



Chapter 5 Energy and Mining Engineering Fronts



5.1 Engineering research fronts

5.1.1 Trends in the Top 12 engineering research fronts

The Top 12 engineering research fronts as assessed by the Energy and Mining Engineering Group are shown in Table 5.1. These fronts involve the fields of energy and electrical science, technology, and engineering; nuclear science, technology, and engineering; geological resource science, technology, and engineering; and mining science, technology, and engineering. Among these 12 research fronts, “research on integrated CO₂ capture and *in situ* utilization”, “discovery of high ionic conductivity solid electrolytes”, and “study on large models of power system operation and maintenance” represent energy and electrical science, technology, and engineering research fronts; “principles of compact fusion and tritium resource conversion”, “simulation and testing of principles of glass solidification (vitrification) and other nuclear waste disposal methods”, and “experimental research on the application of a new type of heat pipe reactor in space reactors” represent nuclear science, technology, and engineering research fronts; “high-resolution remote sensing ore-forming information extraction based on deep learning”, “research on the sources and ore-forming processes of orogenic gold deposits”, and “*in situ* conversion mechanism of Chang 7 shale oil” represent geological resource science, technology, and engineering research fronts; and “Oil and gas with wind-light-heat-storage multi-energy integrated development and utilization”, “intelligent fine characterization of deep oil and gas reservoirs”, and “optimization of sensor networks in intelligent monitoring systems for coal mine safety” represent research fronts of mining science, technology, and engineering. The annual publication status of the core papers related to each front from 2018 to 2023 is shown in Table 5.2.

Table 5.1 Top 12 engineering research fronts in energy and mining engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Research on integrated CO ₂ capture and <i>in situ</i> utilization	50	4 890	97.80	2020.2
2	Principles of compact fusion and tritium resource conversion	2	89	44.50	2018.0
3	High-resolution remote sensing ore-forming information extraction based on deep learning	21	4 103	195.38	2020.7
4	Oil and gas with wind-light-heat-storage multi-energy integrated development and utilization	312	54 332	174.14	2019.9
5	Discovery of high ionic conductivity solid electrolytes	559	26 142	46.77	2021.2
6	Study on large models of power system operation and maintenance	307	6 737	21.94	2021.4
7	Simulation and testing of principles of glass solidification (vitrification) and other nuclear waste disposal methods	24	433	18.04	2019.8
8	Experimental research on application of a new type of heat pipe reactor in space reactors	39	889	22.79	2020.8
9	Research on the sources and ore-forming processes of orogenic gold deposits	42	2 145	51.07	2020.7
10	<i>In situ</i> conversion mechanism of Chang 7 shale oil	18	1 105	61.39	2020.2
11	Intelligent fine characterization of deep oil and gas reservoirs	1 088	12 237	11.25	2021.0
12	Optimization of sensor networks in intelligent monitoring systems for coal mine safety	4	200	50.00	2021.0

Table 5.2 Annual number of core papers published for the Top 12 engineering research fronts in energy and mining engineering

No.	Engineering research front	2018	2019	2020	2021	2022	2023
1	Research on integrated CO ₂ capture and <i>in situ</i> utilization	7	13	7	12	10	1
2	Principles of compact fusion and tritium resource conversion	2	0	0	0	0	0
3	High-resolution remote sensing ore-forming information extraction based on deep learning	0	3	6	7	5	0
4	Oil and gas with wind-light-heat-storage multi-energy integrated development and utilization	65	67	64	72	38	6
5	Discovery of high ionic conductivity solid electrolytes	37	66	75	120	108	153
6	Study on large models of power system operation and maintenance	13	24	49	47	82	92
7	Simulation and testing of principles of glass solidification (vitrification) and other nuclear waste disposal methods	4	5	8	5	2	0
8	Experimental research on the application of a new type of heat pipe reactor in space reactors	1	3	12	10	11	2
9	Research on the sources and ore-forming processes of orogenic gold deposits	3	5	11	11	7	5
10	<i>In situ</i> conversion mechanism of Chang 7 shale oil	2	1	9	5	0	1
11	Intelligent fine characterization of deep oil and gas reservoirs	107	121	159	198	250	253
12	Optimization of sensor networks in intelligent monitoring systems for coal mine safety	0	1	0	1	2	0

(1) Research on integrated CO₂ capture and *in situ* utilization

The integrated carbon dioxide (CO₂) capture and *in situ* utilization refers to the technology by which the adsorbed CO₂ is converted into high-value products without undergoing traditional temperature and pressure swing desorption processes. The core of this technology is to complete CO₂ capture and conversion within the same material system, thereby eliminating processes such as CO₂ separation, purification, storage, and transportation. Theoretically, it can significantly reduce costs and energy consumption, and simplify system processes. The CO₂ capture process can utilize solid adsorption or solution absorption to capture CO₂ and couple it with catalytic conversion. The mainstream technical route uses adsorption catalytic dual functional materials composed of alkali/alkaline earth metal oxide adsorbents and precious metal or transition metal catalysts. The adsorbed CO₂ is converted *in situ* through reaction processes such as methanation, reverse water gas gasification, and methane dry reforming. The main research directions and development trends of integrated CO₂ capture and *in situ* utilization include: ① high-performance, low-cost, and long-life dual functional materials, as well as the coupling reaction mechanism of CO₂ adsorption and *in situ* catalytic conversion; ② process parameter optimization, as well as renewable energy coupling technology; ③ large-scale demonstration application and technical and economic analysis of real scenarios.

(2) Principles of compact fusion and tritium resource conversion

In the field of magnetic confinement fusion, compact nuclear fusion refers to a technology aimed at developing smaller and cost-effective fusion reactors. In the past, several large tokamak devices have been constructed internationally to explore fusion research. However, these devices require significant financial investment. Additionally, the International Thermonuclear Experimental Reactor (ITER), a collaborative international project, demands extensive cooperation and shared financial responsibilities among multiple parties. In recent years, breakthroughs in high-temperature superconducting magnet technology have significantly reduced the economic costs associated with fusion reactors, leading to rapid advancements in compact fusion reactor technology. Compared to traditional nuclear fission, nuclear fusion offers a cleaner and safer energy source. However, for the most feasible deuterium-tritium fusion, the required tritium is extremely scarce in nature. To generate sufficient tritium for

future fusion reactors, lithium blankets are designed within the reactor, where neutrons produced by the fusion reaction bombard the lithium to produce tritium, and develop an efficient tritium recovery system to recycle tritium resources.

