reduce costs, create new markets, and establish and maintain industrial competitiveness.

Source: Prepared by APRC based on various public documents

(2) Science Parks

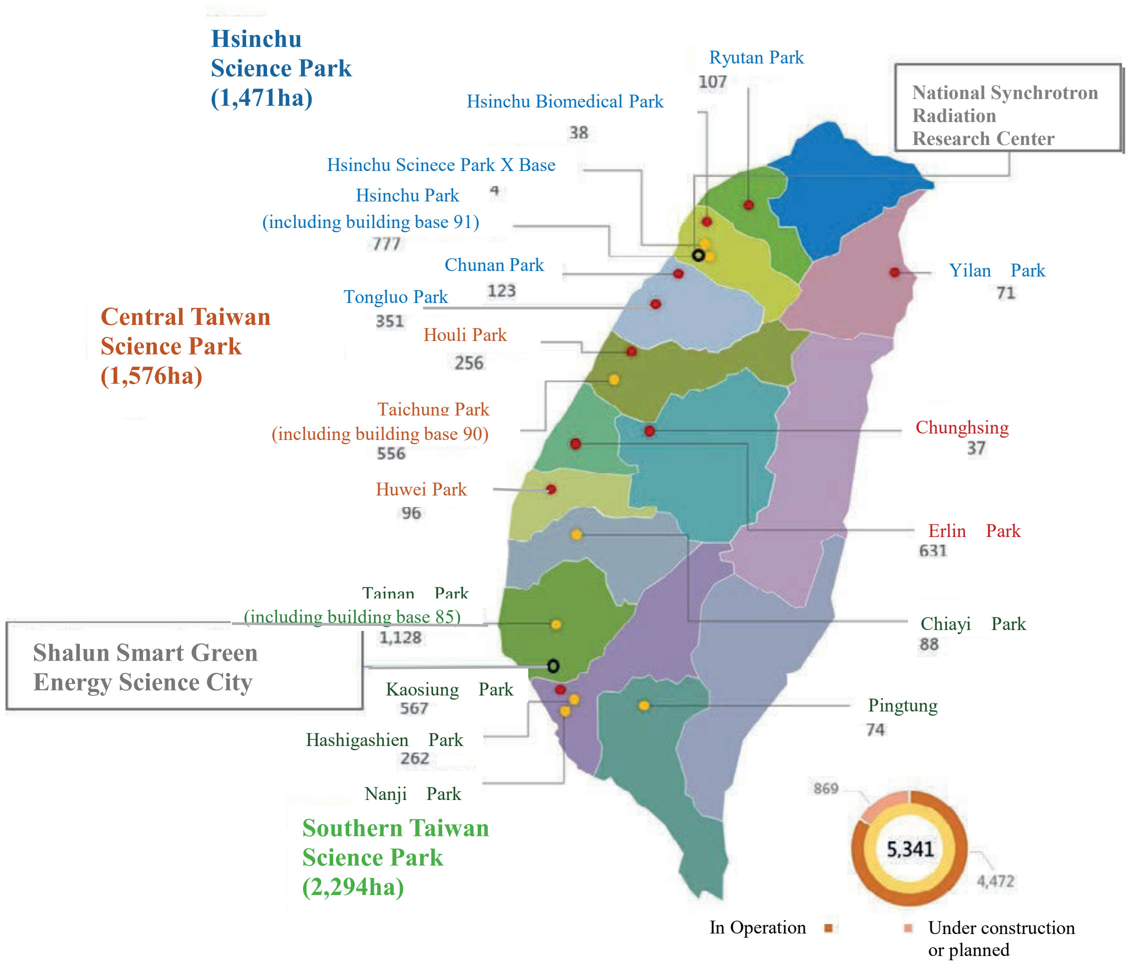
To promote the development of high-tech industries, Taiwan established three science parks: the Hsinchu Science Park in northern Taiwan in 1980, the Southern Taiwan Science Park in southern Taiwan in 1997, and the Central Taiwan Science Park in central Taiwan in 2003. All parks are managed by the NSTC (formerly the Ministry of Science and Technology). These parks have supported Taiwan's industrial development and established its position in the international high-tech industry. This has been achieved through spillover effects on various industries accumulated over the past 30 years, as well as through demonstration and technology dissemination within parks. Southern Science Park, which includes Tainan and Kaohsiung, has established clusters in the optoelectronics, semiconductor, biotechnology, and precision machinery industries. It is actively developing green energy and low-carbon industries. The Shalun Smart Green Energy Science City is located in Tainan Park. Together with existing green energy manufacturers and the surrounding academic research institutions, it forms a " green energy technology and innovative industrial ecosystem."

(3) National Synchrotron Radiation Research Center

The National Synchrotron Radiation Research Center, a research institute under the umbrella of the NSTC, is a large-scale facility used for battery research. Located within Hsinchu Science Park, the synchrotron light source facility at the center is utilized in various fields, including battery material research aimed at investigating material properties, attracting over 2,000 domestic and international researchers annually. The center houses two synchrotron radiation facilities: the Taiwan Light Source (TLS) and Taiwan Photon Source (TPS). The TLS, established in 1993, is the first third-generation synchrotron radiation facility in Asia and the third in the world, featuring a circumference of 120 m, an electron beam energy of 1.5 GeV, and energy bands for UV and soft X-rays. The Taiwan Photon Source (TPS), established in 2016, is one of the brightest synchrotron radiation sources in the world, with a circumference of approximately 520 m and an electron beam energy of 3 GeV. It accommodates 40 beamlines in the soft and hard X-ray energy bands.

In addition to providing a light source, the center has established seven research groups since 2008: molecular science, nanoscience, condensed matter physics, materials science, life sciences, neutrons, soft matter-conducting independent research, and collaborative studies with universities and other institutions. Professor Bing-Joe Huang (National Taiwan University of Science and Technology), a leading expert in Taiwanese battery research mentioned earlier in this section, has published numerous co-authored studies with the center on topics such as the mechanism of dendrite formation in lithium batteries.

The locations of the aforementioned research infrastructure are shown in Figure 3-3-8.



Source: NSTC website, prepared by APRC.

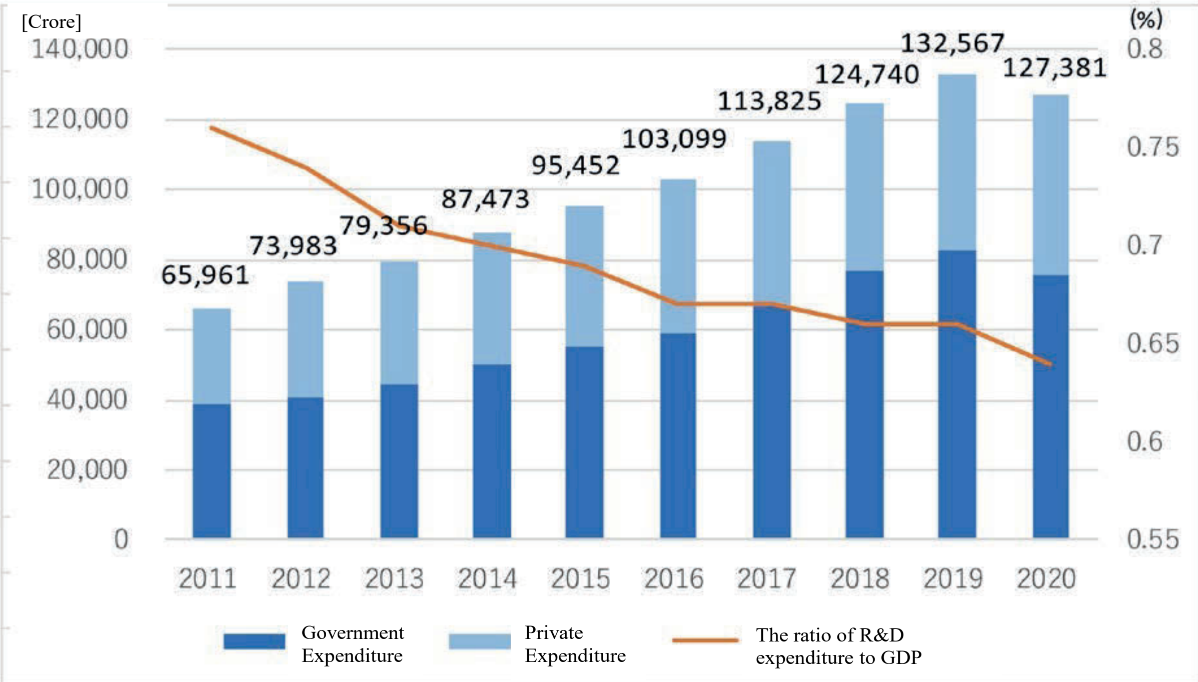
Figure 3-3-8 Map of Science Parks and Other Large Research Infrastructure Locations (as of Q2 2024)

3.4 India

In India, under an economy that continues to expand steadily, with an annual growth rate of 8–10%, the research and development (R&D) of electrochemical devices also shows continuous growth. In particular, collaborative research between industry and academia—both within the country and with leading international institutions—is being promoted, centered primarily around the Indian Institute of Technology

(IIT) Delhi and the Council of Scientific and Industrial Research-Central Electrochemical Research Institute (CSIR-CECRI). Furthermore, as the world's third-largest emitter of CO_2, India has recently seen an increasing focus on clean energy research in certain laboratories equipped with top-tier researchers and research facilities. With electric vehicle (EV) manufacturing designated as one of the nine national missions, future developments are expected to include not only the strengthening of basic research in areas such as water electrolysis, but also the expansion of production lines geared toward industrialization and the fostering of startup companies.

3.4.1 Research Funding

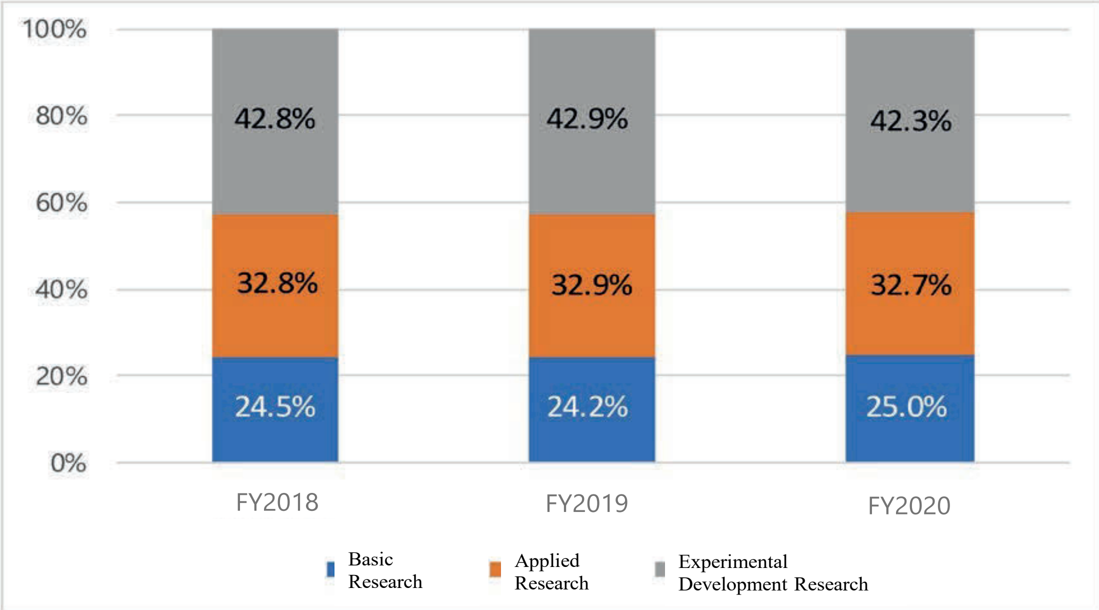


Source: DST S&T Indicators Tables, Research and Development Statistics *2022–23*.[95]

Figure 3-4-1 Trends in R&D Expenditures and Their Ratio to GDP Over Time (Current Prices, Unit: Crore)

Between 2011 and 2019, India's R&D expenditure increased from₹659.61 billion (approximately ¥1.2401 trillion, based on an exchange rate of ₹1 = ¥1.88; ₹1 crore = ₹10 million, same hereafter) to ₹1,325.67 billion (approximately ¥2.4923 trillion), but slightly declined to ₹1,273.81 billion (approximately ¥2.3948 trillion) in 2020. Conversely, the ratio of R&D expenditure to GDP steadily declined from 0.76% in 2011 to 0.64% in 2020 (Figure 3-4-1). This is because the average annual growth rate of R&D expenditure during the period was 7.6%, whereas that of GDP was 9.3%, with the latter outpacing the former. Looking at the breakdown between the public and private sectors, the share of R&D spending by the private sector rose from 41% in 2011 to 44% in 2013 but has generally remained around 40% since then. Notably, the proportion has shown a declining trend since 2018 (Figure 3-4-2).

[95] This statistic was published in June 2023. http://digitalrepository-nstmis-dst.org/



Source: Same as Figure 3-4-1.

Figure 3-4-2 Trends in the Federal Government's R&D Expenditures and Proportions by Research Stage

Looking at the breakdown by "research stage," the proportions of basic, applied, and experimental development research have remained generally balanced over time. Although the share of basic research slightly increased in FY2020, the total budget decreased to approximately ₹85 billion (approximately ¥159.7 billion).

Figure 3-4-3 illustrates the flow of R&D funding in alignment with the R&D system. The federal government oversees the entire system, covering related fields such as universities (basic research), biomedical sciences, renewable energy and environment, and engineering and industry (applied research). Universities receive support primarily through the Ministry of Education, whereas other research institutions are supported via the respective ministries of their associated fields.

Government	IN Government							
Responsible Ministries	MoE	MoHFW	MNRE	MOEF&CC	MST			MoD
Research Funding Agencies	UGC	ICMR	AREAS/SN As	Not known	DSIR	DST	DBT	Not known
Research Institutions	University	University	NISE, NIWE, NIRE, REDA	NCSCM etc.	CSIR	SERB TDB		DRDO
Research Filelds	All fields except medicine	Medicine	Renewable Energy	(Alpine/forest /wildlife)*	Science Industrial	Science Engineering	Biology Engineering	Defence
Research Stages	Basic Reserach	Basic Reserach	Applied Research	Applied Research	Applied Research	Applied Research	Applied Research	Applied Research

IN Government: Indian Government
MoE: Ministry of Education,
MoHFW: Ministry of Health and Family Welfare
MNRE: Ministry of New Renewable Energy
MOEF&CC: Ministry of Environment, Forest, and Climate Change
MST: Ministry of Science and Technology
MoD: Ministry of Defence

UGC: University Grant Committee
ICMR: Indian Council of Medical Research
AREAS/SNAs: Association of Renewable Energy Agencies of States; State Nodal Agencies
DSIR: Department of Scientific and Industrial Research
DST: Department of Science and Technology
DBT: Department of Biotechnology
CSIR: Committee of Science and Industry Research
SERB: Science and Engineering Research Board

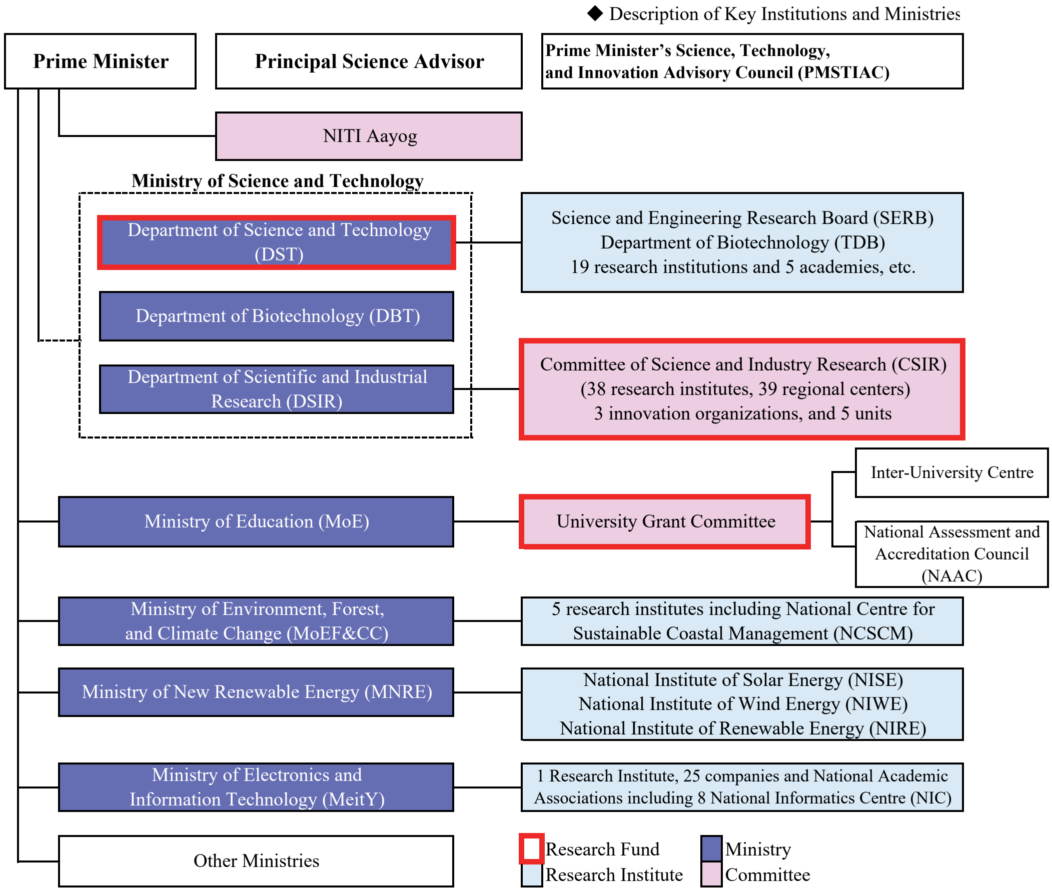
Source: Same as Figure 3-4-2.

Figure 3-4-3 Flow of R&D Funding in Alignment with the R&D System in India

3.4.2 Research Promotion System

Figure 3-4-4 summarizes the organizational structure promoting R&D in India. The DST, under the MST, is responsible for policy formulation, coordination with related organizations, promotion of science and technology with a focus on specific issues, and support for scientific research institutions and academic societies through grants. The MNRE[96] and the Ministry of Electronics and Information Technology actively promote the R&D of storage batteries and hydrogen fuel cells across a broad range of initiatives.

96 Established in 1981 as the Commission for Additional Sources of Energy, it was restructured and renamed in 2006 as the Ministry of Non-Conventional Energy Sources. https://mnre.gov.in/the-ministry/what-does-the-ministry-do/



Source: Compilation based on materials from JST Asia and Pacific Research Center (February 2023).

Figure 3-4-4 India's Science and Technology Administrative Structure

According to the sectoral breakdown for FY2020, approximately 60% of government-sector R&D expenditure in India's federal system came from government sources. Of this, only 6.7% was accounted for by state governments, while the federal government contributed 43.7% (the remaining 10% was self-financed by universities). In terms of both administrative and judicial systems, the federal government holds a dominant position over state governments, maintaining a generally strong, centralized governance structure.[97]

In the broader context of global energy issues, as of 2023, India accounts for 17% of the world's population and under 4% of global CO_2 emissions, making it the third-largest emitter in the world.[98] At COP28, held in Dubai in December of the same year, many challenges in achieving decarbonization goals were highlighted[99]. In recent years, various research institutions have focused on developing water electrolysis technologies.

[97] India R&D Statistics at a Glance 2022–23. However, from the perspective of party politics, in recent years it is not uncommon for decisions made by coalition governments to be overturned due to the influence of small- and medium-sized regional parties. (UEDA Tomoaki, 2015. "Center–State Relations," in Modern India Lecture Series 3: Deepening Democracy, edited by HORIMOTO Takenori and KONDO Norio, University of Tokyo Press, pp. 78–79).

[98] Although India ranks third in the world in terms of total emissions, the percentage varies depending on the source. According to EI statistics, the figure is 8.0% (2.814/35.130 million tons) (https://www.globalnote.jp/post-3235.html#sub_data), while World Bank Open Data reports it as 7.2% (https://eleminist.com/article/2587).

3.4.3 Related Key Policies

The Modi administration envisions coal-fired power generation remaining the primary energy source for the next 30 years, while also significantly increasing the share of renewable energy[100]. As part of its energy policy, the federal government set an ambitious target of achieving net-zero CO_2 emissions by 2070, in line with the Paris Agreement reached in 2015. In response, India submitted its "Long-Term Low-Carbon Development Strategy" to the United Nations Framework Convention on Climate Change in 2022, identifying six key sectors for emissions reduction. The strategy outlines measures, such as promoting the shift to EVs, increasing the use of ethanol-blended fuels to 20% by 2025, and expanding the use of green hydrogen fuel[101].

Since 2022, Ajay Kumar Sood has served as the Principal Scientific Adviser to the Prime Minister. The Prime Minister's Science, Technology, and Innovation Advisory Council has designated "EVs" as one of its nine national missions. Specifically, the mission aims to "develop EVs suited to India's societal needs and promote their production in an economically viable manner, thereby contributing to the reduction of fossil fuel consumption and greenhouse gas emissions." In addition to the DST, the key responsible ministries and agencies include the Department of Heavy Industry, MNRE, Ministry of Power, and government think tank NITI Aayog[102].

Despite establishing such a promotional framework, India initially lacked sufficient domestic manufacturing capacity and relied heavily on imports of battery cells produced in countries such as China and South Korea. According to some reports, the number of imported lithium-ion batteries nearly quadrupled over the four years starting in 2016[103].

However, with a growing population and robust automotive industry, India is viewed as a highly promising and attractive market. According to a report by Research and Markets titled "Global Lithium-Ion Battery Market Forecast 2024–2028," India is emerging as a global manufacturing hub for storage batteries, drawing significant investment. This is driven by the increasing need for reliable energy storage solutions in the renewable energy sector. In addition, initiatives by the Ministry of Heavy Industries through the FAME scheme (an incentive program promoting the adoption of electric and hybrid vehicles) have led to a substantial increase in the number of domestic charging stations.

[99] A domestic media outlet has reported that India has been leading global climate change efforts in recent years. As detailed in section 1.4.6, based on the Paris Agreement, India has set ambitious targets for its Nationally Determined Contributions and has launched the Green Credit Initiative in collaboration with the United Arab Emirates and others (https://ggci-world.in/) to build a platform for dialogue, cooperation, and knowledge sharing on climate change mitigation, https://energy.economictimes.indiatimes.com/news/renewable/cop-28-success-indias-balancing-act-on-the-energy-landscape-and-climate-commitments/106010921

[100] Takahiro Sato and Masaki Ueno (eds.), Complete Guide to the Indian Economy, Hakuto Shobo, 2021, pp. 262–263.

[101] Decarbonizing India: Driving Climate Action through Disclosure. February 2023. CDP India.

[102] JST/APRC Research Report, Survey on Policy and R&D Trends for Scientific and Technological Cooperation with India (FY2021-RR-04), p. 9.

[103] The Hindu, article dated February 12, 2020, https://www.thehindu.com/news/national/four-fold-jump-in-li-ion-battery-imports-since-2016/article30776630.ece

3.4.4 Research Funds and Research Programs

Table 3-4-1 presents the major research funds in India.

Table 3-4-1 Major Research Funding Agencies in India (Ranked by Number of Publications)

Research Funding Agencies	Storage Battery	Fuel Cell	Water Electrolysis
Department Of Science Technology India (DST)	1,831	1,050	211
Council Of Scientific Industrial Research Csir India (CSIR)	814	732	146
University Grants Commission India (UGC)	653	452	137

Source: Compiled by APRC based on Web of Science.

The DST recorded the highest number of published papers across the R&D of all three devices, having provided funding for them. Operating under the MST, the DST plays a central role in promoting science and technology in the country and supports research institutions through its funding programs. Similarly, many individual researchers who have received research support from the DST are also among the most prolific in terms of publications.

The CSIR is an autonomous national research institution under the direct authority of the Prime Minister (further detailed in the annex). The UGC, established in December 1953 and formalized as a government body through an Act of Parliament in 1956, is responsible for setting, regulating, and coordinating standards in university education, examinations (selection), and research.[104] It serves as a key institution in implementing higher education policy. Its budget for FY2023 was 5,360 crore (₹53.6 billion, approximately ¥100 billion yen)[105]. In addition, although not listed in the table, the All-India Council for Technical Education, which primarily oversees engineering education, has maintained a budget of £42 million (approximately ¥8.42 billion, assuming £1= ¥200) over the past three years. The budgets for these four major research funding agencies are said to be on an upward trend in recent years[106].

In line with the policies discussed in section 3.4.3, the Government of India has established a comprehensive national mission policy framework for EV research. Similarly, for research on electrochemical devices and batteries, it has formulated both a comprehensive national mission policy and sector-specific policies (Technology Mission Programs). Each policy outlines specific goals and identifies the institutions responsible for achieving them. As for technologies directly related to the development of electrochemical devices, several types of battery technologies have been designated as priority targets under both the national mission and the "Technology Mission Program on Water and Clean Energy[107]." Several research platforms have been established through collaborations between the DST and various

[104] See the University Grants Commission (UGC) of India, "About UGC," https://www.ugc.gov.in/AboutUGC.aspx.
[105] https://www.indiabudget.gov.in/doc/eb/sbe26.pdf
[106] See the British Council's blog article for details on AICTE's budget and recent trends in educational institutions. https://opportunities-insight.britishcouncil.org/blog/india%E2%80%99s-national-education-budget-2023-24
[107] Accessed on September 15, 2023: Department of Science and Technology website, "Clean Energy Material Initiative (CEMI)," https://dst.gov.in/clean-energy-material-initiative-cemi

universities and research institutions. Many institutions are engaged in R&D focused on storage batteries, hydrogen (fuel cells), and supercapacitor devices.

An overview of the major research programs in India is presented in Table 3-4-2.

Table 3-4-2 Overview of Major Research Programs in India

Device	Research Program	Responsible Ministries / Participating Institutions	Platform Name / Hosting Institution	Principal Scientist(s)
EV	National Mission	DST, DHI, MNRE, Ministry of Power, NITI Aayog	-	-
Battery/ Hydrogen/ Supercapacitor	Clean Energy Material Initiative (CEMI)	IIT Delhi, IISc Bangalore, CGCRI, IICT, IMMT, ARCI-CFCT	Battery Energy Storage Platform DST-IIT Delhi	S. Basu (IIT Delhi)
		IIT Bombay (leader), IIT Guwahati, IIT Kanpur, IIT Tirupati, NIT Rourkela	Hydrogen Energy Storage Platform DST-IIT Bombay	D. Khakhar (IIT Bombay)
		IISc Bangalore (leader), IIT Hyderabad, IIT Madras, CECRI, Pondicherry University	Supercapacitor Energy Storage Platform DST-IISc Bangalore	N.P. Aetukuri (IISc Bangalore) and 3 others
		IISc Bangalore, IIT Madras, IIT Bhubaneswar, Sri Chitra Thirunal College of Engineering	Hydrogen Energy Storage Platform (MECSP) DST-NFTDC	K. Balasubramanian (NFTDC), and 4 Co-PIs
		IIT Kanpur, IIT Madras, CSIR-NIIST, NIT Tiruchirappalli, IIT Guwahati, etc.	Clean Energy Material Acceleration Platform (IC-MAP)	K.S. Nalwa (IIT Kanpur), B.R.K. Nanta (IIT Madras)
		Open to full-time researchers in domestic universities and institutions, technology business incubators (TBIs), and tech startups	National Funding Scheme for Energy Storage Device Design & Development	Ranjith Krishna Pai (DST)

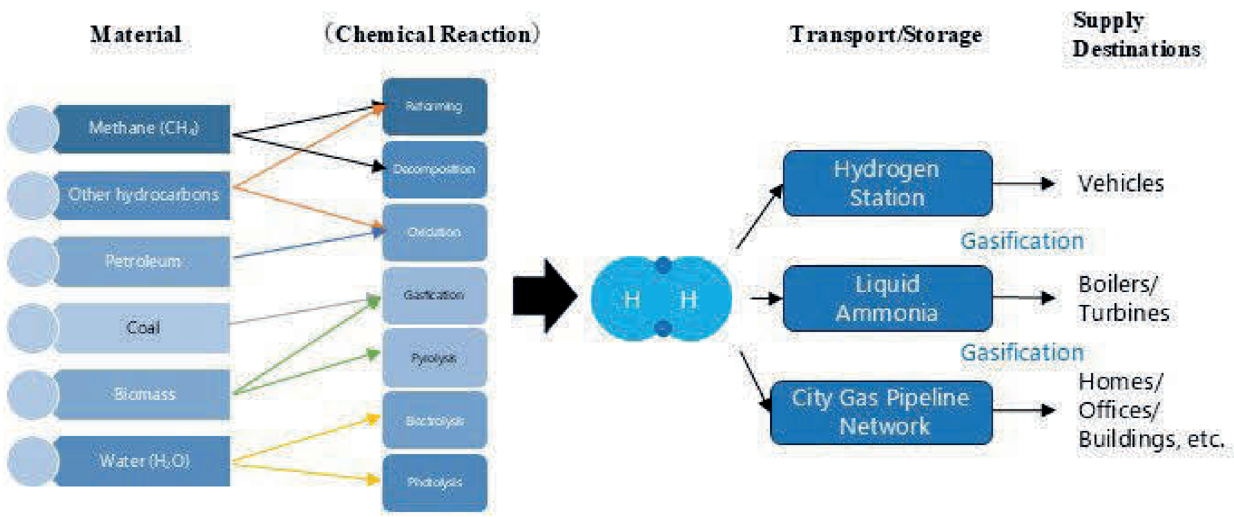
Source: Compiled by APRC based on https://dst.gov.in/clean-energy-material-initiative-cemi.

At the DST, nine national missions related to electrochemistry are defined under "Innovation, Technology, and Program Development." One of these national missions focuses on "EVs" and is closely tied to the R&D of next-generation secondary batteries for automotive use. Another national mission related to "Clean Energy Materials" emphasizes the development of energy storage technologies, establishment of dedicated centers, and creation of national funding mechanisms.

Furthermore, in connection with hydrogen utilization (fuel cells), India is currently implementing the "National Green Hydrogen Mission (launched in January 2023)[108]." Under this mission, a strategic intervention program for the green hydrogen transition (SIGHT) is being deployed. As part of efforts to gradually reduce fossil fuel imports exceeding ₹100,000, the government plans to invest ₹4 billion (approximately ¥7.5 billion) in applied research on hydrogen production, promote domestic manufacturing of water electrolyzers, and aim for the production of approximately 5 million tons of green hydrogen[109].

[108] The Ministry of New and Renewable Energy's "National Green Hydrogen Mission." In addition, the Ministry oversees other national missions such as those related to solar cells.

[109] Hydrogen produced via water electrolysis using electricity generated from renewable energy sources is referred to as green hydrogen. The carbon intensity of the hydrogen depends on the carbon neutrality of the electricity source: when more fossil fuels are used, it is called "grey"; when CO_2 generated during hydrogen production is captured and prevented from increasing atmospheric concentration, it is called "blue"; and when a greater proportion of renewable energy is used, it is called "green." For more information, see the article "India's Green Hydrogen Mission" on the New Energy Foundation Japan website: https://www.nef.or.jp/keyword/ka/articles_ku_04.html



Source: "India Status Report," p.9, created by APRC based on various materials from Japan's Ministry of the Environment.

Figure 3-4-5 The Overall Vision of the Hydrogen Economy Proposed by DST

Prior to the launch of the National Green Hydrogen Mission, the DST published the Status Report on Fuel Cells and Hydrogen Energy (hereinafter referred to as the India Status Report)[110], which outlines India's position in the global context and identifies key research institutions and researchers in the field. The "hydrogen economy" refers to a series of processes involving chemical reactions with various feedstocks to produce, store, and utilize hydrogen. Based on the India Status Report, a conceptual representation of the future of India's hydrogen economy is illustrated in Figure 3-4-5.

It is important to note that the cost of hydrogen production varies significantly depending on the specific reaction process used. According to the MNRE, the domestic cost of hydrogen production in India is summarized in Table 3-4-3, with methods using biomass-based microbes or alkaline electrolyzers estimated to be particularly expensive.

Table 3-4-3 The Domestic Cost of Hydrogen Production in India

	Methane Steam Reforming	Coal Gasification	Biomass Gasification	Biomass-based microbes	Alkaline Electrolyzer
Rupees per kilogram	150	245	258	813	433

Source : The same as Figure 3-4-5

However, considering India's domestic energy mix, coal still accounts for a high proportion on both the supply and demand sides—43.5% of total energy supply in 2020 and 57% of total energy consumption in 2016. Reducing dependence on fossil fuel consumption is essential, but there is also an urgent need to shift toward low-carbon production methods, even in non-fossil fuel generation, and to comprehensively promote the transition to clean energy. The development of water electrolysis technology is increasingly viewed as a promising approach to achieving this goal.

[110] Department of Science and Technology, India Country Status report on Hydrogen and fuel cells, March 2020.

3.4.5 Major Research Institutions and Major Companies

Major Research Institutions

Table 3-4-4 lists the top three research institutions in India with the highest number of published papers related to electrochemical device development between 2013 and 2022[111]. Table 3-4-5 shows the top researchers by number of publications during the same period, categorized by device type, along with their affiliated institutions.

Table 3-4-4 Top Three Research Institutions in India by Number of Publications

Research Institute (India)	Storage Battery	Fuel Cell	Water Electrolysis
Indian Institute of Technology System IIT System	3,426	1,780	247
National Institute of Technology NIT System	1,897	921	129
Council of Scientific Industrial Research CSIR India	1,031	832	215

Source: Compiled by APRC based on Web of Science.

Table 3-4-5 The Top Researchers Categorized by Number of Publications, Device Types, and Affiliated Institutions

	Electrochemical Device Types	Top Researchers Categorized by Number of Publications in India	Number	Affiliated Institution
1	Storage Battery/All Solid	Selvasekarapandian, S.	41	MAT RES CTR
2	Storage Battery/Li-Air	Nookala, Munichandraiah	7	Indian Institute of Science IISc BANGALORE
3	Storage Battery/Li-S	Marimuthu, Sivakumar	27	ALAGAPPA UNIVERSITY
4	Storage Battery/Li Metal Anode	Mitra, Sagar	22	Indian Institute of Technology IIT BOMBAY
5	Fuel Cell/Solid Oxide Type	Basu, Suddhasatwa	35	Indian Institute of Technology IIT DELHI
6	Fuel Cell/Polymer Type	Bhat, Santoshkumar	42	Council of Scientific Industrial Research CSIR India
7	Water Electrolysis	Kundu, Subrata	35	Council of Scientific Industrial Research CSIR India

Source : Compiled by APRC based on Web of Science.

According to Table 3-4-4, the Indian Institutes of Technology Council (IIT Council) has the highest

[111] The following overview of the IITs and NITs in this section is based on: Masayuki Watanabe (2017), "The Development of Admission Selection Systems in Engineering Universities in India," Bulletin of the Graduate School of Education, Kyoto University, No. 63, pp. 560–563, https://repository.kulib.kyoto-u.ac.jp/dspace/bitstream/2433/219222/1/eda63_557.pdf#page=6

number of research publications across all device categories. In particular, for storage batteries, its publication count is twice that of the National Institutes of Technology (NIT, ranked second) and three times that of the CSIR (ranked third). Furthermore, as shown in Table 3-4-5, many of the top-publishing researchers in each device category are affiliated with institutions such as IIIT and CSIR. In particular, IITs show a notably high number of publications on lithium metal anode batteries and solid oxide fuel cells.

The following section outlines the profiles of each research institution, along with their organizational structures and research trends related to the development of electrochemical devices.

(1) Indian Institute of Technology (IIT)

The IITs have published an exceptionally large number of papers across all three electrochemical device types, particularly in batteries and fuel cells, where their publication count is more than twice that of the next-ranking institutions. The first IIT was established in 1951 in Kharagpur, West Bengal, as one of what is now 23 IIT colleges. By 1990, five IITs had been established under the authority of the Institutes of Technology Act of 1961. Initially founded as single-discipline colleges focusing solely on engineering (Colleges of Engineering and Technology), they expanded into other specialized fields under the amended Institutes of Technology Act of 1963 and were renamed to the present-day IITs. Each campus operates independently, but coordinates under an umbrella organization known as the "IIT Council" or "IIT System[112]."

Regarding electrochemical devices, IIT Delhi has published a large number of papers on fuel cells, especially solid oxide fuel cells. IIT Bangalore has produced many publications on lithium-air batteries, and IIT Bombay is known for its numerous papers on lithium-metal anode batteries.

(2) National Institute of Technology (NIT)

Following the IITs, the NITs have the second-highest number of research publications. Modeled after the IITs, the NITs were established under the National Institutes of Technology Act of 2007 and designated as institutions of national importance. Originating from the Regional Engineering Colleges established across India during the 1950s and 1960s, they were renamed NITs in 2003, starting with 17 institutions. As of 2023, there are 31 recognized NITs across the country.

In the field of electrochemical device R&D, NIT Tiruchirappalli is a major center for lithium-ion batteries and fuel cells (membrane research), NIT Calicut is prominent in fuel cell catalyst research, and NIT Rourkela is a key center for water electrolysis and hydrogen storage.

(3) Council of Science, Industry and Research (CSIR)

Following the NITs, the CSIR ranks next in terms of number of research publications. It is an autonomous national research institution established directly under the Prime Minister's Office. Among its institutes, the CECRI[113] was founded in 1948 in Karaikudi as the 12^{th} national laboratory under the

[112] See below, https://www.iitsystem.ac.in/
[113] https://www.cecri.res.in/Default.aspx

CSIR by Alagappa Chettiar—an Indian entrepreneur, philosopher, and educator who was later awarded the Padma Bhushan. CECRI conducts research on a wide range of issues related to electrochemistry. Its establishment was strongly supported by then Prime Minister Jawaharlal Nehru and Dr. Shanti Swarup Bhatnagar, the first Director-General of CSIR. Regional outreach centers were later opened in Madras (now Chennai) in 1971 and Mandapam in 1975.

This institute addresses a wide range of issues encompassing all aspects of the science and technology of electrochemistry, with particular focus on fuel cells, marine corrosion, and offshore corrosion testing. It also conducts numerous collaborative research projects with institutes in India and abroad. Organizations that utilize the expertise of CSIR-CECRI include private companies of various sizes, as well as government agencies in sectors such as nuclear energy, defense, environment, space, ground transportation, and marine development. In addition to basic and applied research, the institute provides surveys, consulting services, and short-term re-skilling courses for industry professionals and academic institutions.

As part of its research initiatives around 2020, CSIR-CECRI developed a prototype lithium-ion battery manufacturing facility for 18,650 cells[114]. This was India's first pilot plant capable of producing lithium-ion batteries with a capacity of 1,500 mAh/V, and it is focused on enhancing battery capacity.

The CECRI Madras Unit, a satellite unit based in Chennai, has been conducting integrated research for over a decade—from basic science to product development—while also addressing the needs of industry-driven research programs. It is equipped with advanced facilities for electrochemical characterization to support basic research, including assessments of electrocatalyst activity, ion conductivity of membranes, fuel cell testing stations, and assembly units for testing cells and stacks of various capacities. These efforts aim to contribute to environmental protection, energy security, and economic growth. The unit's R&D on lithium-ion batteries emphasizes the synthesis of novel materials, such as metal oxides, oxyfluorides, fluorophosphates, fluorosulfates, and NASICON-type materials.

The CECRI Chennai unit has produced a remarkable volume and quality of publications and books covering a wide spectrum of materials related to lithium and sodium batteries. Numerous PhD researchers have completed advanced studies on cutting-edge materials for next-generation systems, such as lithium-ion batteries, sodium-ion batteries, green (organic) batteries, lithium-sulfur batteries, and lithium-air batteries. In the field of materials research for energy applications, the focus is on mixed metal oxide compounds with structures such as pyrochlore, fluorite, and perovskite. From the perspective of industrial applications, lead-acid batteries are widely used for consumer purposes, such as trains and household appliances at CECRI.[115]

Table 3-4-6 shows key ongoing R&D projects related to hydrogen at CSIR-CECRI: two themes on hydrogen gas sensors, one on hydrogen storage alloys, one on copper electrorefining, one on photocatalysis, and one on the development of a 400W water electrolysis prototype led by Dr. Shri S. Mohan.

[114] Department of Science and Technology, India. Energy Technology News, September–October 2020 issue, p.64, https://dst.gov.in/sites/default/files/ETN%20-%20DST.pdf

[115] "Electrochemical Energy Storage: The Indian Scenario," ACS Energy Letters, 2016, 1, 1162-1164.

Table 3-4-6 List of Major R&D Projects of CSIR-CECRI (as of November 2023)

R&D Project Title	Sponsor	Principal Investigator / Chief Scientist (PI/CS)	Area of Expertise (PI/CS)
Electrolysis of cuprous chloride-hydrochloric acid for the formation of cupric chloride and hydrogen gas	Energy Centre of ONGC	Shri V. Nandakumar	Electro hydro metallurgy
Photochemical oxidation of water to produce hydrogen using molecular catalysis	CSIR	S. Vasudevan	Electrochemical water treatment, hydrogen generation by water electrolysis, synthesis of electro-inorganic chemicals, electrochemical waste management.
Electrochemical synthesis of hydrogen storage materials via molten salt technique	CSIR	S. Angappan	Preparation of hexaborides, transition metal oxide compounds are prepared by novel molten salt electrolysis
Development of 400W hydrogen generator based on PEM water electrolyser	Ministry of Non-Conventional Energy Sources *(now MNRE)*	Shri S. Mohan	Electro mechanical design of cells, fabrication of cells and their components, assembling of electrolyser and operation of electrochemical cells for the
Development of hydrogen gas sensor based on conducting polymer nanocomposites materials	DST	M. Paramasivam	Synthesis of conducting polymers and its applications: (i) Rechargable Batteries; (ii) Corrosion Inhibitors; (iii) Gas (H_2) sensors
The development of conducting polymer nanocomposites for hydrogen gas sensors	-	V. Ganesh	Electrochemistry, surface chemistry, electro-analytical chemistry

Source: Compiled by APRC based on https://www.cecri.res.in/

(4) Indian Institute of Science (IISc) Bangalore

It was founded by Jamshetji Nusserwanji Tata, the industrialist known as the "Father of Indian Industry." The Tata Group's institution is one of the most prestigious academic institutions in India. It ranks among the top universities worldwide in terms of the number of citations per faculty publication. Originally established with two departments— "General and Applied Chemistry" and "Electrical Engineering" —it has a long-standing tradition in electrochemistry. As a research institution, it was recognized as a "Deemed University" in 1958 and was awarded the status of an "Institute of Eminence" in 2018.