(3) High-resolution remote sensing ore-forming information extraction based on deep learning

The high-resolution remote sensing ore-forming information extraction technology based on deep learning utilizes deep learning models to automatically identify and extract key geological interpretation information (such as mineralized zones, rock types, and geological structures), ore-forming information extraction (alteration, hydroxyl), and mineral resource-related features from high-resolution remote sensing images. Combined with multi-source data fusion and feature optimization, it achieves precise location and classification of potentially mineralized areas, thereby enhancing the efficiency and accuracy of mineral exploration and providing a scientific basis for resource exploration. The main research directions in this field include feature extraction and identification, multi-source data fusion, spatiotemporal change analysis, and intelligent geological interpretation. Feature extraction and identification involve using deep learning models to automatically extract mineral and geological features from remote sensing images. Multi-source data fusion integrates multi-scale, multi-modal remote sensing data to enhance the capability of ore-forming information identification. Spatiotemporal change analysis uses time-series remote sensing data to monitor dynamic changes in geological bodies and identify potential mineralization activities. Intelligent interpretation automatically generates geological interpretation reports by coupling multi-source information to assist experts in mineral potential assessment. In the future, the high-resolution remote sensing ore-forming information extraction technology based on deep learning will usher in a series of significant development trends. These trends include obtaining more comprehensive ore-forming information through multi-source data fusion and spatiotemporal analysis, enhancing the interpretability and credibility of models to ensure the transparency and reliability of interpretation results, and realizing efficient analysis and mining of massive data through the deep integration of remote sensing big data and artificial intelligence. This technology will play an increasingly important role in mineral resource exploration, ore-forming prediction, and potential evaluation.

(4) Oil and gas with wind-light-heat-storage multi-energy integrated development and utilization

The integrated development and utilization of oil and gas with wind-light-heat-storage refers to the synergistic use of different energy forms during the development and production processes in oil and gas fields. This approach aims to improve energy efficiency and reduce environmental impact. By comprehensively considering the characteristics and advantages of renewable energy sources (such as wind, solar, and geothermal energy) and energy storage technologies, adopting comprehensive planning, shared infrastructure, energy storage and conversion technologies, intelligent management systems, and policy incentives, it aims to achieve multi-energy complementarity and efficient energy utilization in the construction of smart oilfields. The main research directions in this field include: ① the study of integrated development of multi-energy complementary microgrids and oil and gas production; ② theoretical research on the collaborative optimization and control of production in multi-energy complementary microgrids; ③ research on the source-network-load-storage configuration and production scheduling optimization methods for multi-energy microgrids in oil and gas fields. The independent mechanisms and optimization methods for oil and gas, renewable energy (such as wind and solar), and energy storage are gradually evolving into collaborative mechanisms and optimization methods for oil and gas with wind-light-heat-storage. With the advancement of information technology, the integrated development of oil and gas with wind-light-heat-storage is progressing towards efficient simulation, rapid decision-making, and intelligent control.

(5) Discovery of high ionic conductivity solid electrolytes

Compared to organic liquid electrolytes, solid-state electrolytes have a wider electrochemical window and higher safety, making them an important development direction for future power batteries and energy storage batteries. Nowadays, one of the main application bottlenecks of all-solid-state batteries is the limited charging and discharging rates. The strong ion interactions in bulk solid electrolytes and the high impedance at electrolyte-electrode interfaces lead to migration energy barriers that are 10 times higher than those in liquid electrolytes, retarding the charging and discharging processes. High Li-ion conductivity solid electrolytes are generally composed of inorganic ionic compounds. Based on their stable ion transport channels and good

mechanical adaptability at the interface, sulfur-based solid electrolytes exhibit a lithium-ion conductivity greater than 10 mS/cm at room temperature, which is comparable to commercial liquid electrolytes. By designing the electrolyte composition and studying interfacial stability, the reaction and diffusion energy barriers can be reduced, thereby further improving the lithium-ion conductivity of solid electrolytes. The development directions for electrolyte composition design are to optimize the chemical composition and design the crystalline structure, aiming to increase the number of ion conduction channels and reduce the ion-ion interactions to provide favorable conditions for the free diffusion of lithium ions. Research on interfacial stability primarily develops in the direction of interface passivation layers, coating layers, and alleviation of interfacial stress. It is worth noting that the physicochemical processes, such as ion transport and interface electrochemistry between solid electrolyte phases and electrodes, exhibit distinct coupling characteristics of the chemical field, electric field, and force field. By comprehensively considering the multi-field coupling effect, the experimental studies and theoretical models of solid-state electrolytes under real working conditions can effectively reveal the failure and runaway mechanisms in practical applications, which is an important direction for the development of high-ionic conduction solid-state electrolytes in the future.

(6) Study on large model of power system operation and maintenance

Power system is one of the largest and most complex man-made system in the world. In the context of developing a new type of power system, a large amount of distributed energy resources and flexible loads are integrated, leading to high dimensionality, nonlinearity, and dynamicity in system operation and maintenance. Traditional static modeling and centralized optimization methods can hardly satisfy the requirements in terms of calculation efficiency and accuracy.

The state-of-the-art AI techniques, represented by large-scale models, are promising in addressing the aforementioned problems. Generally speaking, large-scale models refer to neural networks with an extremely large parameter scale that can learn complex patterns from diversified data sets. For example, these models can extract patterns from power system time series measurements, images, and topologies to support system operation and maintenance. In a narrower sense, large-scale models refer to large language models (LLMs), such as ChatGPT, which can integrate and create multi-domain knowledge through the interactions between the model and users, and can also serve as an effective way of supporting power system operation and maintenance.

There exist several issues in the research on large-scale power system AI models: ① Fine-tuning of large-scale models based on limited data samples. Compared to the vast amount of textual information available on the Internet, the sample size of power system operational data, especially the data samples under extreme operating conditions, is much less to train a large-scale AI model from scratch. It is important to study how to efficiently train large-scale AI models based on limited data samples. ② Robustness and interpretability of large-scale AI models. The nature of these models is to learn statistical rules based on deep neural network with a hyperscale number of parameters, the process of which is hard to interpret and may generate inaccurate results. Such a characteristic is contrary to the reliability requirements of power system operation. ③ Data security. Power system operational data is highly sensitive and secured. Training AI models with power system data may lead to data security concerns.

(7) Simulation and testing of principles of glass solidification (vitrification) and other nuclear waste disposal methods

The high-level liquid waste treatment technology is the key technology at the back end of nuclear fuel reprocessing and one of the challenges in the sustainable development of nuclear energy in China. Glass solidification (vitrification) is currently the only industrialized high-level radioactive waste liquid treatment technology in the world, mainly including electrical heating ceramic furnaces and the cold crucible glass solidification technology, of which cold crucible technology, as the fourth-generation glass solidification process, is considered to be the most promising vitrification technology. The composition of high-level waste liquid is complex, containing more than 20 components. When it experiences a temperature change of nearly a thousand degrees Celsius with the base glass, complex physical and chemical reactions and phase transformations occur, and the transformation from high-level waste liquid glass compound to glass state is realized. The simulation of the conversion process from the compound to the glass state is the theoretical basis for the safe and efficient operation of the glass curing furnace. With the increase of burnup, the content of fission products and actinides in the spent fuel will rise, leading to high levels of radioactivity, high decay heat, and

high salt content in the high-level waste liquid from the power reactor. This will also significantly increase the content of refractory substances such as Zr and Mo in the glass curing produced by fission and precious metals, resulting in the accumulation of a large amount of precious metals at the bottom of the furnace and causing the blockage of the bottom discharge. The cold crucible, because of its unique induction heating method, can effectively solve these problems. It is necessary to draw on the experience of electric melting furnaces, focusing on basic problem research, long-term equipment and process verification, as well as cold crucible glass curing formula verification and performance research.