(5) Center for Materials Science Research, Bharathiar University

It is one of the top public universities in the state of Tamil Nadu. It traces its origins to the graduate school of the University of Madras, which was previously located in the city of Coimbatore (also known as Koyambuthur). Numerous studies on all-solid-state batteries have been published in the field of electrochemistry.

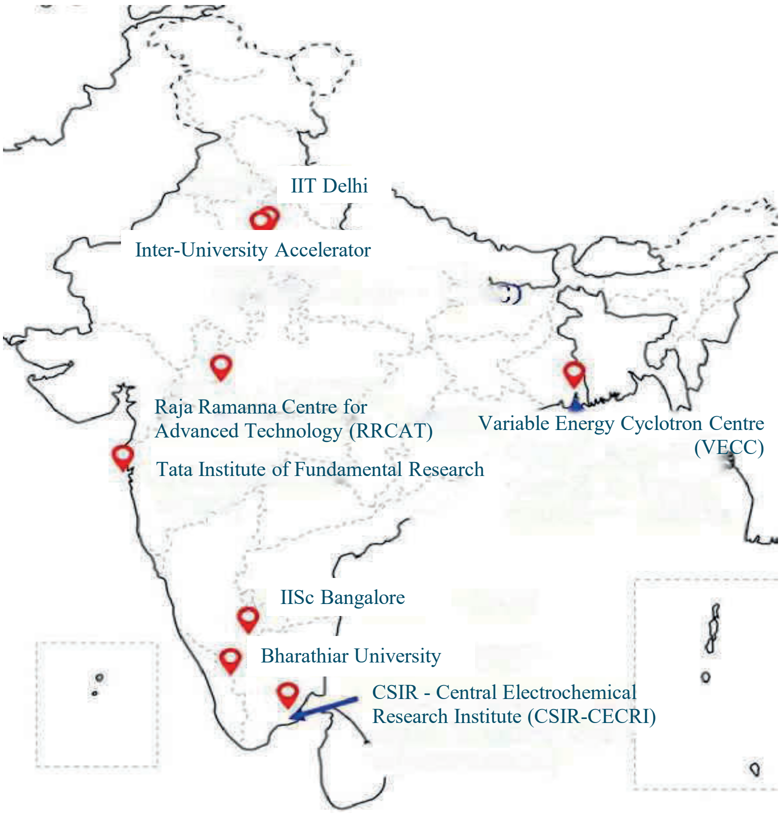
(6) Other Research Institutions

The Materials and Energy Storage Platform, established with the involvement of the DST, is a joint initiative launched in February 2019 by DST and the Non-Ferrous Materials Technology Development

[116] See the overview of Materials and Energy Storage Platform. Unless otherwise specified, the information in this section is sourced from the following website: https://www.nftdc.res.in/ mecsp/

Centre[116]. It focuses on technologies at Technology Readiness Levels 3–7, aiming to integrate materials, processing, and product development.

Figure 3-4-6 shows a map of the locations of the research institutions and large-scale research infrastructure described above.



Source: Compiled by APRC based on DST India, Country Status Report on Hydrogen and Fuel Cells, p.46.

Figure 3-4-6 A map of the locations of the research institutions and large-scale research infrastructure

Industry-Academia Collaboration and Key Startups

Collaboration between state-owned enterprises and research institutions is frequently observed in the field of secondary batteries in India. Companies such as Indian Oil Corporation Ltd. and Bharat Heavy Electricals Ltd. have formed partnerships with research organizations. A prominent example is the Centre for Battery Engineering and Electric Vehicles, which was established at IIT Madras in July 2016 under the initiative of the Ministry of Heavy Industries of the Government of India, using a public-private partnership model[117]. The center focuses on R&D and the provision of commercial products to industry. This research center consists of two Centers of Excellence: the Centre of Battery Engineering and the Centre of Electric Vehicles, and it has fostered several Chennai-based startups, as listed in Table 3-4-7. In addition, Hindustan Petroleum Corporation Ltd. has established the HP Green R&D Centre in Bengaluru to develop innovative and groundbreaking technologies and products.

[117] https://respark.iitm.ac.in/innovation-ecosystem/centres-of-excellence/, "C-BEEV Highlights," presentation by Prabhjot Kaur(CEO, C-BEEV, IIT Madras), http://www.tenet.res.in/Publications/Presentations/pdfs/CBEEV_Introduction_with_Highlights.pdf

Table 3-4-7 List of Major Venture Businesses Originating from the Centre for Battery Engineering and Electric Vehicles (C-BEEV)

Company Name	Business Overview	URL
Motors	Development of energy-efficient and low-cost traction and propulsion systems for industrial and general transport applications	https://www.motorz.in/
Ozone Motors Pvt. Ltd.	Manufacturing of EVs	http://www.ozonemotors.in/
Grinntech Motors & Services Pvt. Ltd.	Development of lithium-ion battery management systems and mechanical packaging for economic and technical sustainability of EVs	https://www.grinntech.com/
Esmito Solutions Pvt. Ltd.	Provision of smart batteries and EV battery swapping (digital services for electric mobility)	https://esmito.com/
Flowtrik Technologies Pvt. Ltd.	Development of swappable and bulk EV smart chargers for use at home and in public spaces	https://flowtrik.com/
Pi Beam Labs Pvt. Ltd.	Manufacture of solar-powered and assisted electric bikes-tricycles	https://www.pibeam.com/

Source: Compiled by APRC based on Websites of WC-BEEV, Tech in Asia and other companies.

3.4.6 International Co-authorship and International Cooperations

Table 3-4-8 lists the top 25 countries involved in international co-authorship for each of the three device categories (based on publications over the 10-year period starting from 2013). The patterns of international collaboration observed from this data are as follows:

Table 3-4-8 The Top 25 Countries Involved in International Co-authorship for Each Device Category

Storage Battery

INDIA	**16,970**
USA	766
SOUTH KOREA	**713**
P. R. C.	**392**
SAUDI ARABIA	332
AUSTRALIA	**294**
ENGLAND	271
SINGAPORE	222
CANADA	221
JAPAN	**212**
TAIWAN	**188**
GERMANY	187
MALAYSIA	168
FRANCE	136
U ARAB EMIRATES	107
ITALY	97
SPAIN	93
DENMARK	88
RUSSIA	84
EGYPT	83
ETHIOPIA	81
SWEDEN	81
NORWAY	74
SOUTH AFRICA	65
VIETNAM	55

Fuel Cell

INDIA	**7,419**
SOUTH KOREA	**339**
USA	324
P. R. C.	**212**
SAUDI ARABIA	176
JAPAN	**142**
ENGLAND	141
MALAYSIA	129
AUSTRALIA	**122**
TAIWAN	**120**
CANADA	104
GERMANY	102
FRANCE	66
VIETNAM	64
ITALY	61
BELGIUM	59
SINGAPORE	55
SPAIN	50
EGYPT	49
RUSSIA	44
IRAN	42
NETHERLANDS	42
THAILAND	39
U ARAB EMIRATES	38
SCOTLAND	35

Water Electrolysis

INDIA	**1216**
SOUTH KOREA	**78**
USA	58
P. R. C.	**45**
SAUDI ARABIA	38
AUSTRALIA	**26**
ENGLAND	26
MALAYSIA	24
VIETNAM	24
JAPAN	**23**
CANADA	19
GERMANY	17
FRANCE	14
BELGIUM	13
TAIWAN	**13**
EGYPT	12
IRAN	11
NETHERLANDS	11
IRAQ	10
ITALY	10
SCOTLAND	10
SINGAPORE	10
BRAZIL	9
RUSSIA	9
ETHIOPIA	8
ISRAEL	7

Source: Compiled by APRC based on Web of Science.

Through R&D on these three types of devices, India has established numerous co-authorship with the U.S., South Korea, and China. Notably, in the fields of fuel cells and water electrolysis, the number of co-authored publications with South Korea surpasses those with the U.S. and China, making it the most frequent partner.

In the area of storage batteries, India's co-authored publications with the U.S. and South Korea both exceed 700, indicating a nearly equal split between the two. Beyond these three countries, India also has a significant number of co-authored publications with Australia and Singapore, both ranking within the top ten. In the case of fuel cells, the number of co-authored publications with the U.S. and South Korea is not as prominent as that of storage batteries. Among countries outside the aforementioned three, Malaysia stands out with a high number of co-authored publications and is also placed within the top ten. For water electrolysis, in addition to the U.S., South Korea, and China, India has a large number of co-authored publications with Australia, Malaysia, and Vietnam—all of which are ranked within the top ten.

In the following section, we discuss India's collaborative relationships with China and South Korea, two countries/regions with which it has a high number of co-authored research publications.

India regards China as both a facilitator in the energy transition and a factor that poses strategic challenges[118]. Although both countries rank among the highest globally in terms of population size, GDP, and economic growth rate, they are also among the top CO_2-emitting nations. They share a common goal of actively promoting EV adoption. For example, the Embassy of India in China issued a press release regarding a meeting of the China-India Industrial Association, stating that "India welcomes China's participation and investment in its EV market[119]."

In the global ranking of internationally coauthored papers with South Korea, India ranks in the top 10. India hosts the Korea-India Science and Technology Cooperation Center (under KIST), which collaborates with institutions such as IISc, IIT Bombay, IIT Bhubaneswar, and JNCASR in fields such as physics, chemistry, materials science, and computer engineering[120].

3.4.7 Large-Scale Research Infrastructure

India has been engaged in the development of particle accelerators for large-scale physics experiments for over half a century. By the 1980s, accelerators had been installed and made available for shared use at the four key locations listed in Table 3-4-9, and related research programs have been actively conducted since then.

The first such facility, the 224 cm Variable Energy Cyclotron Centre (VECC), was established in Kolkata in 1977. This was followed by the construction of two large-scale Electron Storage Rings (Indus-1 and Indus-2) along with a synchrotron accelerator injector (ion injection system) in Indore, which significantly advanced domestic technological development. In addition, superconducting radio-frequency pelletron accelerator facilities operating at high voltage established in Mumbai and New Delhi.[121] Currently, a new facility named ANURIB[122] is being planned for construction at VECC.

118 https://doi.org/10.4324/9781003190905-12
119 https://www.eoibeijing.gov.in/eoibejing_listview/NDAx
120 KIST website (https://jb.kist.re.kr:7443/eng/main/contents.do?menuNo=300113). See also the dedicated site for India (https://ikst.res.in/about/Introduction).
121 Bhandari, R. K.(2020). India's potential to develop particle accelerators for societal, industrial and environmental applications. Current Science,118 (9).1343-1348. https://www.jstor.org/stable/27226433, Kapoor, S.S.(1998). "Accelerator based activities in India," CERN https://accelconf.web.cern.ch/a98/APAC98/4a002.pdf
122 Abbreviation of Advanced National Facility for Unstable and Rare Isotope Beams. Notably, "Anu" also means "atom" in Sanskrit.

Table 3-4-9 Typical Accelerators in India

Name	Facility	Location	Energy
Cyclotron (1977) / Superconducting Cyclotron [SCC] (2009) / Radioactive Ion Beam Accelerator [RIB]	VECC	Kolkata	K=130, K=500, 50 MeV
Synchrotron Sources Indus-1 and Indus-2 (operational since 1999)	Raja Ramanna Centre for Advanced Technology (RRCAT)	Indore	2.5 MeV
15UD Pelletron (operational since 1991)	Inter-University Accelerator Centre (IUAC)	New Delhi	15 MV
BARC/TIFR Pelletron Accelerator (operational since 1988)	Tata Institute of Fundamental Research (TIFR)	Mumbai	14 MV

Source: Compiled by APRC based on the websites of VECC, RRCAT, KEK, and other related institutions.

India, under its agreement with the European Organization for Nuclear Research (CERN), is contributing hardware, software, and human resources to the construction of the Large Hadron Collider, which is currently underway. TIFR has also conducted joint high-energy physics experiments with CERN. India actively participates in international collaborative research, with a strong track record of cooperation with institutions such as Fermilab (USA), TRIUMF (Canada), GSI Darmstadt (Germany), and RIKEN (Japan). Recently, all major domestic facilities have been transitioning to superconducting radio-frequency accelerators, and there has been an increase in research project proposals based on accelerators at institutions such as RRCAT and BARC.

Concurrently, the development of compact electron accelerators (low-energy accelerators) for applications such as medical treatment, food irradiation sterilization, and cargo scanning is underway, with installations expanding across domestic universities and research institutes.

On the computational front, infrastructure is used to search for optimal materials for electrodes and membranes. One of the nine national missions mentioned earlier includes the "National Supercomputing Mission[123]." As shown in Table 3-4-10, 29 supercomputing systems have been installed and are operational to date, with eight of them at the petaflops scale. A key player in this field is the Centre for Development of Advanced Computing (C-DAC), which serves as a major hub for both research and applied computing systems. Headquartered at Savitribai Phule Pune University, C-DAC also has branches in Bengaluru and Chennai, making it one of India's leading research institutions.

[123] See National Missions in the DST website, https://dst.gov.in/national-super-computing-mission.

Table 3-4-10 India's National Large-Scale Computing Infrastructure

【National Supercomputing System】

University / Research Institution	System Name	Computing Power
JNCASR, Bengaluru	PARAM Yukti	1.8 PF
IISER, Pune	PARAM Brahma	1.70 PF
IIT Kharagpur	PARAM Shakti	1.66 PF
IIT Kanpur	PARAM Sanganak	1.66 PF
IIT Roorkee	PARAM Ganga	1.66 PF
IISc Bangalore	PARAM Pravega	3.3 PF
C-DAC, Pune	PARAM AIRAWAT PSAI	13.17 PF
C-DAC, Pune	PARAM Siddhi-AI	5.2 PF/210 PF (AI)
IIT (BHU), Varanasi	PARAM Shivay	838 TF
IIT Hyderabad	PARAM Seva	838 TF
NABI, Mohali	PARAM Smriti	838TF
C-DAC, Bengaluru	PARAM Utkarsh	838TF
IIT Gandhinagar	PARAM Ananta	838TF
NIT Trichy	PARAM Porul	838TF
IIT Guwahati	PARAM Kamrupa	838TF
IIT Mandi	PARAM Himalaya	838TF

【R&D and Application Development Systems】

University / Research Institution	System Name	Computing Power
C-DAC, Pune	Bioinformatics R&D	230 TF
C-DAC, Pune	SANGAM Testbed	150 TF
C-DAC, Pune	PARAM Shrestha	100 TF
C-DAC, Pune	PARAM Embryo	100 TF
C-DAC, Pune	PARAM Neel	100 TF
SETS, Chennai	PARAM Spoorthi	100 TF
C-DAC, Bengaluru	System Software lab	82TF
C-DAC, Pune	PARAM Sampooran	27 TF

【Education/Training Systems】

University / Research Institution	System Name	Computing Power
C-DAC, Pune	PARAM Vidya1	52.3 TF
IIT Kharagpur	PARAM Vidya2	52.3 TF
IIT Parkade	PARAM Vidya3	52.3 TF
IIT Chennai	PARAM Vidya4	52.3 TF
IIT Goa	PARAM Vidya5	52.3 TF

Source: DST website.

In the field of electricity storage, several large-scale industrial plants have been constructed within India. In February 2024, the Solar Energy Corporation of India (SECI) announced the installation of a large-scale Battery Energy Storage System[124]. Supported by a $150 million loan from the International Bank for

[124] Colthorpe, A. "India: Modi welcomes biggest BESS, support for 'Round-the-Clock' renewables discussed," February 26, 2024.

Reconstruction and Development, this system will provide storage infrastructure with an output capacity of 40 MW and 120 MW/h.

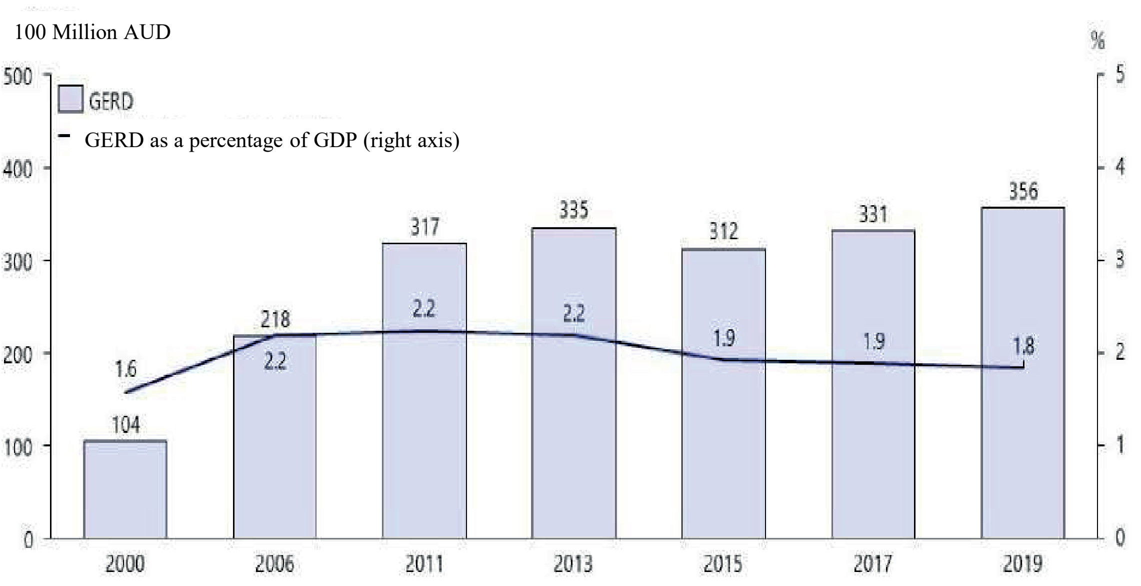
3.5 Australia

In Australia, applied research is more active than in Japan, both in universities and private companies. Strategic basic research strongly oriented toward industrialization has also been promoted in Australia. In light of the market situation in which the automobile industries are not thriving compared to China or India, assembly and recycling processes are strengthened while deploying unique natural resource strategies that leverage abundant mineral resources. With regard to hydrogen energy, a national policy has been developed to promote cutting-edge research on the social implementation of fuel cells and water electrolysis.

3.5.1 Research funding

The Australian Bureau of Statistics divides research and development (R&D) into four stages: pure basic research, strategic basic research, applied research, and experimental development. In this section, an overview of fund distribution according to this definition is described [a1].

(1) Research and development expenditure



Source: [a1]

Figure 3-5-1 Trend of R&D expenditure and their ratio against GDP by year (unit: 100 million AUD / %)

The R&D expenditure of the federal government in 2019 had grown to 3.6 times the level in 2000. However, it has remained stable since 2011. The reason for this trend is that R&D expenditure accounted for more than 2% of gross domestic product (GDP), while it has declined to less than 2% in recent years. This means that R&D expenditure remained stable or expanded even when the ratio against GDP declined because of GDP growth (see Figure 3-5-1).

(2) Breakdown of expenditures by research phase

About half of the R&D expenditure is covered by the private sector in Australia, while one-third of the expenditure is borne by higher educational institutions and 10% by government organizations, with some contribution from non-profit sectors. Nearly 90% of pure basic research is conducted by universities, while less than 10% is conducted by government organizations. Nearly half of the strategic basic research and applied research is conducted by universities, followed by private companies and government organizations. However, more than 80% of experimental development is covered by the private sector (Figure 3-5-2).