(8) Experimental research on the application of a new type of heat pipe reactor in space reactors

Compared with traditional chemical power and solar power, the nuclear reactor power source is one of the preferred solutions for deep space exploration because of its high energy density, long working life, no need for light and oxidant, and other advantages. Since the 1950s, the USA and Russia have designed a variety of nuclear reactor power supply schemes, such as ROMASHK, BUK, TOPAZ, and TOPAZ-2 from Russia, as well as the nuclear auxiliary power system SNAP-10A and Kilopower from the USA. However, as a high-altitude flight system, it is significantly limited by weight and volume. Therefore, it is necessary to reduce the reactor volume by improving heat transfer efficiency. The aviation nuclear power device based on the heat pipe small reactor can precisely solve this problem. With the development of aviation nuclear power systems, it will be applied to strategic cruise missile propulsion systems, nuclear cargo aircrafts, and nuclear propulsion in the future. The heat pipe reactor has become a focal point of research in the field of space nuclear reactors. Different from the traditional reactor design, the heat pipe reactor design offers strong flexibility and innovation. The use of different alkali metal heat pipes and thermoelectric conversion modes has a direct impact on the system power and the overall system quality, among which the thermoelectric converter plays a decisive role in the lifespan of the whole system, and it is possible to combine heat pipes with a variety of different thermoelectric conversion mode. The heat pipe reactor and the modular design are improved for different modules respectively, which reduces the overall system quality and improves the system safety. Therefore, the heat pipe reactor has great development space and potential in the future.

(9) Research on the sources and ore-forming processes of orogenic gold deposits

The classic orogenic gold deposit refers to quartz vein-type gold deposits formed under compression or strike-slip deformation in the accretionary or collisional orogeny at convergent plate margins. In general, the orogenic gold deposit is not simultaneous and has no genetic association with magmatism. The gold in the orogenic gold deposit mainly comes from terrigenous sediments, continental mafic rocks (e.g., komatiites), oceanic crust and its overlying sediments, as well as metasomatized mantle. In the process of sedimentation-diagenesis, gold occurs in arsenic-bearing pyrite in terrigenous sediments, which is released in the subsequent deformation process and extracted by fluid dehydrated from chlorite during progressive metamorphism from greenschist facies to amphibolite facies to form gold-bearing fluids. The fluid activity formed by the dehydration of subducting oceanic crust can extract a large amount of gold elements from the mafic rocks at the bottom of the lithosphere, forming gold bearing fluids. During the metamorphism of the subducted oceanic crust, the gold in gold-bearing sediments can be reactivated and migrated to form gold-bearing fluids. The gold in the metasomatic mantle can also form gold-bearing fluids during brief reactivation events. The gold in these fluids migrates in the form of S and Cl complexes or colloids and deposits in specific locations to form orogenic gold deposits through complex decomposition, metal droplet absorption, and colloid condensation. Thus, current research focuses on understanding the source of gold in orogenic deposits, the mechanisms of gold activation and mobilization, and the processes leading to its efficient concentration and deposition. Advances in this area are expected to result from the application of *in situ* micro-analysis, metal stable isotope, and other experimental techniques.

(10) *In situ* conversion mechanism of Chang 7 shale oil

The *in situ* conversion of shale oil underground at the depth ranging from 300 m to 3 000 m is a physical and chemical process caused by using horizontal drilling and electric heating technology, which converts heavy oil, bitumen, and various organic matter into light oil and gas on a large scale, which can be called an “underground refinery”. *In situ* conversion has significant advantages in CO₂ capture, recoverable resource potential, and the quality of hydrocarbon output. In view of the characteristics of organic matter-rich shale in Chang 7, the efficient conversion technology of underground “horizontal well with electric heating” is an

effective way for development and utilization of shale oil resources.

The origin of over-enrichment of organic matter in the lacustrine basin, the maceral component, and *in situ* conversion kinetics of organic matters are the core scientific problems of *in situ* conversion of shale oil, and the main research directions of *in situ* conversion of shale oil in Chang 7 include the mechanism of formation of organic-rich shale, the *in situ* conversion technology and heat-transfer mechanism, the flow mechanism of *in situ* conversion, and the *in situ* development technology of shale oil.

The organic matter-rich shale in Chang 7 of the Ordos Basin has continuous thickness, high organic matter abundance, and moderate maturity. The shale oil *in situ* conversion of this strata is the most realistic. The future development trend of basic research includes environmental response to organic matter enrichment and the role of the intervention of external substances, maceral component and differential hydrocarbon generation characteristics under energy field, the multi-phase conversion of the heat conduction dynamics of the organic matter, evolution of multi-phase hydrocarbon fluid field and the *in situ* conversion efficiency of hydrocarbon expulsion, the enrichment mechanism and resource distribution of shale oil with low-medium maturity, etc. In terms of engineering technology, the development of stabilized electric heating rods, high-efficiency composite heating technology, heater downhole process, precise and controllable reservoir conversion, the oil recovery process technology, etc. are the future development trends.

(11) Intelligent fine characterization of deep oil and gas reservoirs

The intelligent fine-grained representation methods of deep oil and gas reservoirs refer to the high-precision quantitative description and analysis of the structure, physical properties, and fluid distribution of deep underground oil and gas reservoirs by integrating multiple sources of geophysical data, geologic models, and artificial intelligence algorithms. The aim is to more accurately describe the complex structure of the deep reservoirs and their fluid distribution characteristics, thereby improving the precision of exploration and development efficiency of the oil and gas reservoirs.

The main research directions include: ① using artificial intelligence and machine learning to form a multivariate data fusion method of seismic data, well logging data, core analysis results, etc., in order to construct a more detailed reservoir model; ② establishing a digital model of deep reservoirs to simulate the generation, migration, and accumulation processes of oil and gas based on high-resolution 3D seismic data and geological information; ③ strengthening the application of machine learning and deep learning algorithms to make the prediction of reservoir parameters and identification of fluid distribution more accurate, and integrating different methods to provide a more comprehensive guide to the development of deep oil and gas reservoirs.

With the improvement of computing power and the development of the big data technology, intelligent fine-grained representation methods increasingly rely on real-time data processing and dynamic model updating. The future research trend ① will focus on real-time data acquisition and processing during drilling, and dynamic fine-grained characterization of reservoirs; ② integrated analysis of reservoir properties at different scales; ③ more precise and automated characterization methods to complete the fine-grained characterization of reservoirs with minimal human intervention.

(12) Optimization of sensor networks in intelligent monitoring systems for coal mine safety

The intelligent monitoring system for coal mine safety is a comprehensive system that integrates various sensor technologies, data processing techniques, and communication technologies. Its core function is to continuously monitor environmental parameters within the mine, such as gas concentrations, temperature, humidity, and pressure, in real-time through sensors. The data collected is then transmitted to a central control system via a network. Optimizing the sensor network involves enhancing sensor layout, data transmission efficiency, and information processing capabilities to achieve real-time, efficient, and secure monitoring objectives, thereby ensuring the safety of miners and the proper operation of equipment. The main research directions include sensor layout optimization, data fusion and processing technologies, communication network optimization, and intelligent early warning systems.

In the future, the sensor networks of the intelligent monitoring systems for coal mine safety are expected to develop towards intelligence, automation, and integration. Specific trends include the continuous development of highly intelligent sensors (such

as multifunctional sensors and intelligent monitoring devices) to enhance the diversity and accuracy of data collection; with the development of the Internet of Things (IoT) technology, more sensors will be connected via networks to achieve real-time data sharing and intelligent analysis, thereby forming an efficient safety monitoring network; the utilization of cloud computing and big data analytics will facilitate the storage, processing, and analysis of vast amounts of data, providing decision support for coal mine safety management; and the development of adaptive monitoring systems will automatically adjust the operation of sensors and monitoring strategies based on environmental changes to improve flexibility and responsiveness in monitoring activities.

5.1.2 Interpretations for four key engineering research fronts

5.1.2.1 Research on integrated CO₂ capture and *in situ* utilization

The carbon dioxide (CO₂) capture and utilization (CCU) technology is a key technology to achieve the dual goals of “carbon peaking and carbon neutrality”. However, the traditional CCU process requires a large amount of energy and complex systems for CO₂ desorption, purification, transportation, storage, and subsequent utilization, which greatly restricts the promotion and application of CCU technology. The integrated CO₂ capture and *in situ* utilization (ICCU) technology provides a new strategy by which CO₂ is captured and utilized in the same material. The CO₂ adsorbed is catalytically converted into fuel or chemicals in the adsorption state without the need for desorption, purification, storage, and transportation processes. This can reduce system complexity and greatly improve energy utilization efficiency.

In ICCU technology, the CO₂ capture process can use solid adsorption or solution absorption to capture CO₂ and couple it with catalytic conversion. In 2015, Professor Melis’s group at Columbia University first proposed the concept of adsorption catalytic dual functional materials (DFMs), which were formed by loading calcium oxide adsorbents and ruthenium catalysts on alumina supports to create DFMs. This technical route based on DFMs composed of alkali/alkaline earth metal oxide adsorbents and precious metal or transition metal catalysts, gradually developed into the mainstream ICCU technology. In current research on ICCU technology, the *in situ* catalytic conversion pathway of CO₂ is primarily conducted through reaction processes such as methanation, reverse water gasification, and methane dry reforming. The main research directions of ICCU technology include: ① high-performance, low-cost, and long-life dual functional materials, as well as the coupling reaction mechanism of CO₂ adsorption and *in situ* catalytic conversion; ② process parameter optimization, as well as renewable energy coupling technology; ③ large-scale demonstration applications and technical and economic analysis of real scenarios.

In the research front of “research on integrated CO₂ capture and *in situ* utilization”, the countries with the greatest output of core papers and the citations per paper are China and the USA, respectively (Table 5.3), and there are numerous collaborations among China and the UK (Figure 5.1). Among the top ten institutions in terms of the number of papers published, East China University of Science and Technology and Chinese Academy of Sciences rank top two, while the institutions with the highest citations per paper are China University of Geosciences and Sichuan University (Table 5.4). There are many collaborations between the University of Electronic Science and Technology of China and China University of Geosciences, as well as between the University of Electronic Science and Technology and Sichuan University (Figure 5.2). Countries and institutions with the greatest output of citing papers are shown in Tables 5.5 and 5.6.

For large-scale industrial demonstration applications in the next 5 to 10 years, the ICCU technology will further improve the performance of dual-functional materials, achieve low-cost mass preparation, and reduce operational energy consumption through reactor design, process optimization, and renewable energy coupling. At the same time, through material innovation, application scenarios can be expanded, such as direct air CO₂ capture combined with *in situ* conversion integration, exploring new conversion pathways, such as photocatalysis, electrocatalysis, plasma catalysis, homogeneous catalysis, etc. At present, the ICCU technology has completed laboratory small-scale verification, and it is expected to achieve thousand-ton level demonstration verification, and industrial demonstration by 2034 (Figure 5.3).

Table 5.3 Countries with the greatest output of core papers on “research on integrated CO₂ capture and *in situ* utilization”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	37	74.00	3 782	102.22	2020.3
2	USA	7	14.00	738	105.43	2019.0
3	UK	6	12.00	512	85.33	2020.7
4	Singapore	4	8.00	283	70.75	2020.8
5	Switzerland	3	6.00	213	71.00	2019.3
6	Australia	2	4.00	645	322.50	2019.0
7	Canada	2	4.00	165	82.50	2021.0
8	Sweden	2	4.00	130	65.00	2020.0
9	Egypt	1	2.00	155	155.00	2020.0
10	India	1	2.00	155	155.00	2020.0

Figure 5.1 Collaboration network among major countries in the engineering research front of “research on integrated CO₂ capture and *in situ* utilization”Table 5.4 Institutions with the greatest output of core papers on “research on integrated CO₂ capture and *in situ* utilization”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	East China University of Science and Technology	4	8.00	269	67.25	2022.0
2	Chinese Academy of Sciences	3	6.00	809	269.67	2018.3
3	University of Electronic Science and Technology of China	3	6.00	752	250.67	2020.0
4	Queen's University Belfast	3	6.00	301	100.33	2021.7
5	National University of Singapore	3	6.00	216	72.00	2021.0
6	Nanjing University of Science and Technology	3	6.00	160	53.33	2020.0
7	China University of Geosciences	2	4.00	672	336.00	2020.0
8	Sichuan University	2	4.00	567	283.50	2019.5
9	University of Science and Technology of China	2	4.00	420	210.00	2019.0
10	University of Southern California	2	4.00	337	168.50	2019.0