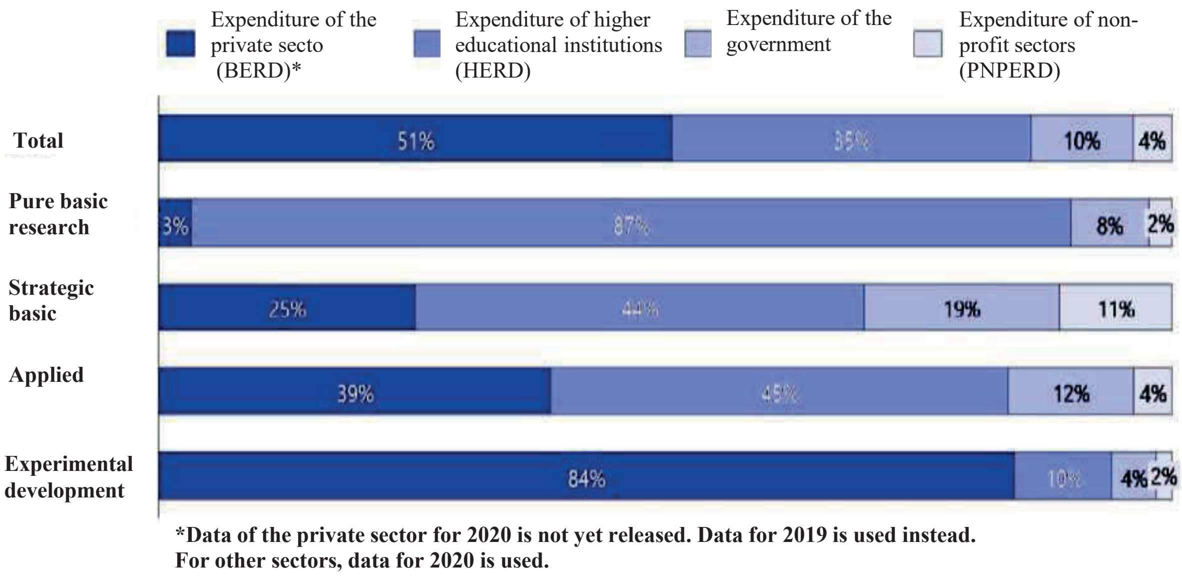
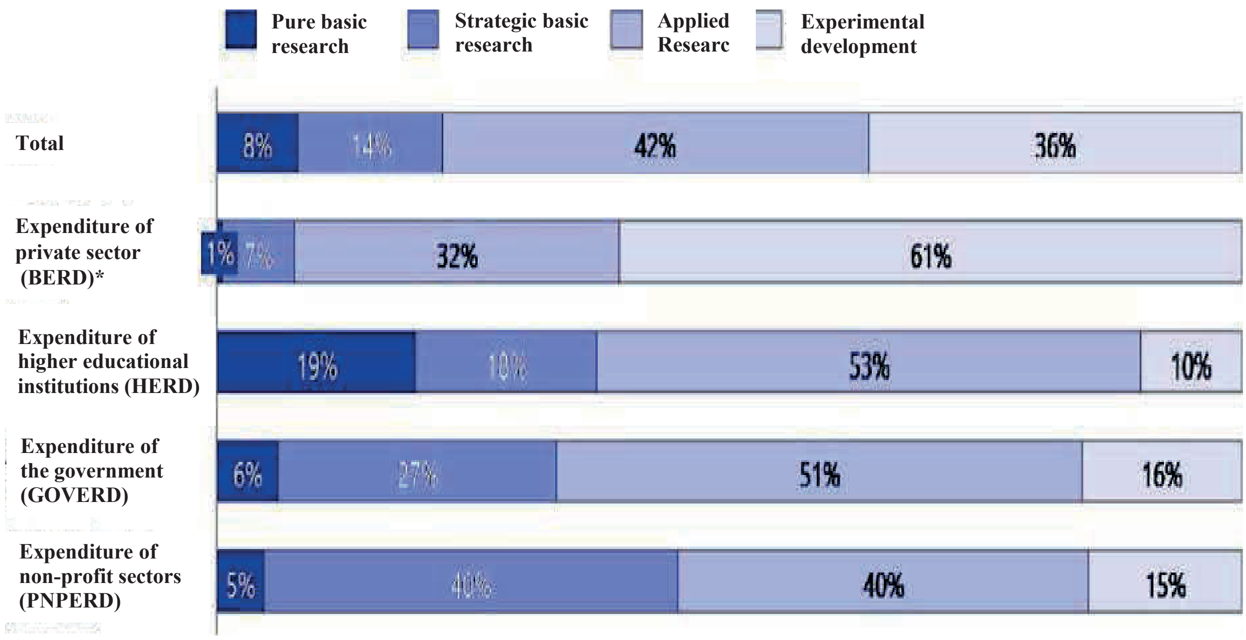


Figure 3-5-2 Breakdown of R&D expenditure by sectors for each research phase in Australia [a1]

Regarding the composition of total expenditure in each section, applied research has the largest share at just over 40%, followed by experimental development at just under 40%, strategic basic research at over 10%, and pure basic research at under 10%. In private sector, experimental development accounts for approximately 60% and applied research approximately 30%, while the share of basic research is limited. In higher educational institutions, the share of applied research is as large as over 50%, with pure basic research being larger than in other sectors, and experimental development comparatively small. The share of strategic basic research in governmental institutions and non-profit sectors is higher than those of private sector and higher educational institutions, while applied research of governmental institutions also constitutes a significant portion (see Figure 3-5-3).



*Data of the private sector for 2020 is not yet released. Data for 2019 is used instead. For other sectors, data for 2020 is used.

Figure 3-5-3 Breakdown of R&D expenditure by the research stages for each sector in Australia [a1]

A breakdown of R&D expenditures by research stage for each sector in Japan is shown in Figure 3-5-4 for comparison. In this figure, pure basic research and strategic basic research are aggregated as "basic research." According to the results, experimental development has the largest share at two-thirds of the total, and the shares of basic and applied research are comparatively smaller than those in Australia (Figure 3-5-3). There are two major differences between Japan and Australia. First, the percentage of experimental development in private sector's research expenditure is 61% in Australia, which is 15 points lower than in Japan. Another factor is that the private sector constitutes approximately 50% of the total research expenditure in Australia, which is relatively small compared with Japan (80%), leading to less influence from private sector in Australia. Regarding universities, the proportion of basic research in Japan is 54%, which is higher than that of universities in Australia (37%) (pure basic research and strategic basic research combined).

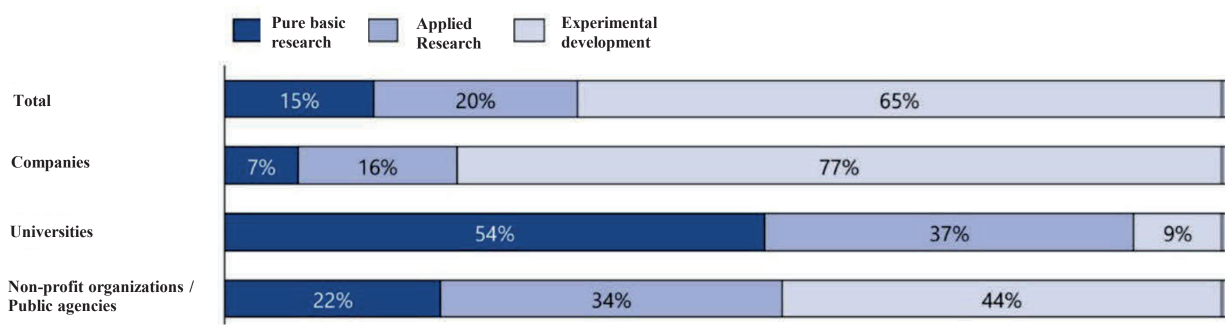
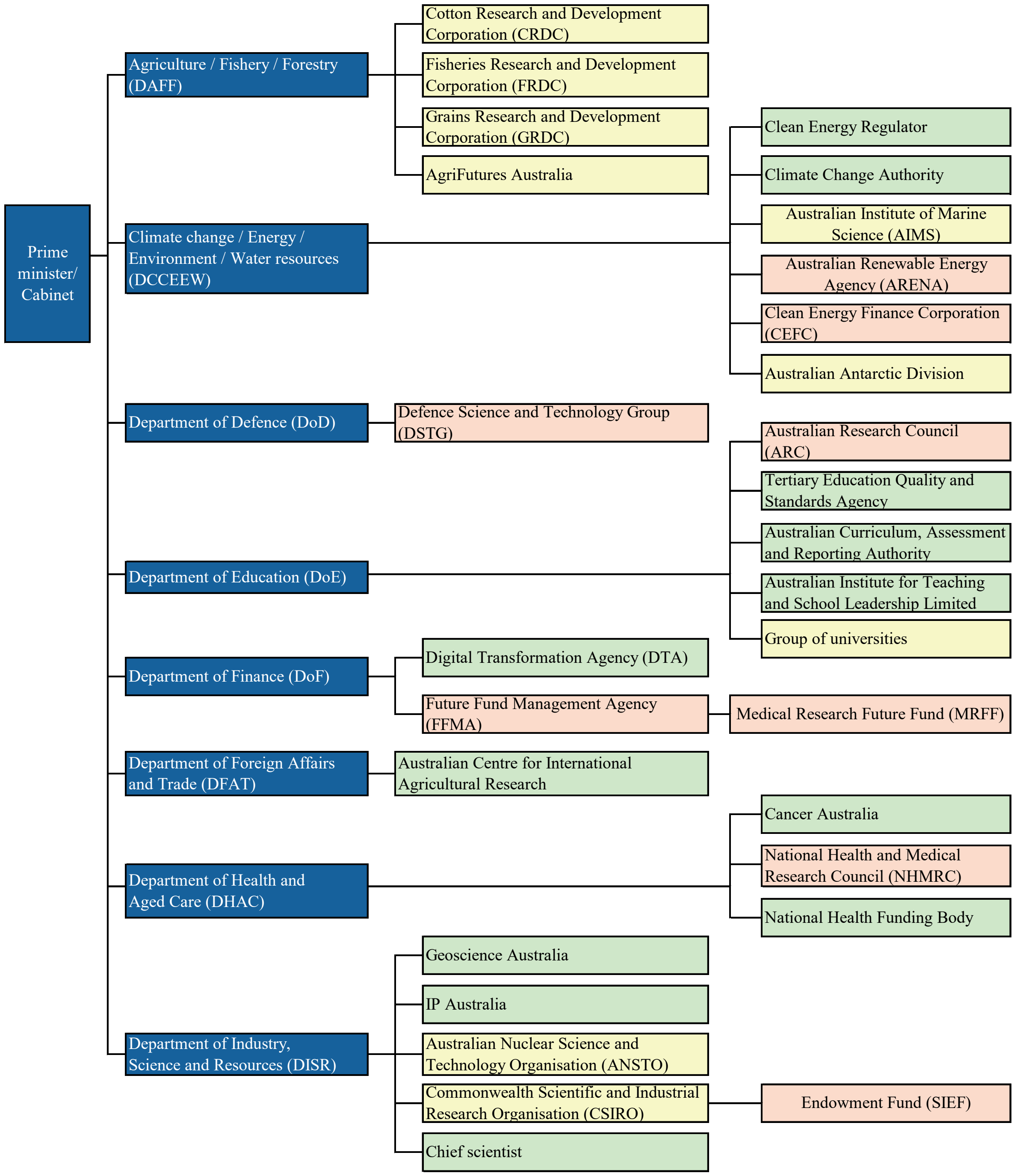


Figure 3-5-4 Breakdown of R&D expenditure by research stage for each sector in Japan [a1]

3.5.2 Research Promotion System

Institutions related to Science and Technology Innovation (STI) policies in Australia can be roughly classified into three categories: institutions that determine the direction and policies of STI, institutions providing research funds for implementing the policies (funding agencies), and institutions that actually carry out the research (Figure 3-5-5).

(1) Organizational structure of the whole government and departments related to STI



Source: [a1], p.27

Figure 3-5-5 Organizations related to the STI in Australia

(2) Flow of the research fund

Policymaking has a hierarchical structure consisting of ministries, governmental agencies, and their subsidiary institutions, in addition to the government. The Commonwealth Scientific and Industrial Research Organisation (CSIRO), universities, and nonprofit research institutes receive public research funds as research institutes. These institutes are shown according to the flow of research funds in Figure 3-5-6, and the research fields and stages of each institute are shown in Figure 3-5-7. Major research funding agencies include the Australian Research Council (ARC) for basic research, the National Health and Medical Research Council (NHMRC) for medical and health research, the Cooperative Research Centres (CRC) Program for industry-academia collaborative research, and the Australian Renewable Energy Agency (ARENA) for renewable energy research.

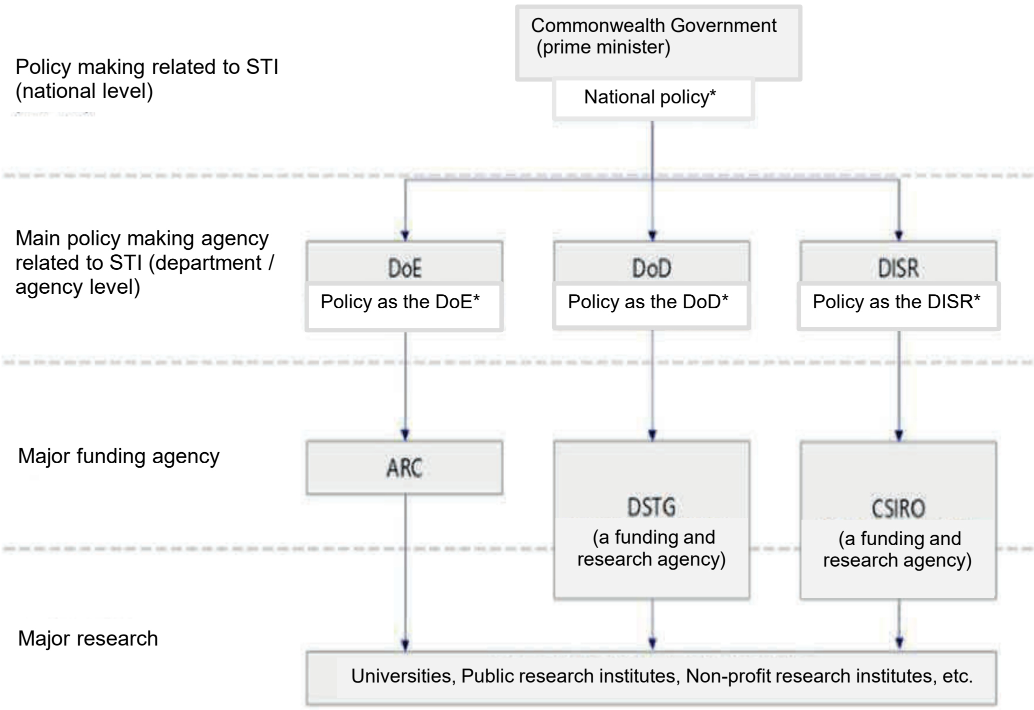


Figure 3-5-6 Flow of research funds from policymaking to the research institute

Government	AU Government							
Responsible ministries	DoE	DHAC	ARENA	DISR (former DIIS)			DCCEEW	DoD
Research funding agencies	ARC	NHMRC		CSIRO	ANSTO	DISR	CEFC	DSTG
Research institutes	Universities	Universities		CSIRO				DSTG
Research fields	General (except medicine)	Medicine	Renewable energies	Industrial technologies in general	Nuclear power	Solve problems of industry	Zero emission	National defence
Research stages	Basic	Basic - Application	Commercialization	Demonstration of applied research	Application	Industry-academia collaboration	Application	Application

The top seven research funding institutes contributing the largest number of published papers from 2013 to 2022 are shown **in bold.**

AU Government	Australian Government
DIIS	Department of Industry, Innovation and Science
DISR	Department of Industry, Science and Resources
DHAC	Department of Health and Aged Care
DOD	Department of Defence
DCCEEW	Department of Climate Change, Energy, the Environment and Water
ARENA	Australian Renewable Energy Agency
ARC	Australian Research Council
NHMRC	National Health and Medical Research Council
CSIRO	Commonwealth Scientific and Industrial Research Organisation
ANSTO	Australian Nuclear Science and Technology Organisation
DSTG	Defence Science and Technology Group
CEFC	Clean Energy Finance Corporation
CRC	Cooperative Research Centres (CRC Program)

Figure 3-5-7 Major research funding agencies in Australia

3.5.3 Related Key Policies and R&D Trends

(1) Characteristics of Australian research and development policies

According to the summary provided by universities, CSIRO, the government, and domestic and foreign industries are aligned with the R&D phases of basic research, applied research, technology development, and production [d1], as shown in Figure 3-5-8. The characteristics of each stage are summarized as follows.

The ARC, an agency under the Department of Education (DoE), operates a "Discovery Program" in which individual researchers or teams of researchers engage, and a "Linkage Program" to realize large-scale industry-academia collaboration[125].

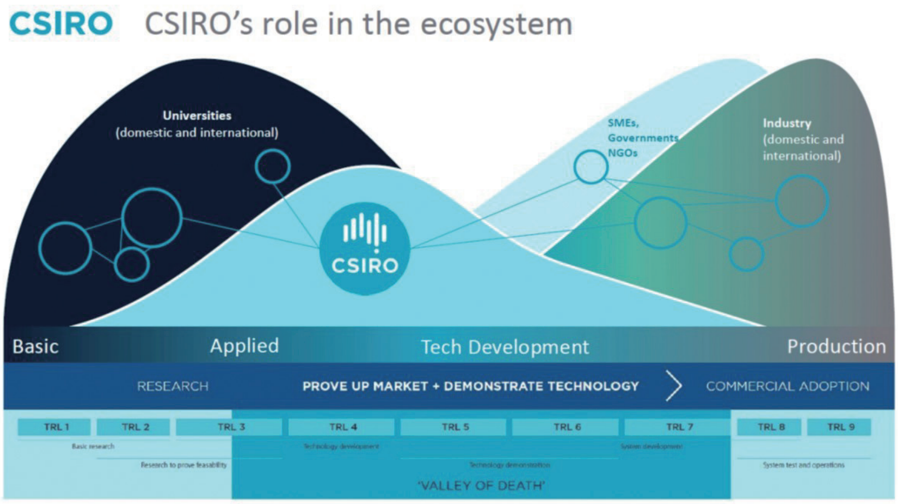
Companies lead the operation of joint research programs under the CRC Program, which is overseen by the Department of Industry, Science, and Resources (DISR), at the applied research phase. When it began, the program focused on supporting the domestic manufacturing industry. Joint research programs are now also carried out with other major sectors such as mining, health care, agriculture, and the environment.

[125] Refer to the Australian Research Council (ARC) website. https://www.arc.gov.au/sites/default/files/minisite/static/396/2014-15/part-2-performance/chapter-4-programme-11-discovery.html, https://www.arc.gov.au/sites/default/files/minisite/static/396/2014-15/part-2-performance/chapter-5- programme-12-linkage.html

At the technological development phase, the Australian government aims to diversify and innovate industries through the large-scale National Reconstruction Fund (NRF), approved by the Australian Parliament in March 2023. This fund is designed to ensure future prosperity and sustainable economic growth. The NRF targets mature, large-scale technology development projects that require accelerated development, by setting seven priority fields in the industry. The NRF is a featured policy of the Albanese government.

The following three characteristic points can also be highlighted.

First, the Australian government is currently examining the Australian Universities Accord as an opportunity to develop an anticipatory plan for Australian universities and the higher education sector, in order to promote continuous and innovative reform of the higher educational system[126]. Second, while Australia's research system is internationally acclaimed for its large share of published papers, citation counts, and international collaborative research, the government remains aware of the necessity to reform industry for future needs. It is actively engaged in revising the system through democratic consultation processes. Third, the Australian government places high expectations on deeper collaboration with Japanese companies to utilize research achievements for practical applications and industrialization, particularly as many Japanese companies have already established operations in Australia.



Source: CSIRO Critical Minerals Capabilities, Material received by JST [d1]

Figure 3-5-8 Role of CSIRO in the ecosystem of Australia

(2) Rechargeable battery technology development at CSIRO

CSIRO is a government agency subsidiary of DISR. The research fields of CSIRO, which is integrated into Australia's innovation ecosystem, include humanities in addition to natural science, technology, economy, and industries. The organization consists of 5,672 personnel with 53 sites and 11 units and utilizes a budget of 10.2 billion AUD (FY 2022). The employees include university graduates, interns, doctoral students, and researchers with PhDs.

[126] Refer to the followings for reference. Additionally, this examination is considered to lead to a revision of ARC. https://www.education.gov.au/download/17995/australian-universities-accord-final-report-summary-report/36761/australian-universities-accord-final-report-summary-report/pdf

The Energy Storage Research team in CSIRO conducts mission-oriented research to create new materials, make the materials recyclable, and create fundamental technologies. Li–air and Li–sulfur batteries for power grids and automobiles are also within the scope of R&D. It concurrently carries out a market forecast based on expected demand to understand social needs. CSIRO also conducts material and process research at TRL1 and TRL2 stage (basic research phase) as a future foundation of science.

According to the CSIRO, establishing a large-scale battery cell factory is difficult in Australia, where competitive automobile companies do not exist. Therefore, the development of technologies for automobile battery pack assembly processes after importing cells and recycling used batteries was conducted by the CSIRO. The CSIRO plans to introduce a single-cell verification technology for the "safety testing of automobile battery packs" at Deakin University and Queensland University of Technology to ensure compliance with UN38.3[127]. It also has a testing and evaluation system in collaboration with the University of Technology Sydney (UTS) and the University of Adelaide.

The supply chain of battery minerals such as Ni, Co, Li, Cu, Al, and black lead and the processing of mineral resources into raw materials, for example, by establishing a nickel sulfate factory, was further reconstructed in collaboration with the U.S. It focuses on lithium-ion iron phosphate (LFP) rechargeable batteries and lithium-ion manganese iron phosphate rechargeable batteries[128] as its resource strategy, which is safer and mainly uses general-purpose metals, while they have approximately 20 to 30% less performance compared with other alternatives. Economic recycling of general-purpose and inexpensive manganese material is not possible, even when applying MagSonic technology[129]. Currently, new materials are less expensive than recycled materials. Therefore, CSIRO believes that re-engineering the economic feasibility of the battery value chain (mineral refinement, material, battery cell, battery pack, and recycling) is necessary.