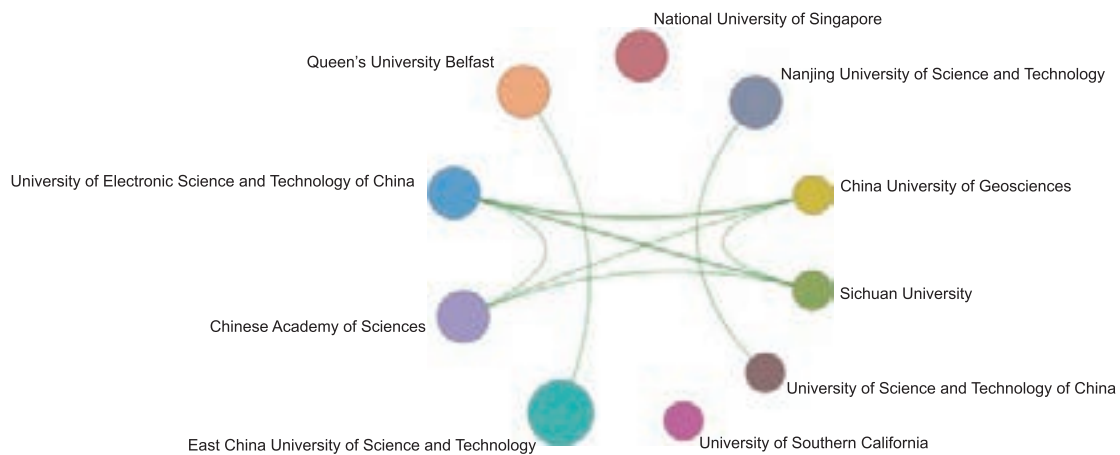


Figure 5.2 Collaboration network among major institutions in engineering research front of “research on integrated CO₂ capture and *in situ* utilization”

Table 5.5 Countries with the greatest output of citing papers on “research on integrated CO₂ capture and *in situ* utilization”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	458	57.76	2020.8
2	USA	68	8.58	2020.3
3	Australia	55	6.94	2020.6
4	UK	35	4.41	2020.9
5	India	34	4.29	2020.5
6	Singapore	30	3.78	2021.0
7	Republic of Korea	27	3.40	2020.6
8	Germany	23	2.90	2020.8
9	Japan	22	2.77	2020.6
10	Canada	21	2.65	2021.0

Table 5.6 Institutions with the greatest output of citing papers on “research on integrated CO₂ capture and *in situ* utilization”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	66	24.81	2020.3
2	China University of Geosciences	33	12.41	2020.7
3	University of Science and Technology of China	26	9.77	2020.9
4	Zhengzhou University	24	9.02	2021.1
5	Jiangsu University	23	8.65	2020.8
6	Tianjin University	19	7.14	2020.6
7	University of Electronic Science and Technology of China	18	6.77	2021.3
8	Tsinghua University	16	6.02	2021.4
9	Nanyang Technological University	15	5.64	2020.9
10	Beijing University of Chemical Technology	14	5.26	2020.4



Figure 5.3 Roadmap of the engineering research front of "research on integrated CO₂ capture and *in situ* utilization"

5.1.2.2 Principles of compact fusion and tritium resource conversion

The development of nuclear fusion technology began in the mid-20th century. Early research primarily focused on large-scale fusion devices, which achieved some experimental success. For instance, the Tokamak Fusion Test Reactor (TFTR) was constructed in 1982 at the Princeton Plasma Physics Laboratory in the USA, becoming a prominent device for deuterium-tritium experiments. The TFTR had a major radius of 3.1 meters, a minor radius of 0.96 meters, a magnetic field of 6 T, a plasma current of 3 MA, and a total heating power of 50 MW. In Europe, the Joint European Torus (JET) was built, becoming the first device to conduct 50%:50% deuterium-tritium experiments. Similarly, Japan constructed a large Tokamak device, JT-60 (Torus-60), which, along with TFTR and JET, became one of the three major Tokamak facilities in the world. To further advance fusion energy, the International Thermonuclear Experimental Reactor (ITER) project was initiated, involving collaboration among the European Union, China, Republic of Korea, Russia, Japan, India, and the USA. ITER is the largest and most influential international scientific endeavor in the world to date. These large-scale devices aimed to explore the feasibility of developing and utilizing magnetic confinement fusion energy. However, due to their enormous scale and high costs, commercial applications face challenges. In the 21st century, with breakthroughs in high-temperature superconducting magnet technology, researchers began focusing on the development of compact fusion devices. The compact fusion technology, leveraging high-temperature superconducting magnets, can achieve the miniaturization of fusion devices, significantly reducing the economic costs of fusion development. Notable examples include the SPARC device developed by Commonwealth Fusion Systems, an independent nuclear fusion startup spun out from the Massachusetts Institute of Technology (MIT). The superconducting coils of SPARC are expected to generate a magnetic field of up to 20 T. The SPARC project is scheduled to be completed and conduct deuterium-tritium experiments by 2025. Another example is the STEP device, overseen by the Culham Centre for Fusion Energy in the United Kingdom. Research in compact nuclear fusion heavily relies on international collaboration. This cooperation not only includes bilateral or multilateral agreements between research institutions, but also necessitates multidisciplinary collaboration, involving material science, plasma physics, engineering, etc. In summary, research in compact nuclear fusion is being conducted globally, requiring close cooperation among countries and regions to tackle technological challenges and promote the sustainable development of this field.

In the research front of "principles of compact fusion and tritium resource conversion", the top three countries in terms of the number of core papers published are the UK, Germany, and Canada (Table 5.7 and Figure 5.4). The primary contributing institutions of core papers are Culham Science Centre, EUROfusion Consortium, Karlsruhe Institute of Technology, Kinectrics Inc., and Open University (Table 5.8). Among the top five institutions, there are more collaborations among Culham Science Centre, EUROfusion Consortium, and Karlsruhe Institute of Technology, as well as more collaborations between Kinectrics Inc. and Open University (Figure 5.5). The main output countries of citing papers are Germany and the USA (Table 5.9), while the main output institutions of citing papers are Karlsruhe Institute of Technology and Max Planck Institute for Plasma Physics (Table 5.10).

The future development of compact nuclear fusion technology will focus on optimizing technology, innovating materials, and scaling up applications. The main areas of focus include:

- 1) Application and optimization of high-temperature superconducting magnets: High-temperature superconducting magnets are critical components of compact nuclear fusion devices. Future research will aim to develop more efficient and stable superconducting magnets to enhance plasma confinement, reduce the size of the devices, and increase energy density. Institutions like the Massachusetts Institute of Technology (MIT) have already made initial breakthroughs in this area, and future efforts will focus on further optimizing magnet materials and cooling technologies.