(3) Clean energy technology development at the CSIRO

A revision of the national strategy for hydrogen energy is currently under examination and is expected to be announced. The CSIRO envisions the Future Science Platform (FSP), focusing on power generation, energy storage, and metal recycling, including a revolutionary energy storage system in the clean energy field (Figure 3-5-9). It sets the challenging goal of becoming a great nation of renewable energy by constructing an optimal supply chain and promoting the New Battery Strategy, Powering Australia, and Co-specific Research Australia.

[127] Safety test standards for transportation of lithium ion batteries and cells specified by the United Nations (UN). Requirements are shown in part 38.3 of the United Nations Manual of Tests and Criteria for the Transport of Dangerous Goods (pages 424 to 436). https://unece.org/fileadmin/DAM/trans/danger/ST_SG_AC.10_11_Rev6_E_WEB_-With_corrections_from_Corr.1.pdf

[128] Replace part of iron used as an anode material of LFP with manganese. It has equivalent level of safety with LFP while realizing higher energy density.

[129] Carbothermal reduction and supersonic nozzles are used to prevent reverse reactions against highly reactive magnesium and achieve high-quality commercial production, a new technology developed by the CSIRO. This is regarded as a cost efficient alternative compared with conventional methods, and can reduce carbon emission by up to 70% (CO_2 equivalent). https://www.csiro.au/en/work-with-us/industries/mining-resources/Processing/MagSonic

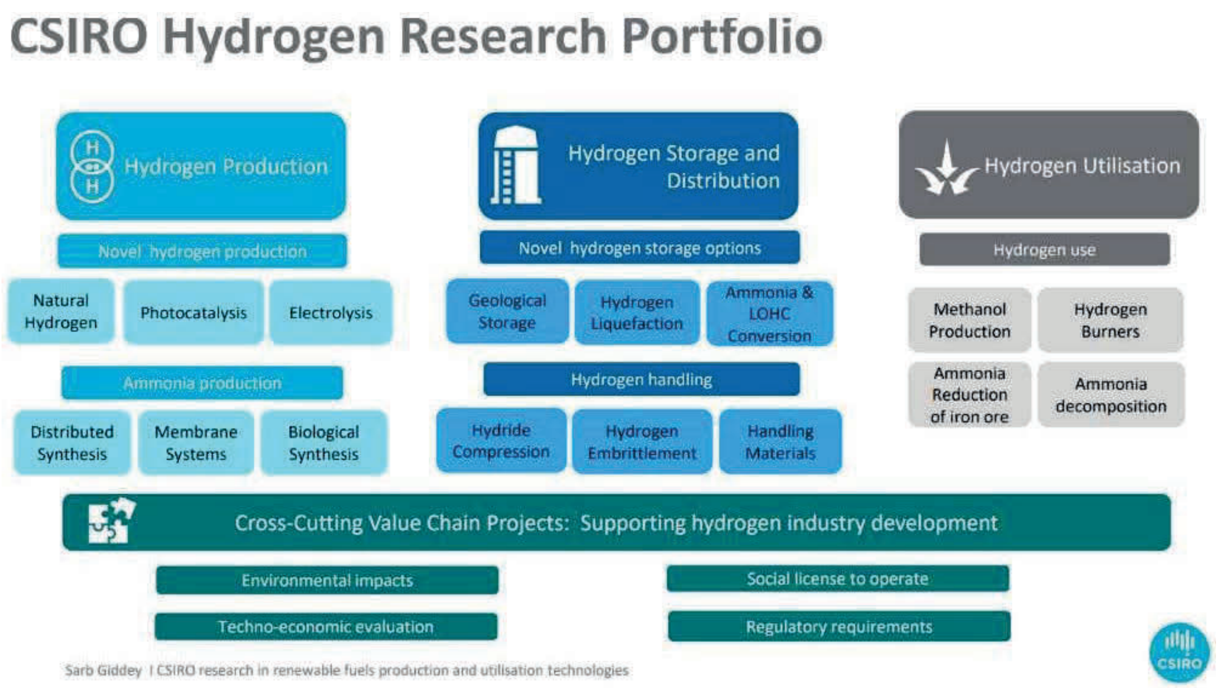


Figure 3-5-9 CSIRO hydrogen research portfolio (received material [d1])

In addition, CSIRO is funding research on fluid catalytic cracking (FCC) of biomass and waste materials. However, CO_2 reduction and carbon capture and storage (CCS) technology development for the CO_2 emission problems of heavy industries, including steel, cement, and aluminum refining, is currently carried out through the corporate collaboration fund of the CRC [d1]. As for hydrogen transport, the gas pipeline network is dominant in Australia, while maritime transportation of liquefied ammonia, liquefied hydrogen, and organic hydride, to which Japan has advantages over other countries, is frequently referred to in documents, and the CSIRO examines the optimum combination of hydrogen transportation technologies with hydrogen generation and storage technologies in Australia.

(4) Critical mineral and earth sciences

Geoscience Australia (GA), a government agency subsidiary of DISR, provides advice to the government on every aspect of earth science to manage the national knowledge of geographic and geological data. The Australian government provides geographical, land, and geological information based on topographical maps and satellite images for open data collection. It carries out a systematic geological and geophysical mapping of the continent based on mineral resource exploration.

Efficient water electrolysis using natural energy sources is indispensable for the mass production of Green Hydrogen. However, long-term R&D is necessary to realize this technology. Therefore, to mass-produce Blue Hydrogen, a transitional solution, CO_2 capture and storage (CCS), EGR, and carbon credit are combined to design an economical solution, and increasing social awareness is anticipated. CCS is currently in its practical development phase in Australia. Many clean energy projects have been planned, and commercial cases have begun. Additionally, technological developments for the underground storage of hydrogen are steadily progressing, thereby forming a foundation for hydrogen suppliers. It also pays close attention to natural hydrogen as a technology for the future and has started exploratory research.

We should introduce the advanced approach made by Australia to ensure stable energy sources and realize a stable and environmentally friendly treatment of CO_2 emissions, because Japan relies on imports for most of its energy.

3.5.4 Research Funds

(1) Research funds related to electrochemistry

Research funds deeply related to the three electrochemical devices were extracted from a list of funds that supported the largest number of published papers (Tables 3-5-1, 3-5-2, and 3-5-3). Funding agencies in Australia, such as ARC and DIIS (currently DISR), support a greater number of published papers. Among the funding agencies outside Australia (white cells in the tables), Chinese agencies, including the National Natural Science Foundation of China (NSFC), outperformed the funding agencies of other countries, followed by funds from the U.S., U.K., and Japan. (Funding agencies outside Australia mentioned here are believed to supply funds to international collaborative research partners of Australian research institutes.)

Table 3-5-1 Electrochemical fields _ Australia _ Number of published papers for each fund (rechargeable batteries)

Funding agency	Number of published papers
Australian Research Council	2,748
National Natural Science Foundation of China (NSFC)	2,245
Australian Government	634
National Health and Medical Research Council (NHMRC) of Australia	476
Department of Industry, Innovation and Science	357
China Scholarship Council	309
China Postdoctoral Science Foundation	271
Fundamental Research Funds for the Central Universities	264
Cooperative Research Centres (CRC) Program	201
National Key Research and Development Program of China	165
Australian Renewable Energy Agency (ARENA)	145

Table 3-5-2 Electrochemical fields _ Australia _ Number of published papers for each fund (fuel cell)

Funding agency	Number of published papers
Australian Research Council	768
National Natural Science Foundation of China (NSFC)	542
Australian Government	95
National Health and Medical Research Council (NHMRC) of Australia	78
China Scholarship Council	61
United States Department of Energy (DOE)	53
Fundamental Research Funds for the Central Universities	52
UK Research and Innovation (UKRI)	52
Ministry of Education, Culture, Sports, Science and Technology, Japan (MEXT)	46
China Postdoctoral Science Foundation	44

Table 3-5-3 Electrochemical fields _ Australia _ Number of published papers for each fund (water electrolysis)

Funding agency	Number of published papers
Australian Research Council	316
National Natural Science Foundation of China (NSFC)	239
Fundamental Research Funds for the Central Universities	33
Australian Government	32
China Scholarship Council	27
China Postdoctoral Science Foundation	23
Natural Science Foundation of Shandong Province	20
Australian Renewable Energy Agency (ARENA)	17
Commonwealth Scientific and Industrial Research Organisation(CSIRO)	16
Natural Science Foundation of Jiangsu Province	15

Note: Numbers of papers are from the Web of Science 2013– 2022; blue cells are agencies within Australia.

3.5.5 Major Research Institutes and Major Companies

Major research institutes

(1) Deakin University

Deakin University is a public university located in Victoria, Australia. Its main campus is located near Melbourne and has more than 12,000 students. The Strategic Research and Innovation Centres (SRIC) are conducting large-scale, world-class research on five impacting themes.

The Institute for Frontier Materials (IFM)[130] addresses complex problems in the fields of energy, health, environment, and manufacturing, leveraging the strong research capacity of the university in material science. Regarding materials for electrical and energy applications, a team of battery materials and technologies is conducting pioneering research on alternative battery technologies, including new electrolytes, lithium-ion batteries, sodium-ion batteries, and metal-air batteries.

(2) University of Wollongong (UOW)

UOW is a public university headquartered in Wollongong in New South Wales, Australia. It has multiple campus locations across Australia and overseas, including Dubai, Hong Kong, and Malaysia, with 33,000 students.

UOW has played an important role in driving the growth of the country for approximately 50 years. For Australia to fulfill international responsibilities in climate change, the university aims to play a catalytic role by combining expertise to realize the full capabilities of clean energies and to promote innovation in the transition to sustainable energies. UOW supports the generation of meaningful and persistent changes by providing skills and knowledge to the future workforce through engagement with the community, education and training, support for industries, and cutting-edge research through the UOW Energy Futures Network and Energy Futures Skills Centre.

The UOW Energy Futures Network builds a comprehensive environment for conducting energy-related research by bringing together the entire university network of researchers working on energy problems. It provides strategies clearly defined by data and evidence to the government, public services, regulators, device suppliers, and communities as reliable opinions. Research related to energy includes power systems integrated with renewable energy systems, sustainability (building designs, etc.), quality and reliability of electrical power, energy storage with batteries and management systems, distributed energy generation, microgrids, infrastructure modeling and economics, and a hydrogen-intensive economy[131].

(3) University of Technology Sydney (UTS)

UTS has a campus at the center of Sydney, the largest city in Australia, and is a comprehensive university with departments of architecture, engineering, and IT, as well as business management, economics, communication, law, education, and international relations. It has approximately 24,000

[130] https://ifm.deakin.edu.au/research/electromaterials/

[131] UOW Capability Statement, "Cleaner, fairer and more reliable energy." https://documents.uow.edu.au/content/groups/public/@web/@pmcd/@smc/documents/doc/uow270594.pdf

students, including 8,600 foreign students.

The Centre for Clean Energy Technology of the UTS aims to innovate and create groundbreaking achievements with a global target for zero-emission energies. It focuses on the development of efficient devices for energy harvesting, storage, and conversion with the aim of supporting the reduction of CO_2 emissions and the realization of sustainable development through both basic and applied research. Rational approaches are adopted in education and research, combining first-principles calculations and modeling, the design of new material architecture and synthesis, and system integration. The research covers lithium-ion batteries, lithium-air (oxygen) batteries, sodium/sodium-metal batteries, lithium-sulfate batteries, two-dimensional (2D) nanomaterials, electrochemical and photochemical catalysts, and hydrogen production and storage of hydrogen[132].

(4) Curtin University

Curtin University is a comprehensive university located in Perth, Western Australia, and was founded as the first technology university in Australia. It has 58,000 students. Research-wise, it aims to balance need-oriented research to solve specific problems of industries or society and seed-oriented research to expand the boundary of scientific knowledge.

The Fuel Cell Research Group of the Fuels and Energy Technology Institute of Curtin University[133] conducts basic research on fuel cells and pursues practical applications of fuel cells, supercapacitors, and electrochemical conversion, including the electrolysis of water, and hydrogen storage systems to realize green power and energy generation as an economical and efficient system.

The Green Electric Energy Park (GEEP)[134] is a unique, state-of-the-art facility that supports Curtin University's efforts for superiority and innovation in sustainable development. Four research stations are available in the GEEP laboratory as renewable energy power conversion systems. Through the development of new power converters and sophisticated control algorithms, three-phase main-grid or microgrid power sources, isolated load banks or battery banks, and equipment to connect to motors and energy storage devices are provided.

(5) University of New South Wales Sydney (UNSW)

UNSW is a national university headquartered in Sydney. It is recognized as one of the best universities in the APAC region because of its excellent educational records and research achievements. It has approximately forty thousand students.

The vision of UNSW's 2025 Strategy is to improve the lifestyles of people in the world through innovative research, education, and efforts to realize a fair society. Universities are the center of a sophisticated global knowledge system to form the future, and UNSW aims to be a global university that innovates and improves lifestyles worldwide by promoting discovery, invention, and innovation.

[132] Centre for Clean Energy Technology, UTS. https://www.uts.edu.au/research/centre-clean-energy-technology/about-centre/welcome
[133] Fuels and Energy Technology Institute, Curtin University. http://energy.curtin.edu.au/
[134] Green Electric Energy Park, Curtin University. https://research.curtin.edu.au/research-areas/energy-transition/geep-green-electric-energy-park/

Five research projects regarding electrochemical research are currently underway at the university[135]: "Design and optimization of electrolyzer for hydrogen production" to explore the optimum production process by combining a computational fluid dynamics (CFD) approach and experiments; "Phase diagrams calculations and materials design for renewable energy-focused materials" to develop materials to be used in devices by combining phase diagram calculations and a thermodynamics database; "numerical optimization of hydrogen storage tank design" and "numerical and experimental study of the water electrolyzer flow channel design and optimization" focusing on the structure of a tank and the reaction flow; and "Pore-scale numerical study of the particle behaviors in the porous transport layer of membrane electrodes during water electrolysis" that addresses the problem of electrode contamination with the direct electrolysis of saline water.

Major companies

The secondary battery market in Australia is not controlled by a few large enterprises but is segmented by competition among various companies, large and small, domestic and international. CSIRO has created more than 200 tech companies, and their cumulative market capitalization amounts to more than 3 billion AUD (approximately 309 billion yen)[136]. Among these companies, Hadean, Endua, Evergen, and EnergyOS are battery/energy-related. An overview of Hadean and Endua, which specifically address the R&D of water electrolysis, is described below.

CSIRO developed a durable proton exchange membrane, a Zr-based ceramic ion transport membrane, as a solution to the technical problems of the water electrolysis process, and is further working to reduce the overvoltages.

Hadean is a company established by separating from the energy business division of the CSIRO and has developed a "tubular solid oxide electrolysis (tSOE)" technology that is more efficient and lower in cost compared to the conventional technologies, including solid polymer electrolyte (SPE) cells and alkaline electrolysis. It does not require expensive platinum-group metals. The tubular design enables highly scalable production, and complex stacking and sealing are not necessary, thereby reducing power consumption by up to 30% compared with PEM or alkaline electrolysis. Solid oxide electrolysis (SOE) is the most efficient process when combined with industrial waste heat. SOE uses ceramic electrolytes to convert vapor into hydrogen and oxygen through electrochemical reactions. Because cell efficiency can be improved using industrial waste heat, the energy efficiency of SOE can be 30% higher than that of PEM or alkaline electrolysis. The cell structure of the tubular solid oxide electrolysis by Hadean reduces both the cost and complexity of the system. The stacking technology for solid oxides may have further implications. It is highly likely to be applied to ammonia decomposition (to hydrogen and nitrogen) and the separation of hydrogen from ammonia using a metal membrane.

Endua, founded in 2021, has a mission to support industries in ensuring self-sufficient, sustainable, and cost-efficient energy by getting the most out of renewable energies through partnerships such as Ampol, CSIRO, and Main Sequence. The "Clean hydrogen modular power bank" of Endua enables the

[135] https://www.unsw.edu.au/research/promo/our-research/hydrogen-generation-and-storage
[136] Refer to the CSIRO website. https://www.csiro.au/en/work-with-us/ip-commercialisation/Our-portfolio-companies

improvement of self-sufficiency and stability of energy supply by accessing on-demand power sources according to the demand of each on-grid / off-grid / edge-grid industry. Hydrogen-based technology accommodates various electrical power markets to realize the self-supply of energy for several days, thereby addressing the problems of a region where a stable supply of renewable energy is not possible.

3.5.6 International Co-authorship and International Cooperations

Researchers with the largest number of published papers on electrochemical devices in Australia for the ten years from 2013 to 2022 and their affiliated research institutions are shown in Table 3-5-4. Researchers ranked 2nd to 7th have Chinese family names. International co-authorships, especially the trend of the relationship with China, are analyzed below.

Table 3-5-4 Type of the electrochemical devices _ author with largest number of published papers _ affiliated research institution

	Type of the electrochemical devices	Australia _ Author with largest number of published papers	Number of published papers	Affiliated research institute
1	Rechargeable batteries / All-solid-state	Forsyth, Maria	84	DEAKIN UNIVERSITY
2	Rechargeable batteries / Li-air	Liu, Hua Kun	25	UNIVERSITY OF WOLLONGONG
3	Rechargeable batteries / Li-S	Wang, Guoxiu	76	UNIVERSITY OF TECHNOLOGY SYDNEY
4	Rechargeable batteries / Li metal cathode	Dou, Shi Xue	72	UNIVERSITY OF WOLLONGONG
5	Fuel-cell batteries / Solid oxide type	San Ping Jiang	82	CURTIN UNIVERSITY
6	Fuel-cell batteries / Polymer type	San Ping Jiang	16	CURTIN UNIVERSITY
7	Water electrolysis	Zhao, Chuan	32	UNIVERSITY OF NEW SOUTH WALES SYDNEY

Source: Created by APRC from Web of Science

International co-authorship partners of each country/region of Highly Cited Papers (top 1% for each field [rechargeable batteries] in each year) for the last three years were compared with those for the last 10 years [f1] (Figure 3-5-10).

Rechargeable batteries 2013–2022 Co-authorship _ Highly cited papers _Number of papers

Battery World 2013-2022 6,487 Country of the co-authors/ Reporting country	China	USA	Australia	England	Singapore	Canada						
China	3,894	727	331	130	229	147						
USA	727	1,850	76	76	42	97						
Australia	331	76	501	24	14	11						
England	130	76	24	332	9	17						
Singapore	229	42	14	9	371	5						
Canada	147	97	11	17	5	324						
Germany	117	80	27	39	10	28	400	19	23	5	11	19
Japan	87	39	32	11	3	7	19	231	20	2	9	12
Korea	97	117	27	22	21	11	23	20	388	6	31	5
Taiwan	29	19	7	4	5	1	5	2	6	65	4	1
India	25	25	7	6	6	11	11	9	31	4	162	9
France	24	46	9	27	7	13	19	12	5	1	9	163
Global share %	60.0	28.5	7.7	5.1	5.7	5.0	6.2	3.6	6.0	1.0	2.5	2.5

Rechargeable batteries 2013–2022 Bilateral _ Highly cited papers _ Share of co-authorship of papers (%)

Battery World 2013-2022 6,487 Country of the co-authors/ Reporting country / Denominator	China	USA	Australia	England	Singapore	Canada	Germany	Japan	Korea	Taiwan	India	France
China	100.0	18.7	8.5	3.3	5.9	3.8	3.0	2.2	2.5	0.7	0.6	0.6
USA	39.3	100.0	4.1	4.1	2.3	5.2	4.3	2.1	6.3	1.0	1.4	2.5
Australia	66.1	15.2	100.0	4.8	2.8	2.2	5.4	6.4	5.4	1.4	1.4	1.8
England	39.2	22.9	7.2	100.0	2.7	5.1	11.7	3.3	6.6	1.2	1.8	8.1
Singapore	61.7	11.3	3.8	2.4	100.0	1.3	2.7	0.8	5.7	1.3	1.6	1.9
Canada	45.4	29.9	3.4	5.2	1.5	100.0	8.6	2.2	3.4	0.3	3.4	4.0
Germany	29.3	20.0	6.8	9.8	2.5	7.0	100.0	4.8	5.8	1.3	2.8	4.8
Japan	37.7	16.9	13.9	4.8	1.3	3.0	8.2	100.0	8.7	0.9	3.9	5.2
Korea	33.9	30.2	7.0	5.7	5.4	2.8	5.9	5.2	100.0	1.5	8.0	1.3
Taiwan	51.8	33.9	12.5	7.1	8.9	1.8	8.9	3.6	10.7	116.1	7.1	1.8
India	15.4	15.4	4.3	3.7	3.7	6.8	6.8	5.6	19.1	2.5	100.0	5.6
France	14.7	28.2	5.5	16.6	4.3	8.0	11.7	7.4	3.1	0.6	5.5	100.0
Global share %	60.0	28.5	7.7	5.1	5.7	5.0	6.2	3.6	6.0	1.0	2.5	2.5

Note: The share of co-authorship by China is highlighted by the color of the cell. Green, > 30%; yellow, > 40%; pink, > 50%.

Figure 3-5-10 Highly cited papers for the last ten years (2013–2022), International co-authorship

Rechargeable batteries 2020–2022 Co-authorship _ Highly cited papers _ Number of papers

Battery World 2020-2022 2,654 Country of the co-authors/ Reporting country	China	USA	Australia	UK	Singapore	Canada						
China	1,947	269	174	70	97	92						
USA	269	536	32	34	9	41						
Australia	174	32	241	15	3	7						
England	70	34	15	154	3	9						
Singapore	97	9	3	3	113	3						
Canada	92	41	7	9	3	145						
Germany	56	33	13	18	5	10	139	8	6	5	6	9
Japan	31	12	16	5	1	3	8	63	7	1	4	3
Korea	46	41	12	13	7	5	6	7	139	5	19	1
Taiwan	17	5	6	1	2	0	5	1	5	32	3	0
India	18	15	6	4	3	9	6	4	19	3	92	2
France	13	14	4	11	1	5	9	3	1	0	2	45
Global share %	73.4	20.2	9.1	5.8	4.3	5.5	5.2	2.4	5.2	1.2	3.5	1.7

Rechargeable batteries 2020–2022 Bilateral _ Highly cited papers _ Share of co-authorship of papers (%)
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Battery World 2020-2022 2,654 Country of the co-authors/ Reporting country/ Denominator	China	USA	Australia	England	Singapore	Canada	Germany	Japan	Korea	Taiwan	India	France
China	100.0	13.8	8.9	3.6	5.0	4.7	2.9	1.6	2.4	0.9	0.9	0.7
USA	50.2	100.0	6.0	6.3	1.7	7.6	6.2	2.2	7.6	0.9	2.8	2.6
Australia	72.2	13.3	100.0	6.2	1.2	2.9	5.4	6.6	5.0	2.5	2.5	1.7
England	45.5	22.1	9.7	100.0	1.9	5.8	11.7	3.2	8.4	0.6	2.6	7.1
Singapore	85.8	8.0	2.7	2.7	100.0	2.7	4.4	0.9	6.2	1.8	2.7	0.9
Canada	63.4	28.3	4.8	6.2	2.1	100.0	6.9	2.1	3.4	0.0	6.2	3.4
Germany	40.3	23.7	9.4	12.9	3.6	7.2	100.0	5.8	4.3	3.6	4.3	6.5
Japan	49.2	19.0	25.4	7.9	1.6	4.8	12.7	100.0	11.1	1.6	6.3	4.8
Korea	33.1	29.5	8.6	9.4	5.0	3.6	4.3	5.0	100.0	3.6	13.7	0.7
Taiwan	53.1	15.6	18.8	0.7	1.4	0.0	15.6	0.7	15.6	100.0	9.4	0.0
India	19.6	16.3	6.5	4.3	3.3	9.8	6.5	4.3	20.7	3.3	100.0	2.2
France	28.9	31.1	8.9	24.4	2.2	11.1	20.0	6.7	2.2	0.0	4.4	100.0
Global share %	73.4	20.2	9.1	5.8	4.3	5.5	5.2	2.4	5.2	1.2	3.5	1.7

Note: The share of co-authorship by China is highlighted by the color of the cell. Green, > 30%; yellow, > 40%; pink, > 50%.

Figure 3-5-11 Highly cited papers for the last three years (2020–2022), International co-authorship

Countries or regions where the share of co-authorship of highly cited papers with China over the last 10 years (Figure 3-5-10) is more than 50% are Australia, Singapore, and Taiwan. Over the last three years (Figure 3-5-11), the number increased to five countries/regions with the addition of Canada and the United States, and the shares of Singapore and Australia increased significantly to 85.8% and 72.2%, respectively. Incidentally, in Japan and Korea, where the R&D of rechargeable batteries has advanced, the share of co-authorship with China is less than 50%, although it has been increasing recently.

According to interviews conducted in Australia, many universities still believe that the further enhancement of diversity is effective in improving research capabilities. R&D activities previously depended on foreign students and grants from other countries as financial sources, while the situation changed completely in 2019 when the “risk of interference from foreign countries” began to attract more attention than before, and the following guidelines were published.

The University Foreign Interference Taskforce (UFIT) in Australia publishes the “Guidelines to Counter Foreign Interference in the Australian University Sector,” the guideline on “Due Diligence, Specific to the Transnational Education Environment,” and the “Report on Implementation of the Guidelines to Counter Foreign Interference in the Australian University Sector.” Interviews on foreign interference measures have been frequently conducted by the government over the last five years. According to the report, many universities and government agencies participate in roundtable meetings for comprehensive consultation on what should be done and to what extent, or for deeper understanding and implementation of the guidelines. The report pointed out that interference measures against foreign countries are an ongoing process that requires adaptability and advancement of the approach, and more frequent sharing of concrete information that the government has—through sharing the functioning status and case studies of the guidelines—would lead to the continuous implementation of the guidelines by universities.

Guidelines [e8] presented by UFIT [e7] operate under collaboration between UFIT and universities. The government provides a Readiness Assessment Procedure (framework), whereas universities are responsible for risk management. Each university identifies valuable information and knowledge on technologies as “Supreme Treasure” to recognize the risk facing the treasure at the vice president level and manages the risk voluntarily. The selection of partners for Readiness Assessment, compiling of evidence, and reporting to the government are essential. Each university shares optimal implementation cases, including the management processes for grants, through UFIT. The ARC, the main distributor of public research funds, checks the reported results on operating conditions [a1].

Appendix: Electrochemical Devices and Technical Issues

This appendix outlines the essential knowledge of the electrochemical devices covered in this report, along with their positioning and associated technical issues. Electricity generated from natural energy sources must be stabilized to smooth output fluctuations and converted into a carrier that can be transported in large quantities to ensure a stable supply to consumption areas. From the perspective of ensuring a stable supply of renewable energy, this report positions "batteries" as power storage devices, "water electrolysis" as hydrogen production devices, and "fuel cells" as hydrogen utilization devices. It outlines the characteristics, reaction mechanisms, and technical issues of each electrochemical device, along with technological strategies for resolving these issues through materials innovation and theoretical exploration.

1 Utilization of Renewable Energy

Power generation from natural energy sources such as solar and wind power is subject to fluctuations due to day-night cycles, weather conditions, and seasonal changes. These fluctuations complicate balancing electricity supply and demand, making surplus power storage essential. Batteries and hydrogen are viable means of energy storage (Figure 1). Ideally, when supply matches demand, electricity should be used in its original form with minimal energy conversion frequencies and transmitted via the power grid. However, there is a real gap between electricity supply and demand, and a mechanism to address this imbalance is essential for the stable use of renewable energy.

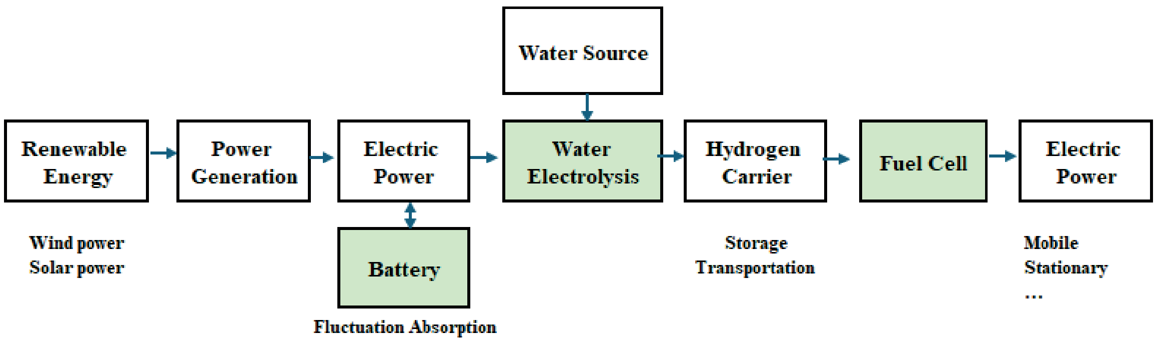


Figure 1 Positioning of three electrochemical devices for stable use of renewable energy (reposted from Figure 1-1)

Devices that can ensure a stable power supply include pumped storage power generation and batteries; however, hydrogen offers potential for large-scale storage and transport of renewable energy. Therefore, as a roadmap for social implementation, countries and regions are improving the efficiency of fossil resource use (resource and energy conservation) while simultaneously developing clean energy supply infrastructures such as power grids, charging stations, and hydrogen gas pipeline networks.

To expand the use of hydrogen in the future, major countries worldwide are advancing their technological development. The formation of the future hydrogen market is expected to depend heavily on government policies, including incentives and promotion schemes for renewable energy-derived "green hydrogen[137]." However, many challenges remain, including the technological development of the water electrolysis process, the practical application of equipment, hydrogen pricing, and the creation of a sufficiently large market [c1].

Candidates for hydrogen storage and transportation include liquefied hydrogen, liquefied ammonia, and liquefied methane (Table 1), assuming large-scale maritime transportation of fuel for power generation. While liquefied hydrogen is still in the testing and verification stages, liquefied ammonia—which liquefies at a relatively low pressure of 30 to 40 bar at ambient temperatures—has already been transported for use in denitrification at thermal power plants. Conversely, liquefied methane is expected to leverage existing LNG import/export infrastructure. These hydrogen carriers can be used as fuels in large quantities, and combustion experiments have already begun. Additionally, Carbon Capture and Storage (CCS)—which involves recovering and storing carbon dioxide generated during the hydrogen production stage—has entered the demonstration and verification phases from geological and mineralogical perspectives. Countries that accept carbon dioxide are also developing domestic legislation to ensure compliance with the Basel Convention [d2].

Table 1 Examples of physical properties of hydrogen carriers

Chemical formula	-	H_2	NH_3	CH_4
Name	-	Hydrogen	Ammonia	Methane
Molecular weight	g/mol	2.016	17.03	16.04
Melting point	°C	-259.2	- 77. 7	-182.5
Liquid density	kg/m_3	70.8 (-253°C)	674 (-33.4°C)	422 (-33.4°C)
Boiling p oint	°C	-252.9	- 33. 4	-161.5
Gas density	kg/m_3	0.052 (21.1°C, 0.1MPa)	0.771 (0°C, 0.1MPa)	0.422 (-33.4°C)
Gas specific gravity (relative to air)	-	0.07	0.771	0.55
Higher heating value (0°C, latm)	MJ/kg	141.8	22. 5	55. 5
Lower heating value (0°C, latm)	MJ/kg	121.5	18.6	50.0

2 Batteries

(1) All-solid-state batteries for automotive use

In the automobile industry, Japanese companies have been committed from an early stage to reducing

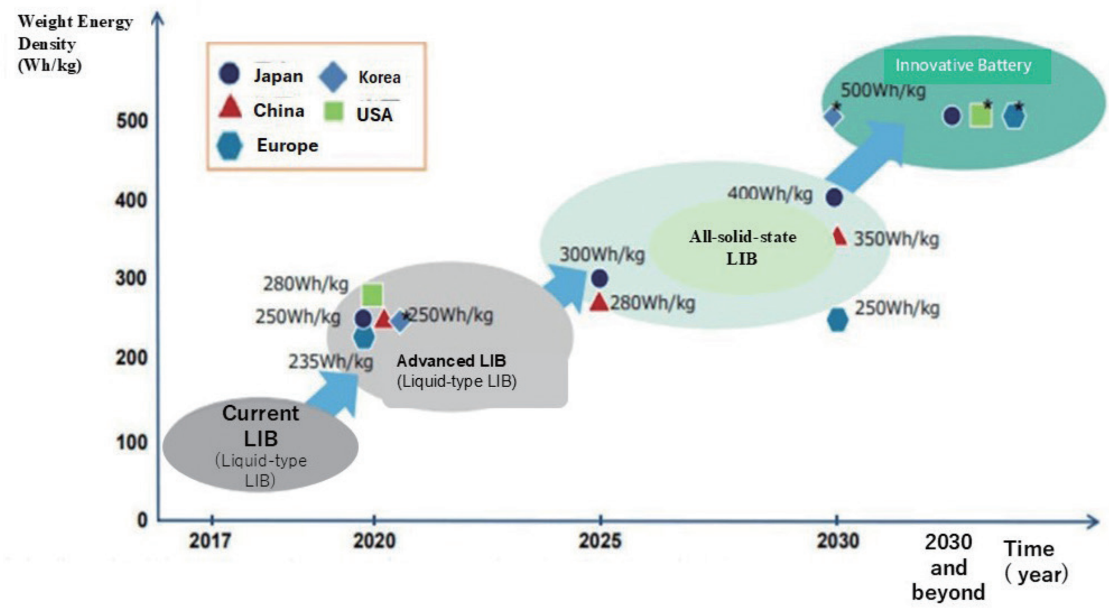
[137] When focusing on existing industrial hydrogen production processes that serve as competitors, "reformed hydrogen" is one such example. In terms of reforming raw materials, natural energy is superior because of its low carbon dioxide emission intensity, followed by low-cost LPG and coal. The use of biomass is also being considered on the premise that stable quantities can be secured. To qualify as a clean energy source, "blue hydrogen" must be combined with Carbon dioxide Capture, Utilization, and Storage (CCUS) to manage the by-product carbon dioxide. In local interviews conducted in various countries and regions, catalyst and mineral resource researchers have frequently mentioned the practical application and industrialization of technologies related to blue hydrogen. However, during the transition from basic to applied research, studies on green hydrogen have been more active than those on blue hydrogen [c1].

carbon dioxide (CO_2) emissions by advancing technological development and promoting awareness of both environmental stress reduction and safety [b1]. For instance, in the technological development of power supplies, there has been a shift from Internal Combustion Vehicles (ICVs) that rely on fossil fuels to Hybrid Electric Vehicles (HEVs) that combine internal combustion engines with batteries, to Fuel Cell Vehicles (FCVs) that use hydrogen as fuel, and finally to pure Battery Electric Vehicles (BEVs).

One of the challenges facing automotive batteries is their weight. Currently, "automotive batteries" weigh approximately 400 to 500 kg per vehicle, raising concerns about the potential for increased damage in traffic accidents and additional stress on road surfaces.

A reduction in battery weight is required for further development, and a competitive race is emerging among South Korea, China, Europe, and the United States to develop various types of batteries. Unfortunately, it is not possible to significantly reduce battery weight along the current trajectory of Lithium-ion Batteries (LIBs). Therefore, "all-solid-state batteries," which are expected to have the most advanced characteristics among new battery systems, have been proposed. Technological development of all-solid-state batteries using solid electrolytes is progressing due to their anticipated advantages over liquid electrolytes, such as non-flammability, stability, high output, and no need for cooling [e2][e3].

In 2019, the composition of new energy vehicles in China was 972,000 BEVs, accounting for 80.6% of the total domestic market [a4]. Indeed, the rapid pace of adoption is evident from the widespread installation of charging stations at various locations, including university campuses. However, current BEVs still have certain limitations, and ICVs using gasoline or diesel fuel, as well as HEVs, remain more advantageous for long-distance use. Although there are examples of policy incentives, such as the regulations on obtaining vehicle registration plates and subsidies, it is believed that the final choice will ultimately depend on the needs of the driver [b1].



Source [f7]

Figure 2 National objectives for progress in battery technology

(2) Research trends in batteries

The 64th "Battery Symposium in Japan" was held in Osaka in November 2023 under the auspices of the Committee of Battery Technology, the Electrochemical Society of Japan. The symposium was a large-scale academic conference, with 528 presentations listed in the program. Presentation trends from this symposium are used as a benchmark for organizing research trends in other countries.

The number of presentations by battery type (Figure 3) shows that lithium-ion battery improvement studies accounted for the largest share, with 229 presentations. Among these, presentations on all-solid-state batteries have been steadily increasing, reaching 99. There were also presentations on battery systems using non-lithium drivers, such as sodium, reflecting resource strategy considerations.

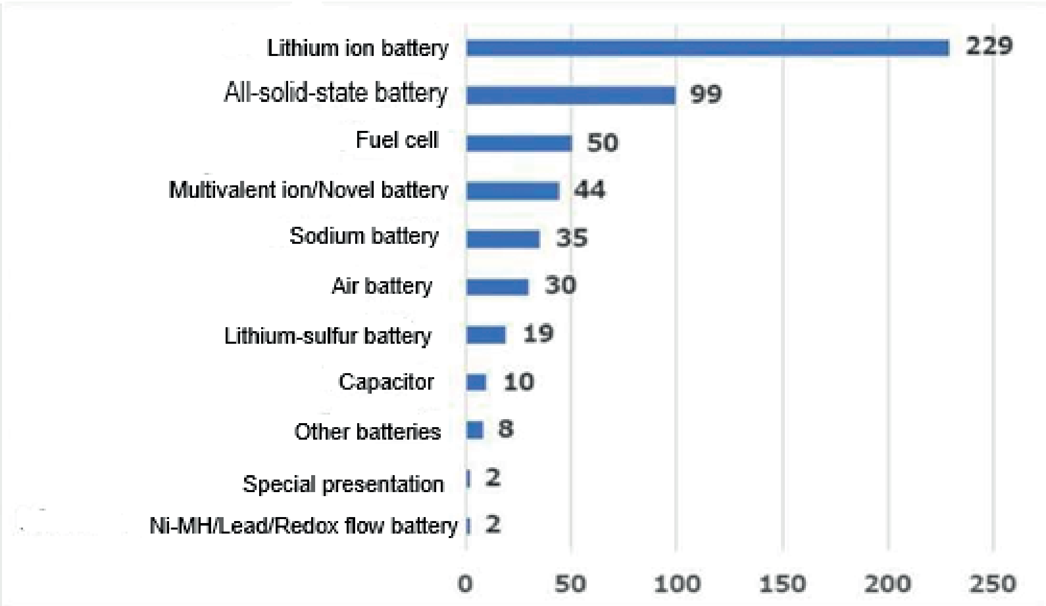


Figure 3 The 64th Battery Symposium in Japan – The number of presentations by battery type (Total: 528)

Referring to the breakdown of the 229 presentations on lithium-ion batteries (Figure 4), there were 23 presentations on metal anodes, 18 on carbon anodes, and 15 on oxide anodes. For cathodes, seven presentations focused on high-potential cathodes and 69 on general cathodes, indicating a strong focus on research aimed at increasing energy density. Additionally, there were 32 presentations on electrolytes and 43 on large batteries (battery packs), evaluation, and safety.

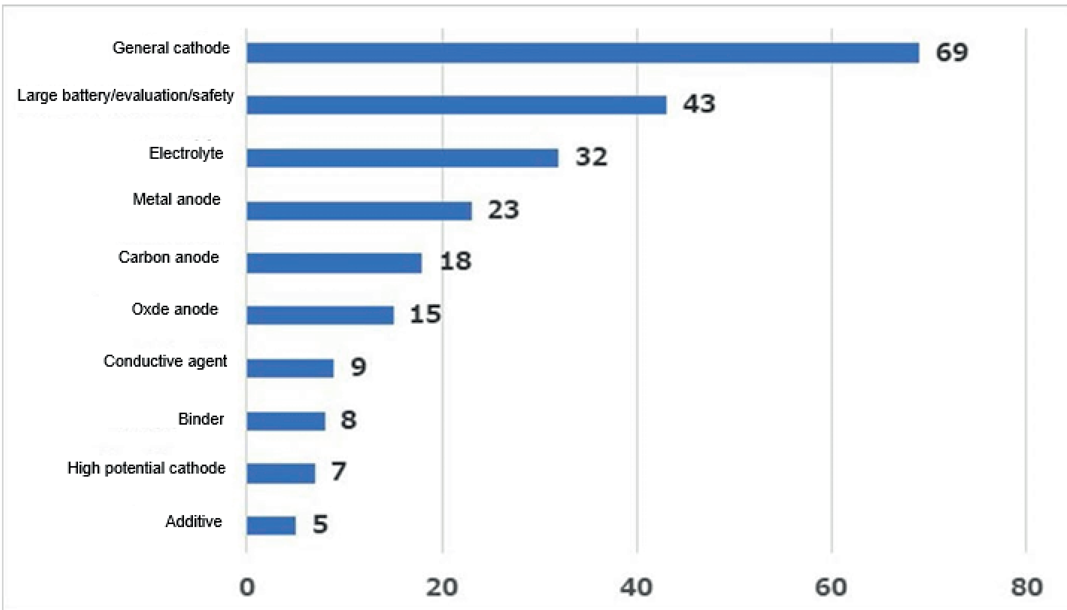


Figure 4 The 64th Battery Symposium in Japan – Lithium-ion batteries (Breakdown of 229 presentations)

The number of presentations by metal element (Figure 5) shows an increase in research on sodium and potassium as alternatives to lithium as a driver, as well as on multivalent metals such as zinc, magnesium, and calcium.