Table 5.7 Countries with the greatest output of core papers on “principles of compact fusion and tritium resource conversion”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	UK	2	100.00	89	44.50	2018.0
2	Germany	1	50.00	48	48.00	2018.0
3	Canada	1	50.00	41	41.00	2018.0

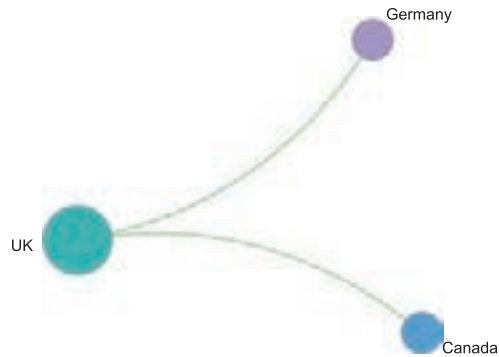


Figure 5.4 Collaboration network among major countries in the engineering research front of “principles of compact fusion and tritium resource conversion”

Table 5.8 Institutions with the greatest output of core papers on “principles of compact fusion and tritium resource conversion”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Culham Science Centre	1	50.00	48	48.00	2018.0
2	EUROfusion Consortium	1	50.00	48	48.00	2018.0
3	Karlsruhe Institute of Technology	1	50.00	48	48.00	2018.0
4	Kinectrics Inc.	1	50.00	41	41.00	2018.0
5	Open University	1	50.00	41	41.00	2018.0

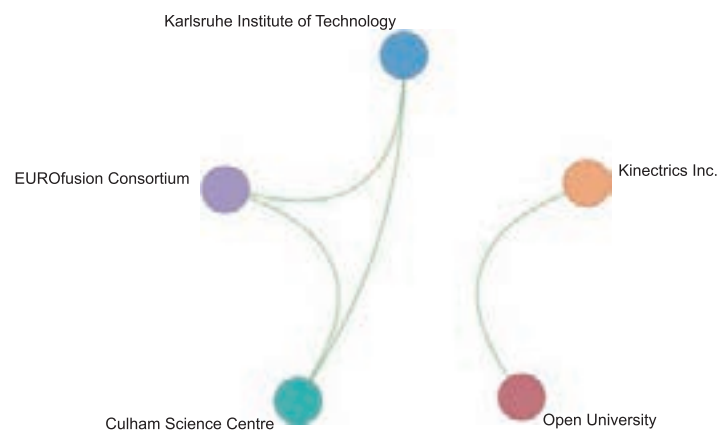


Figure 5.5 Collaboration network among major institutions in the engineering research front of “principles of compact fusion and tritium resource conversion”

Table 5.9 Countries with the greatest output of citing papers on “principles of compact fusion and tritium resource conversion”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	Germany	19	19.59	2020.4
2	USA	19	19.59	2021.6
3	Italy	14	14.43	2021.3
4	UK	12	12.37	2020.9
5	China	10	10.31	2020.8
6	Russia	6	6.19	2020.5
7	Japan	6	6.19	2021.8
8	France	4	4.12	2021.0
9	Romania	3	3.09	2020.0
10	Canada	2	2.06	2022.0

Table 5.10 Institutions with the greatest output of citing papers on the “principles of compact fusion and tritium resource conversion”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Karlsruhe Institute of Technology	10	19.61	2020.6
2	Max Planck Institute for Plasma Physics	6	11.76	2020.2
3	EUROfusion Consortium	5	9.80	2019.8
4	Politecnico di Torino	5	9.80	2022.0
5	Chinese Academy of Sciences	4	7.84	2021.2
6	Culham Science Centre	4	7.84	2020.2
7	China Academy of Engineering Physics	4	7.84	2021.2
8	Italian National Agency for New Technologies, Energy and Sustainable Economic Development	4	7.84	2021.5
9	Sun Yat-sen University	3	5.88	2019.7
10	Bauman Moscow State Technical University	3	5.88	2020.0

2) Development of new materials: The materials used in fusion devices must withstand extremely high temperatures and intense radiation. Future research will focus on developing new materials that are resistant to high temperatures and radiation, thereby improving the lifespan and safety of fusion reactors.

3) Tritium fuel cycle system: The production, recovery, and management of tritium are crucial for the sustained operation of compact nuclear fusion devices. Research directions include efficient tritium production technologies, tritium recovery, and recycling systems.

4) Miniaturization and modularization of reactor design: Developing smaller and modular reactor designs will be a key area of focus, allowing for more flexible and cost-effective fusion devices.

The future trends will involve transitioning from experimental validation to prototype development and commercial exploration. Compact nuclear fusion holds enormous potential for energy security and sustainability. Furthermore, advancements in the fusion technology will drive progress in other high-tech fields. In the future, the compact nuclear fusion technology will prioritize the exploration of high-temperature superconducting magnets, new materials, and tritium fuel cycle systems (Figure 5.6). The technology has vast potential for development and a wide range of application scenarios. It is not only expected to solve the energy crisis but also to drive technological progress and economic development. However, commercial applications still require time and collaborative international efforts.

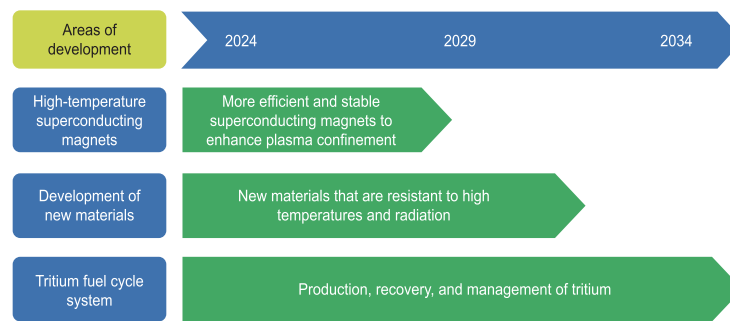


Figure 5.6 Roadmap of the engineering research front of “principles of compact fusion and tritium resource conversion”

5.1.2.3 High-resolution remote sensing ore-forming information extraction based on deep learning

The high-resolution remote sensing ore-forming information extraction technology is an integrated approach that relies on remote sensing image processing, geological information analysis, and deep learning. It is applied in the field of geological mineral exploration. The core of this technology is the use of deep learning algorithms to automatically identify and extract relevant features such as geological interpretations of fault structures, ore-forming information, and mineral resources from high-resolution remote sensing images. By combining multi-source data fusion and feature optimization, precise localization and classification of potentially mineralized areas can be achieved, thereby improving the efficiency and accuracy of mineral exploration and assisting in geological exploration and resource evaluation. The development of ore-forming information extraction technology based on remote sensing images has evolved from traditional image interpretation to automation, multi-source data fusion, and intelligent deep learning algorithms. Initially, remote sensing ore-forming information extraction relied on expert experience and manual interpretation. With the widespread application of high spatial and hyperspectral remote sensing data, the extraction of ore-forming information has gradually shifted towards pixel-based and feature-based automated analysis. New methods such as new RGB combinations, band ratios, and selective principal component analysis have been used to highlight and extract remote sensing alterations related to minerals, achieving indirect mineral identification. In recent years, with the continuous launch of remote sensing satellites equipped with high spatial and hyperspectral resolution optical sensors and the popularization of the UAV remote sensing technology, methods such as weakly supervised object detection, semantic segmentation, and change detection have been employed to achieve high-precision identification and extraction of ore-forming information. In this context, the “artificial intelligence + remote sensing big data” model has become the mainstream direction in the field of ore-forming information extraction. The main research directions include the “spatial-spectral-temporal” joint feature extraction of high-resolution images and the development of automated ore-forming information extraction algorithms based on deep learning. These high-precision, intelligent ore-forming information extraction technologies have an important practical significance and strategic value in mineral resource exploration, national strategic resource security, and other aspects.