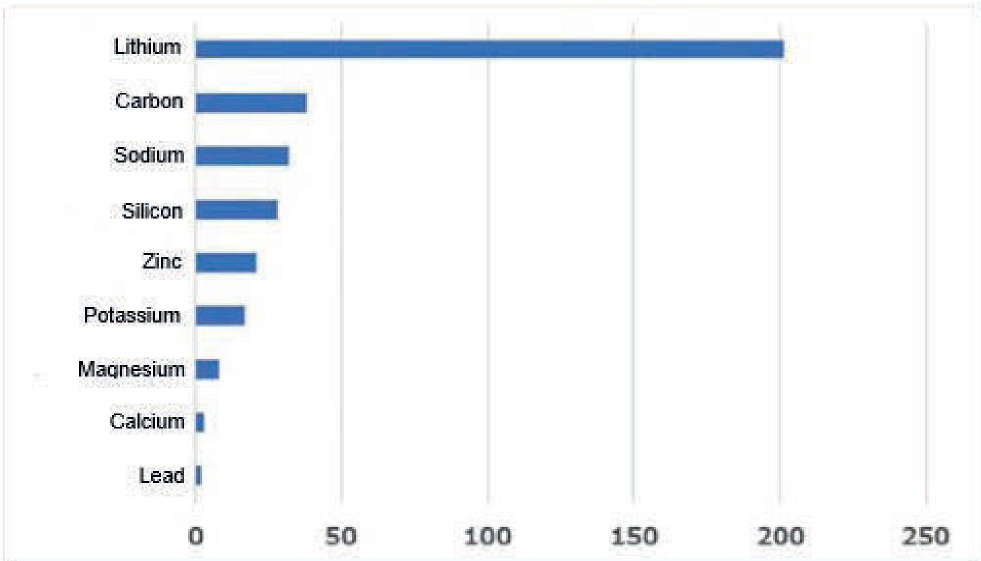


Figure 5 The number of presentations by metal elements

(3) Sodium-ion batteries

Professor Shigeto Okada of Kyushu University and Professor Shinichi Komaba of Tokyo University of Science were the pioneers in the field of "sodium-ion batteries," which received the Battery Technology Committee Award at the Battery Symposium in 2013. Although lithium iron phosphate (LFP) batteries have been widely adopted in China, Contemporary Amperex Technology Co., Limited (CATL) announced the market launch of sodium-ion batteries, which were found to be superior to LFP batteries in certain performance aspects [f8]. In response to CATL's announcement—the world's largest battery manufacturer—Chinese battery material manufacturers have accelerated development, confident in the practical application and industrialization of sodium-ion batteries [f5]. Although sodium batteries were considered to be in an early stage, CATL has recognized the social demand for electric vehicles in Chinese cities and regions and is advancing the technological development of suitable sodium-ion batteries.

(4) Recycling technology

Automotive companies are also engaging in BEV-related recycling as part of their R&D efforts to capture the global EV market. As BEV adoption has progressed, the handling of scrap batteries after use will become an issue. However, recycling components is difficult—not only for batteries but also for components in general. Recovery of metallurgical raw materials and lead batteries for automobiles, magnets for motors, and platinum for synthetic catalysts is currently in progress. However, for magnesium batteries, which are made from commonly available materials, recycled products will ultimately be more expensive than new ones. To achieve a circular economy, it is necessary to create value through recycling or to design a social system that enables profitable resource collection, similar to the system in place for consumer electronics. During R&D, designing the structure and composition to facilitate battery recycling is critical.

3 Fuel cells

(1) Characteristics of fuel cells

"Fuel cells are energy-conversion devices that directly convert the chemical energy of fuel molecules into electrical energy with 'high conversion efficiency.'" In conventional power generation methods, such as thermal power generation, the energy conversion process is repeated, resulting in lower conversion efficiency than that of fuel cells. Furthermore, the heat generated by fuel cells during power generation can be reused to further improve energy efficiency. Hydrogen-based fuel cells produce only water and do not emit greenhouse gases or air pollutants.

Fuel cells exhibit high efficiency even at low output levels, making them attractive for use in vehicles and as stationary power sources for homes. However, the power generation unit of a fuel cell consists of a planar cell that requires a large surface area and a multilayer structure. Consequently, fuel cells do not benefit from economies of scale through increasing their size, unlike thermal power generation. While improvements in power density are ongoing, reducing costs and extending lifespan remain key challenges for fuel cells.

Focusing on "automotive applications," FCVs are more suitable for long-distance travel compared to BEVs. The broader adoption of FCVs or BEVs will depend on customer preferences, based on factors such as convenience and cost-effectiveness. Automakers are preparing for both types as environmentally friendly options. If hydrogen becomes widely available at a low cost, FCVs will likely take the lead; conversely, if all-solid-state batteries become commercially available, BEVs will be the main contender. Currently, BEVs are considered less convenient, require sales subsidies, and are unlikely to become the mainstream choice unless battery performance significantly improves beyond that of existing LIBs.

(2) Types of fuel cells

Fuel cells are used for different purposes depending on the types of electrodes, fuels, and electrolytes, leading to the development of various types. The main types of fuel cells, listed in ascending order of operating temperature, are Polymer Electrolyte Fuel Cells (PEFCs), Phosphoric Acid Fuel Cells (PAFCs), Molten Carbonate Fuel Cells (MCFCs), and Solid Oxide Fuel Cells (SOFCs).

PEFCs are already in practical use, such as in FCVs, and offer advantages such as easy start-up and shutdown at low temperatures. They use a polymer ion exchange membrane as the electrolyte, through which hydrogen ions move. Due to the low operating temperature of approximately 80° C, the air electrode has low reactivity, requiring an expensive platinum catalyst to initiate the chemical reaction, which remains an issue from both resource strategy and cost perspectives. Additionally, platinum catalysts are susceptible to poisoning by carbon monoxide, requiring the fuel to have a low concentration of carbon monoxide. To address these issues while improving durability, iron-based and nitrogen-doped carbon-based catalysts—non-precious metal catalysts and Oxygen Reduction Reaction (ORR) catalysts—have attracted attention.

PAFCs use a phosphoric acid solution as the electrolyte, apply a platinum catalyst, and operate at around 200° C. Although energy efficiency can be improved by recovering reaction heat, components exposed to phosphoric acid are prone to accelerated corrosion.

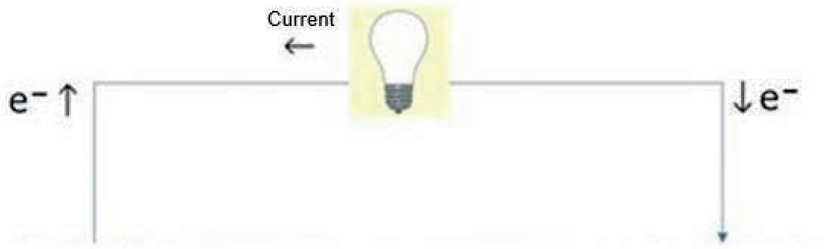
MCFCs use molten carbonate as the electrolyte and operate at around 650° C. Carbonate ions CO_2^{3+} migrate through molten carbonate. Since platinum catalysts are not used, carbon monoxide can be employed as a fuel. For the molten carbonates, mixed salts of lithium carbonate, potassium carbonate, and sodium carbonate are used.

SOFCs operate in the high temperature range of 700 to 1000° C to ensure sufficient oxide ion O_2- conductivity. They can use carbon monoxide as a fuel without using precious metal catalysts. Additionally, by using waste heat to drive the generator, they demonstrate higher power generation efficiency than PEFCs. However, the high operating temperature limits the choice of materials, resulting in drawbacks such as brittleness and fragility. Therefore, to ensure stability, a ceramic material known as Yttria-Stabilized Zirconia (YSZ), in which yttria (Y_2O_3) is dissolved in zirconia (ZrO_2), is used as the electrolyte. By substituting tetravalent Zr^{4+} with trivalent Y^{3+}, an oxygen defect is introduced into the crystal structure, thereby increasing ionic conductivity.

(3) Oxygen reduction reaction in fuel cell

All types of fuel cells require two electrodes, an electrolyte, fuel, and oxygen. PEFCs and SOFCs are typical examples of fuel cells classified by the type of electrolyte used. The electrolyte allows the passage of ions while blocking the flow of electrons. In solid polymer electrolytes, hydrogen ions (H^+) are permeated, while in solid oxide electrolytes, oxide ions (O^{2-}) are permeated. At the same time, the electrolyte prevents the permeation of hydrogen gas supplied to the cathode (air electrode) and oxygen gas supplied to the anode (fuel electrode), thereby preventing the mixing of the two gases.

The fuel cell process can be understood as an electrochemical oxygen reduction reaction (Figure 6). First, when the positive pole of the external load is connected to the cathode of the fuel cell, and the negative pole of the external load is connected to the anode of the fuel cell, an electric current begins to flow. An ORR occurs at the cathode (air electrode), while a Hydrogen Oxidation Reaction (HOR) occurs at the anode (fuel electrode).



Anode HOR	Electrolyte	Cathode ORR
$H_2 \rightarrow 2H^+ + 2e^-$	Solid polymer type $H^+ \rightarrow$	$2H^+ + 1/2O_2 + 2e^- \rightarrow H_2O$
$H_2 + O^{2-} \rightarrow H_2O + 2e^-$	$\leftarrow O^{2-}$ Solid oxide type	$1/2O_2 + 2e^- \rightarrow O^{2-}$

Cathode: In electrolysis and batteries, the electrode where electrochemical reduction occurs.
Anode : In electrolysis and batteries, the electrode where electrochemical oxidation occurs.

Hydrogen Oxidation Reaction (HOR)
Oxygen Reduction Reaction (ORR)

Figure 6 Oxidation and reduction reaction in a fuel cell

In the case of a "solid polymer type electrolyte," hydrogen ions (H^+) and electrons (e^-) are generated at the anode, which is the fuel electrode, as the oxidation number of hydrogen (H_2) increases (oxidized). The generated electrons flow from the anode to the external load (in the opposite direction of the current) and reach the cathode through the external wiring. The hydrogen ions (H^+) generated at the anode permeate the solid polymer electrolyte and move to the cathode, which is the fuel electrode. At the cathode, which is the air electrode, oxygen (O_2) reacts with hydrogen ions (H^+) and electrons (e^-) (reduced) to form water (H_2O). Here, it is known that a phenomenon called flooding occurs, in which the generated water overflows and obstructs the supply of oxygen gas, causing unstable power generation. As a countermeasure, studies have been conducted on models of two-phase gas diffusion phenomena in porous materials and on controlling the surface properties of catalysts.

On the other hand, in the case of a "solid oxide electrolyte," hydrogen (H_2) reacts with oxide ions (O^{2-}) (and is oxidized) at the anode, which is the fuel electrode, to generate water (H_2O) and electrons (e-). The generated electrons flow from the anode to the external load (in the opposite direction to the electric current) and reach the cathode via external wiring. At the cathode, which is an air electrode, O_2 reacts with electrons (e^-) (reduced) to form oxide ions (O^{2-}). The oxide ions (O^{2-}) generated at the cathode permeate the solid oxide electrolyte following a concentration gradient and move to the anode, which is the fuel electrode. Porous manganese oxide, a conductive ceramic that exhibits high oxide ion (O^{2-}) conductivity, is used as the electrolyte. However, since thermal deformation may cause cell collapse, progress has been made in predicting this using temperature-distribution models inside the fuel cells during high-temperature operation. The properties required for new electrode materials include reaction activity, electronic conductivity, and a coefficient of expansion compatible with that of other components. Perovskite oxides are considered potential candidates.

4 Water Electrolysis

There are two primary types of hydrogen that do not emit carbon dioxide: "green hydrogen" and "blue hydrogen." "Green hydrogen" is produced from renewable energy sources, while "blue hydrogen" is produced from fossil resources combined with CCUS technology. In this research, we focused on "green hydrogen" using renewable energy sources and conducted studies on green hydrogen and related electrochemical devices. Water-splitting technology at high temperatures using nuclear energy remains a challenge for the development of heat-resistant materials. However, this topic was excluded from the scope of the present research.

(1) Hydrogen from the perspective of carbon dioxide emission intensity

In April 2023, the International Energy Agency (IEA) published a report, "Towards hydrogen definitions based on their emissions intensity" [e6], which proposes an approach to evaluate hydrogen based on its emissions intensity. This report was prepared to provide information to policymakers, hydrogen producers, investors, and the research community in advance of the G7 Ministers' Meeting on Climate, Energy and Environment. Representative emission intensities are shown in Figure 7.

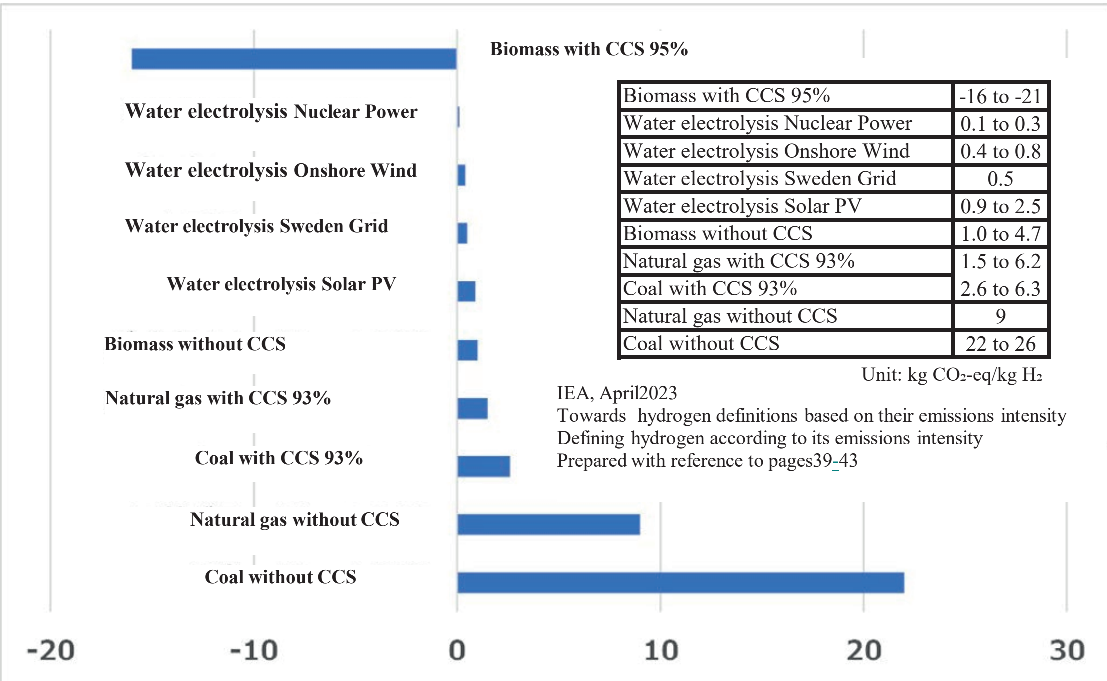


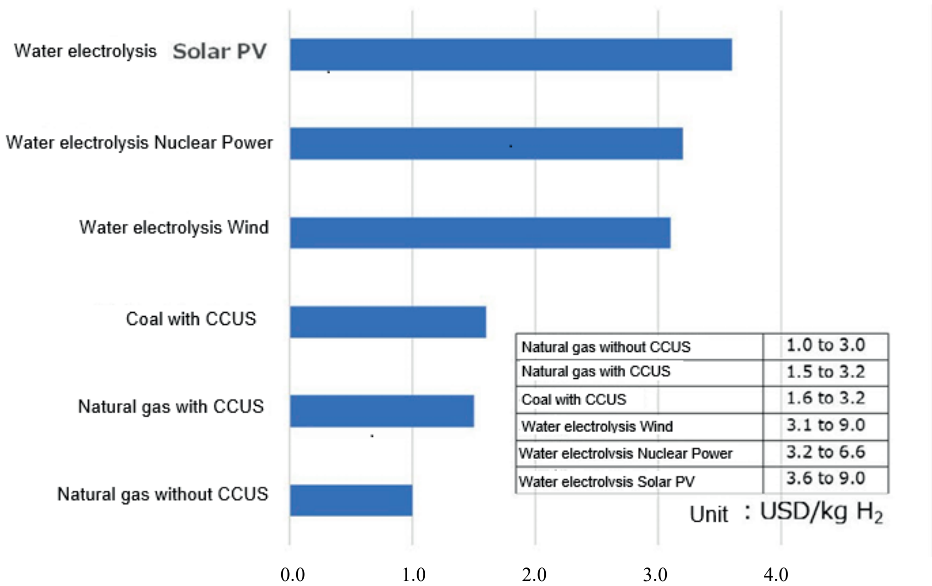
Figure 7 Carbon dioxide emission intensity by hydrogen production route (Figure shows low-level data)

Among these, the process of producing hydrogen is referred to as "water electrolysis." Renewable energy can be converted into hydrogen, a chemical energy source, and this process is gaining attention as a key process for achieving zero carbon dioxide emissions. The challenges of water electrolysis include hydrogen transportation, component durability, and hydrogen production cost reduction. The widespread adoption of this technology depends on policy incentives, promotion schemes, and regulatory frameworks that encourage "green hydrogen." Many challenges remain, including research on water electrolysis technology, development of water electrolysis equipment, and creation of a hydrogen market.

(2) Hydrogen from the perspective of production cost

Various hydrogen production routes exist; however, the main low-emission methods include water electrolysis using renewable energy, as well as partial oxidation and steam reforming for hydrocarbon resources—provided these are combined with CCS. Among the various hydrogen production routes, water electrolysis using renewable energy is positioned in a cost range several times higher than the method using hydrocarbon resources (considering both lower and higher cost data provided by the IEA), indicating a significant gap with current market prices (Figure 8).

When considering the factors involved, the key issues are the variable cost of renewable energy input, amortization of the initial investment, device lifetime, and replacement cost. Current water electrolysis devices have a two-dimensional planar sheet-stacked structure, which is less scalable than chemical reactors with simple three-dimensional structures. Furthermore, durability against power supply fluctuations and replacement cycles associated with membrane degradation remain issues to be addressed. For performance per unit area, reducing power consumption by minimizing overvoltage (the total value of the activation overvoltage, concentration overvoltage, and resistance overvoltage). In other words, progress is expected in R&D where the water electrolysis method will outperform hydrocarbons with CCS, including economy performance. In the meantime, as stated in the Australian National Hydrogen Strategy [c12], it is anticipated that the optimal balance of emission intensity, cost, and supply volume will be pursued through combining hydrocarbon-derived hydrogen using CCS with hydrogen from the water electrolysis method.



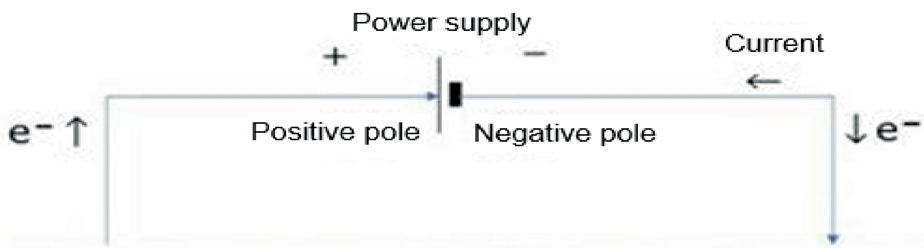
https//beyond-coal.jp/documents/iea-hydrogen-definitions-2023/
IEA Report "Towards hydrogen definitions based on their emissions intensity"
Prepared based on The cost of hydrogen supply, p. 22, Figure 5

Figure 8 Hydrogen costs by production route (Figure shows low-level data)

According to the action plan of the Green Growth Strategy [f6], "The key to hydrogen production in the future is the water electrolysis equipment that produces hydrogen through the electrolysis of water. As the cost of renewable energy and water electrolysis equipment continues to decline, it is expected that by 2050 hydrogen will be cheaper to produce in some areas than hydrogen produced from fossil fuels with CCUS." In the future, approaches to increase equipment size, reduce equipment costs, and improve durability are expected to be pursued amid international competition. In India, companies interested in hydrogen production and utilization are first focusing on improving the commercially established Alkaline Water Electrolysis (AWE) process to produce green hydrogen in combination with renewable energy [c1].

(3) Oxygen reduction reaction in water electrolysis

The water electrolysis process can be understood as an electrochemical oxygen reduction reaction (Figure 9). There are two primary types of electrolyte: basic solution and acidic solution (see Figure 11 for the solid oxide type). First, the negative pole of the external power supply is connected to the cathode of the water electrolysis equipment, and the positive pole is connected to the anode, allowing electric current to flow. A Hydrogen Evolution Reaction (HER) occurs at the cathode, whereas the Oxygen Evolution Reaction (OER) occurs at the anode.