In China’s new round of strategic actions for achieving breakthroughs in mineral exploration, there is an emphasis on advancing the integrated remote sensing mineral exploration system that combines satellite, aerial, ground, and subsurface methods. Research has been conducted at three levels: ① For mineralized belts, satellite remote sensing data, particularly the hyperspectral satellite data recently launched by China, is used to select prospective mining areas. ② In key research areas, aerial or drone remote sensing data is employed to pinpoint locations or delineate target areas. ③ At the minefield scale, ground or core spectrometers are used to conduct detailed alteration mineral mapping of the surface or core samples, analyze the ore-forming environment, and identify hydrothermal centers, providing technical support for subsequent mineral exploration deployment.

In the research front of “high-resolution remote sensing ore-forming information extraction based on deep learning”, China ranks first in the number of core papers, with 20 papers accounting for 95.24% of the total. The proportion of papers from other countries is less than 10.00%. Italy ranks second with two core papers, accounting for 9.52% (Table 5.11). Regarding the main output institutions of core papers (Table 5.12), 8 of the top ten institutions are from China, with Wuhan University, the Chinese

Academy of Sciences, and Beihang University occupying the top three positions. China is also the leading country in terms of the number of cited core papers in this research front, accounting for 73.04% of the total. The USA ranks second, with 96 papers, accounting for only 5.98% (Table 5.13). Among the institutions producing the most cited core papers, Wuhan University, the Chinese Academy of Sciences, and Xidian University rank in the top three positions (Table 5.14). Collaborations in this field are primarily between China, Italy, the USA, and the Netherlands (Figure 5.7). There are institutional collaborations among Wuhan University, Nanjing University of Information Science and Technology, the Italian Space Agency, and China University of Mining and Technology (Figure 5.8).

In the next 5 to 10 years, the high-resolution remote sensing ore-forming information extraction based on deep learning will usher in a series of significant development trends (Figure 5.9). The optimization and innovation of deep learning models will lead to the emergence of more models specifically optimized for remote sensing data characteristics, such as lightweight models and self-supervised learning models, which will enhance the accuracy and efficiency of ore-forming information extraction. Multi-source data fusion and joint analysis using the “time-space-spectrum” combined analysis model will achieve a more comprehensive extraction of ore-forming information. The coordinated application of drones and ground-based remote sensing will enhance exploration accuracy through high-precision data collection and ore-forming feature analysis. The integration of satellite remote sensing, aerial remote sensing, ground surveying, and deep exploration will form an integrated mineral exploration system (satellite-air-ground-depth integrated remote sensing exploration system), which will improve the capability and application level of ore-forming information extraction at different scales. The deep integration of remote sensing big data and artificial intelligence will enable efficient analysis and mining of massive datasets. As these development trends advance, the application prospects of high-resolution remote sensing ore-forming information extraction based on deep learning will become more widespread, providing more powerful tools for resource management, ore-forming prediction, and mineral resource potential evaluation.

Table 5.11 Countries with the greatest output of core papers on “high-resolution remote sensing ore-forming information extraction based on deep learning”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	20	95.24	4 037	201.85	2020.6
2	Italy	2	9.52	466	233.00	2020.5
3	USA	2	9.52	69	34.50	2022.0
4	Netherlands	1	4.76	623	623.00	2019.0
5	Australia	1	4.76	61	61.00	2020.0

Table 5.12 Institutions with the greatest output of core papers on “high-resolution remote sensing ore-forming information extraction based on deep learning”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Wuhan University	9	42.86	2 248	249.78	2020.1
2	Chinese Academy of Sciences	3	14.29	368	122.67	2020.7
3	Beihang University	2	9.52	795	397.50	2020.5
4	Nanjing University of Information Science and Technology	2	9.52	468	234.00	2020.0
5	China University of Mining and Technology	2	9.52	277	138.50	2020.0
6	Xinjiang University	2	9.52	253	126.50	2021.5
7	Capital Normal University	2	9.52	194	97.00	2021.5
8	University of Utrecht	1	4.76	623	623.00	2019.0
9	Collaborative Innovation Center of Geospatial Technology	1	4.76	347	347.00	2020.0
10	Italian Space Agency	1	4.76	347	347.00	2020.0

Table 5.13 Countries with the greatest output of citing papers on “high-resolution remote sensing ore-forming information extraction based on deep learning”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	1 173	73.04	2022.1
2	USA	96	5.98	2021.8
3	India	58	3.61	2022.4
4	UK	50	3.11	2022.0
5	Germany	47	2.93	2021.8
6	Italy	42	2.62	2021.8
7	Republic of Korea	40	2.49	2021.8
8	Canada	33	2.05	2021.8
9	France	24	1.49	2021.8
10	Australia	22	1.37	2021.9

Table 5.14 Institutions with the greatest output of citing papers on “high-resolution remote sensing ore-forming information extraction based on deep learning”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Wuhan University	179	26.09	2021.9
2	Chinese Academy of Sciences	166	24.20	2022.0
3	Xidian University	55	8.02	2022.2
4	China University of Geosciences	49	7.14	2022.0
5	Nanjing University of Information Science and Technology	46	6.71	2021.8
6	Sun Yat-sen University	40	5.83	2022.0
7	Northwestern Polytechnical University	34	4.96	2021.8
8	Beihang University	31	4.52	2022.0
9	Nanjing University of Science and Technology	29	4.23	2022.1
10	Ministry of Natural Resources	29	4.23	2022.2

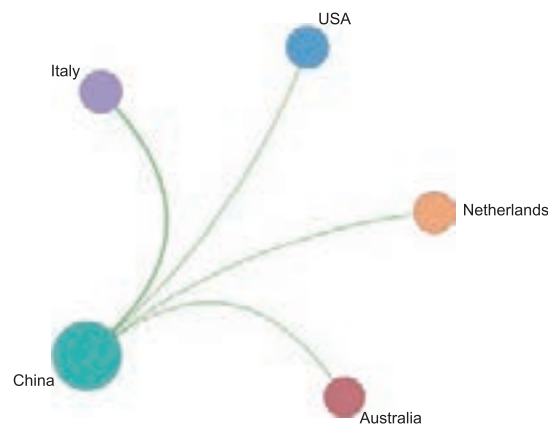


Figure 5.7 Collaboration network among major countries in the engineering research front of “high-resolution remote sensing ore-forming information extraction based on deep learning”