Anode OER	Electrolyte	Cathode HER
$2OH^- \rightarrow H_2O + 1/2O_2 + 2e^-$	$\leftarrow OH^-$ Basic solution	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$
$H_2O \rightarrow 2H^+ + 1/2O_2 + 2e^-$	Acidic solution $H^+ \rightarrow$	$2H^+ + 2e^- \rightarrow H_2$

Cathode: In electrolysis and batteries, the electrode where electrochemical reduction occurs.
Anode : In electrolysis and batteries, the electrode where electrochemical oxidation occurs.
Oxygen Evolution Reaction (OER)
Hydrogen Evolution Reaction (HER)

Figure 9 Oxidation and reduction reaction in water electrolysis

In the case of a basic solution, electrons (e^-) flow from the negative pole of the power supply to the cathode (in the opposite direction of the electric current). At the cathode, water gains electrons (e^-) and the oxidation number decreases (reduced) to generate hydrogen gas and hydroxide ions (OH^-). The generated hydroxide ions (OH^-) then permeate the electrolyte membrane and move through the basic solution. At the anode, the hydroxide ions (OH^-) lose electrons (e^-) and the oxidation number increases (oxidized), producing oxygen gas and water.

In the case of an acidic solution, electrons (e^-) flow from the negative pole of the power supply to the cathode (in the opposite direction of the electric current). At the cathode, the hydrogen ions (H^+) gain electrons (e^-) and the oxidation number decreases (reduced) to generate hydrogen gas. At the anode, water loses electrons (e^-) and the oxidation number increases (oxidized), producing oxygen gas and hydrogen ions (H^+). The generated hydrogen ions (H^+) then permeate the electrolyte membrane, move through the acidic solution, and are supplied to the cathode.

The electrolyte membrane allows hydroxide ions (OH^-) in basic solutions and hydrogen ions (H^+) in acidic solutions to permeate, while simultaneously preventing the permeation of hydrogen gas generated at the cathode and oxygen gas generated at the anode, thus preventing the mixing of hydrogen gas and oxygen gas.

(4) Types of water electrolysis devices

Water electrolysis devices can be classified according to the electrolyte material and operating temperature. A performance comparison of water electrolysis cells is shown in Figure 10. Energy efficiency improves when the cell voltage on the vertical axis is lower, whereas productivity is higher when the current density on the horizontal axis is greater.

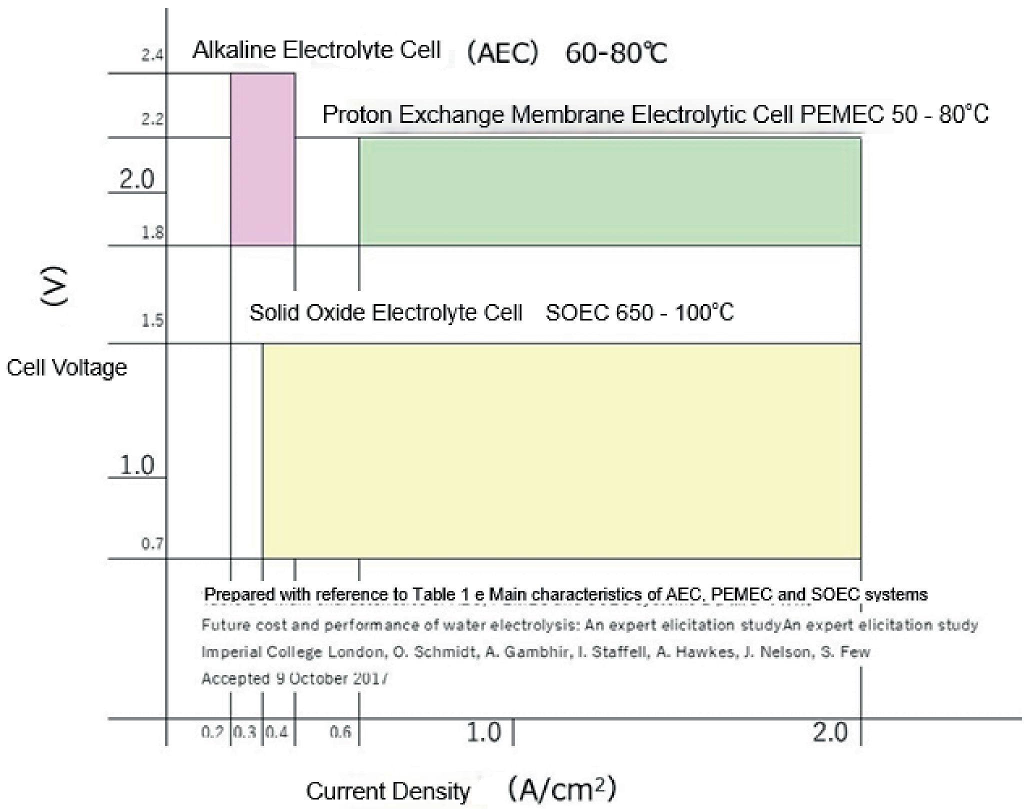


Figure 10 Performance comparison of water electrolysis methods (see [f5])

Methods for performing water electrolysis at low temperatures below 100° C include AWE and Polymer Electrolyte Membrane (PEM) water electrolysis. In India, AWE is positioned as a state-of-the-art improvement, whereas PEM water electrolysis is considered a research topic for future technology. AWE allows larger cell areas and has a strong track record for commercial applications. It is well-suited for locations where low-cost renewable energy can be secured on a large scale.

PEM water electrolysis allows high-density current flow, making it possible to build a compact system.

Another characteristic is its ability to produce high-purity hydrogen. PEM systems are suitable for small- and medium-scale sites where renewable energy sources are distributed. The challenge lies in using non-precious metals as electrode catalysts or minimizing the amount of precious metals used.

In contrast, the Solid Oxide Electrolysis Cell (SOEC), which employs a solid oxide-type electrolyte, is used for electrolyzing high-temperature steam (Figure 11). SOECs have high electrolysis efficiency because thermal energy can be used as part of electrolysis energy. This high-temperature process does not require precious metal catalysts and is resistant to catalyst poisoning by substances such as CO. Technological development efforts are focused on reducing cell voltage (V) to save energy and increasing current density (A/cm^2) to achieve higher efficiency. The challenge is to find the optimal balance between developing heat-resistant materials and lowering process temperatures. Research continues to reduce the temperature to around 800 to 600° C.

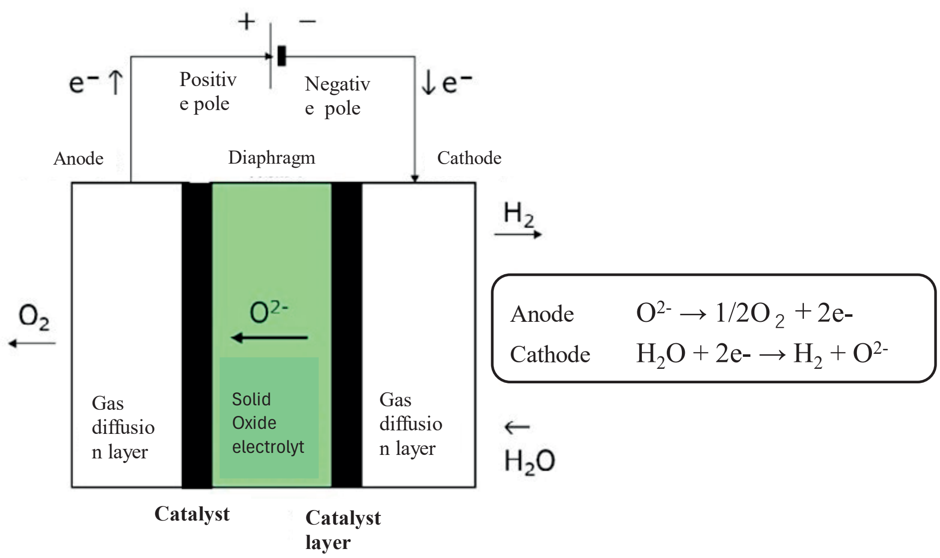


Figure 11 High-temperature steam electrolysis process

(5) Background of water electrolysis technology

The development of different water electrolysis methods is rooted in the electrochemical and electronic devices from which they originated (Figure 12). Researchers and companies advancing R&D are developing water electrolysis devices based on their accumulated technological expertise. Specifically, AEW and Anion Exchange Membrane (AEM) from Ion Exchange Membrane (IEM) have been adopted from caustic soda production via brine electrolysis. PEM technology derives from Liquid Crystal Displays (LCD) used as large-area substrates. SOECs originate from Multilayer Ceramic Capacitor (MLCC). Polymer Electrolyte Membrane Electrolysis Cells (PEMEC) are based on PEFCs, and SOECs come from SOFCs. The fuel cell reaction is the reverse of water electrolysis and shares the same electrolyte membrane.

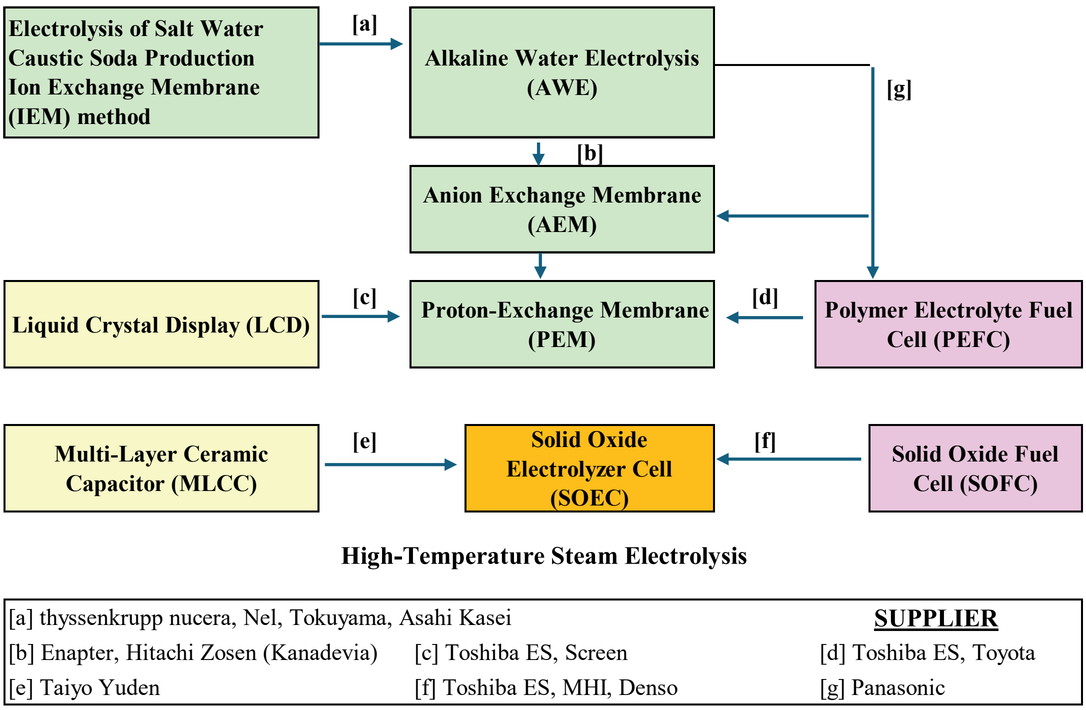


Figure 12 Background of water electrolysis technology (see [e4])

5 Materials Innovation

This section discusses innovations in materials used for electrodes and membranes in electrochemical devices, using a backcasting approach from society to theory—i.e., the flow from "society → integrated products → devices → materials → theory."

(1) Elements of interest

In Japan, the Committee of Battery Technology, the Electrochemical Society of Japan holds the Battery Symposium (2,000 to 3,000 participants) [f3] annually.

Past recipients of the Battery Technology Committee Award have conducted research on metal-air battery reaction analysis, cathode materials for sodium-ion batteries, solid electrolytes for all-solid-state batteries, and cathode materials for fluorine-ion batteries. According to the periodic table [c13], elements such as Li, Na, and F have traditionally been used as charge carriers for batteries, and more recently, elements such as Mg and H are being considered as promising alternatives.

(2) Solid electrolyte

The sulfide solid electrolyte Lithium Germanium Phosphorus Sulfide (LGPS), invented by Professor Ryoji Kanno of the Tokyo Institute of Technology and Toyota Motor Corporation, was featured on the cover of the first issue of Nature Energy in 2016. Japan has a top-class track record in solid electrolyte materials research, and further research is underway to replace Ge in LGPS with elements such as Si and halogens.

Figure 13 illustrates materials innovation. The vertical axis represents the electrode thickness. Mass productivity increases in the order of thin film, coating, and granules. While thicker electrodes offer higher capacity, they also increase electrode resistance. On the other hand, the horizontal axis represents ionic conductivity. Although the ionic conductivity of the electrolyte is limited to 10^{-2} S/m, solid electrolytes have the potential to reach up to 10^{-1} S/m. Higher ionic conductivity leads to greater power output. Innovations in solid electrolyte materials are expected to enable rechargeable batteries to achieve both high capacity and high output, while also allowing for mass productivity on a scale comparable to that of dry-cell batteries.

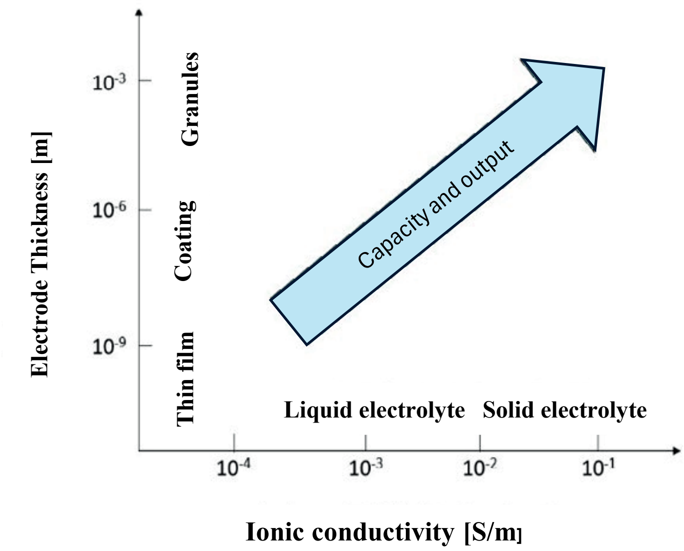


Figure 13 Image of materials innovation aiming for both high capacity and output, as well as mass productivity

(3) Solid interface

In all-solid-state devices, the solid interface is critically important. Maintaining contact between hard solid particles under varying conditions such as charging and discharging is essential. While it is preferable for ion movement resistance within the solid to be low (for high ionic conductivity), it is even more crucial to reduce the resistance at the much larger solid-particle interfaces. Figure 14 illustrates interface types (1) to (7) in all-solid-state batteries. In particular, the interface resistance between the electrode active material and the electrolyte was successfully reduced through coating, bringing the practical application of all-solid-state batteries closer to realization.

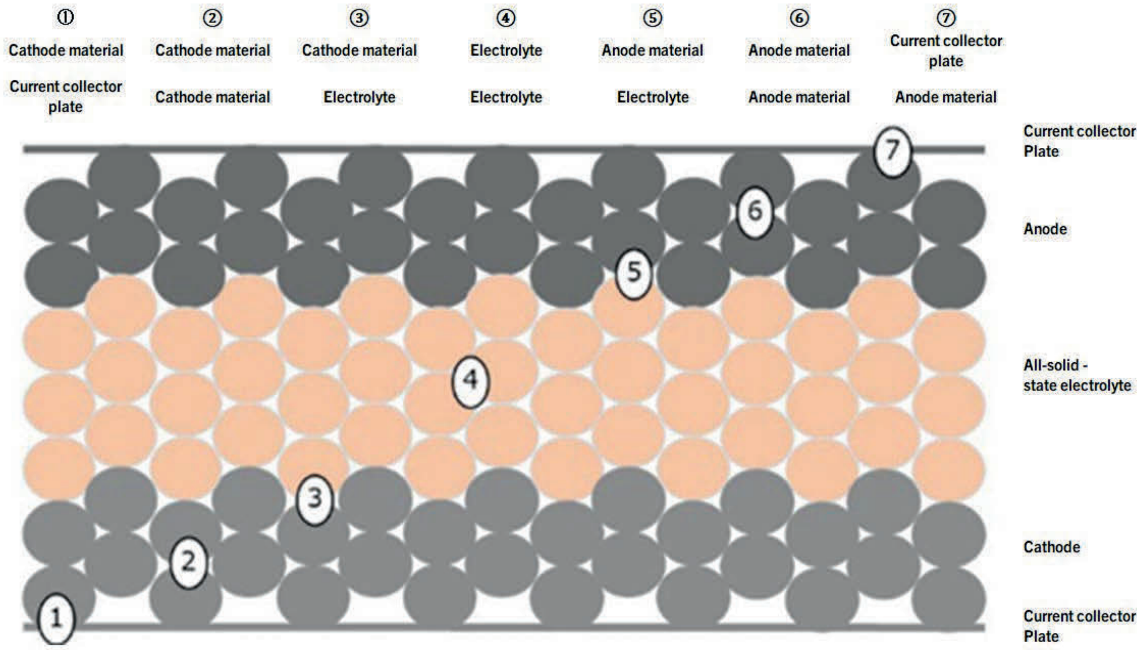


Figure 14 Types of interfaces in all-solid-state batteries (in addition, there are also interfaces with other additive auxiliaries)

(4) Exploration of new materials

In recent years, there has been an increasing number of proposals for new materials based on predictions from computational science, including Artificial Intelligence (AI). However, while AI excels at optimizing existing materials, it is said to be less effective at creating new materials. Breakthrough inventions in the past have often emerged from unexpected situations, such as experimental failures. Today's computers have not yet reached a comparable level of performance, and even the most advanced quantum computers still lag behind in terms of performance. Furthermore, the next challenge lies in determining whether the predicted new materials can actually be synthesized.

(5) Materials informatics (MI)

In electrochemical materials research, the use of informatics (information science) is advancing. As a new approach to materials research, the interdisciplinary field of "Materials Informatics (MI)" is gaining momentum, and consolidation and utilization of international research databases have begun. In addition to successful positive data, it is also essential to accumulate unsuccessful negative data [c1]. These initiatives are supported by recent improvements in semiconductor performance and the associated improvements in computational infrastructure. Machine learning and other technologies are being used to improve the efficiency of materials development for a variety of materials, including organic, inorganic, and metallic materials. Conventional research has discovered new materials experimentally, but in the "U.S. Materials Genome Initiative[f4]," Massachusetts Institute of Technology (MIT) and Samsung have discovered materials for high-performance batteries that are comparable to those found in cutting-edge conventional research without conducting experiments.

(6) Utilization of high-throughput experiments and computational infrastructure

In new research on electrode catalysts, AI provides support including the creation of experimental designs. AI preprocesses extensive datasets obtained from high-throughput automated unmanned experiments into a machine-learnable format, incorporates image processing to evaluate the experimental results, and suggests potential candidates for the next experimental plan. At the experimental results evaluation stage, AI analyzes the relationships within the large volumes of data obtained from high-throughput experiments—such as catalyst lifetime, reaction rate, catalyst composition, fabrication methods, and experimental conditions—and supports interpretation and hypothesis generation through image processing in a form easily understood by researchers. The construction and utilization of a large-scale materials database that organizes both negative and positive experimental data has been proposed to improve research efficiency.

6 Pursuit of Theories

(1) Exploration of principles and elucidation of mechanisms

Fundamental research requires establishing relevant theories. In the technological development of electrochemical devices, hypotheses are being formulated and tested based on scientific knowledge in fields such as chemistry, physics, and electrochemistry. Through phenomenal, structural, and compositional analyses, fundamental principles are being explored to elucidate these mechanisms.

(2) Design and theory

The establishment of theories in fundamental research is essential for manufacturing electrochemical devices. "A clear understanding of the underlying principles and mechanisms in the design of electrochemical devices facilitates battery production and reduces the likelihood of failure [b1]." It is essential to explore principles and elucidate mechanisms to integrate various design elements, such as multiscale materials and structures from the molecular to the nanoscale, multiphase reactions including charge-discharge processes and aging, and related multiphysics science. Electrochemical devices have been applied in materials research. In recent years, there has been increasing demand for the design of resource circulation, including considerations of durability and lifetime, which also relies on establishing theoretical foundations in fundamental research.

(3) Scientific and technological capabilities

Japan's scientific and technological capabilities often show a decline in technological development across companies, universities, and national research institutes. However, Japan continues to maintain a strong position in fundamental research in the field of materials, and it cannot be said that its scientific and technological capabilities in this field are declining. "What has changed is the approach to R&D in the field of materials research, and the real question is how Japan can find smarter, more effective ways to conduct R&D to remain competitive with Europe, the United States, and China [b1]."

For example, in a project supported by the Japan Society for the Promotion of Science (JSPS), many researchers are working together to advance research focused on establishing theories for constructing interfaces capable of freely transporting ions at high speeds and accumulating them at high concentrations, with the aim of enhancing the performance of solid-state battery devices, including all-solid-state batteries. The researchers noted, “There are plenty of opportunities for enthusiastic discussions anytime, anywhere, which facilitates progress in overcoming challenges [b1].” Research from this project has shown that “interfacial ion dynamics” —ion motion that differs from that within the solid—occurs at material interfaces, where ions, in addition to electrons and holes, are mobile. This theory provides guidelines for designing interfacial ion dynamics in solid-state ionic devices with both scientific and societal significance. A comprehensive understanding of this theory can elucidate the reasons for the occurrence of solid-state interfacial resistance in areas that are otherwise difficult to understand and explain.

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Field Survey Record

South Korea	December 2023
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India	March 2024 (Online)

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