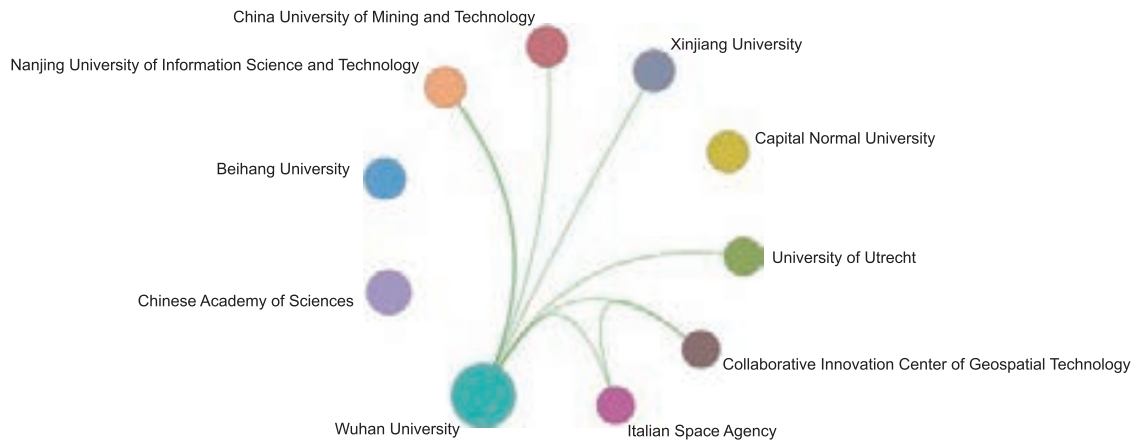


Figure 5.8 Collaboration network among major institutions in the engineering research front of “high-resolution remote sensing ore-forming information extraction based on deep learning”

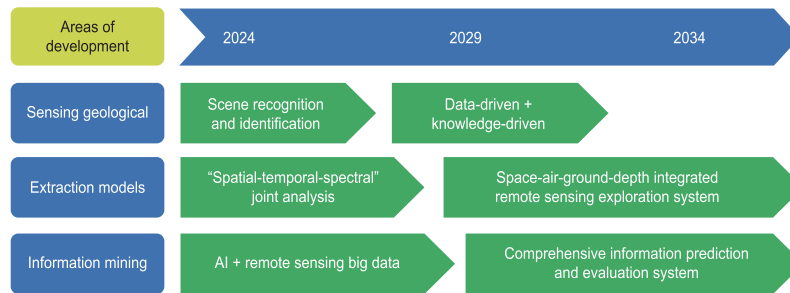


Figure 5.9 Roadmap of the engineering research front of “high-resolution remote sensing ore-forming information extraction based on deep learning”

5.1.2.4 Oil and gas with wind-light-heat-storage multi-energy integrated development and utilization

The integrated development and utilization of multiple energy sources is a key approach to building a clean, low-carbon, safe, and efficient new energy system, and is also an inevitable trend in addressing energy challenges in oil and gas exploration and development. In the context of oil and gas field development, combining new energy sources such as wind, solar energy, and geothermal energy with traditional fossil fuels enables the complementary synergy of multiple energy sources. This further promotes the steady increase and efficient development of oil and gas production, thereby advancing the sustainable development and green, low-carbon transformation of the oil and gas industry.

In the field of multi-energy integration, countries such as the USA and Japan have actively issued policies to support this development. For instance, as early as 1989, Sweden established a solar and biomass combined heating project. In recent years, the integrated development and utilization of wind-light-heat-storage, which involves the synergistic optimization of new energy and energy storage, has become a research hotspot. The research mainly focuses on systems composed of photovoltaic and wind power stations with storage batteries, or systems paired with electric heating and heat accumulation devices, aiming to optimize equipment capacity and analyze the economic performance of power generation systems. With increasing uncertainties such as energy supply shortages and unclear global economic prospects, promoting the development of wind-light-heat-storage integration in oil and gas field scenarios will provide effective means for the high-quality development of the oil and gas industry. Fully leveraging wind power development to supply green electricity to oil and gas platforms can create a complementary power supply model between wind power and regional oil and gas field power systems, enhancing the local consumption capacity of

new energy. In oil and gas mining areas and their surrounding regions, utilizing solar energy for heat collection and accumulation technology can fully harness the diverse functions of geothermal energy storage, such as peak shaving, frequency regulation, emergency backup, and capacity support, thereby promoting the application of geothermal energy in both power supply and oil and gas exploration scenarios, and advancing the coordinated development of energy storage and new energy sources. In the later stages of crude oil extraction, energy consumption per ton of oil is approximately 140–160 kW·h, with electricity expenses accounting for over 30% of development costs. The integrated development and utilization of wind-light-heat-storage can locally consume photovoltaic and wind energy at a transaction price lower than that of the State grid, optimizing oil and gas development, maximizing economic benefits, and ensuring safe and environmentally friendly operations.

The research directions for the integrated development and utilization of oil and gas with wind-light-heat-storage will focus on improving the accuracy of wind and solar resource forecasting and the precision of wind and photovoltaic power generation forecasting. It will also aim to enhance the adaptability of wind and photovoltaic power generation to power system disturbances, expand the functions of geothermal energy storage for peak shaving and frequency regulation, and support the stable operation of oil and gas production. Additionally, for oil and gas field application scenarios, optimizing system equipment configuration schemes according to local conditions will be essential to achieve the economic supply of energy through a coordinated multi-energy system. Furthermore, strategies will be developed to address real-time fluctuations in weather conditions, such as solar intensity, wind speed, and temperature, as well as energy demand, ensuring flexible and reliable energy supply. System parameter control methods will be optimized, and the distribution of electrical and thermal energy will be rationalized to achieve flexible and reliable energy supply.

In the research front of “oil and gas with wind-light-heat-storage multi-energy integrated development and utilization”, the main contributing countries are China, the USA, and Germany (Table 5.15 and Figure 5.10). The primary contributing institutions are Chinese Academy of Sciences, Tsinghua University, and National University of Singapore (Table 5.16). There are institutional collaborations among Chinese Academy of Sciences, Tsinghua University, Swiss Federal Institute of Technology Zurich, University of Cambridge, Lawrence Berkeley National Laboratory, University of California, Berkeley, Massachusetts Institute of Technology, and Colorado School of Mines (Figure 5.11). The top three countries in terms of citing papers are China, the USA, and Australia (Table 5.17). The main output institutions of citing core papers are Chinese Academy of Sciences, Tsinghua University, Tianjin University, Zhengzhou University, and University of Science and Technology of China (Table 5.18).

Multi-energy synergy can promote the integrated development of new and traditional energy industries, serving as an important means of building a clean, low-carbon, safe, and efficient new energy system. By focusing on clean substitution, various green electricity devices can be deployed at production sites, abandoned oil and gas wells (fields), and other locations, maximizing the substitution rate of green electricity in oil and gas fields.

Table 5.15 Countries with the greatest output of core papers on “oil and gas with wind-light-heat-storage multi-energy integrated development and utilization”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	121	38.78	18 982	156.88	2019.9
2	USA	57	18.27	12 905	226.40	2019.9
3	Germany	35	11.22	8 282	236.63	2019.8
4	UK	31	9.94	6 135	197.90	2019.8
5	Australia	23	7.37	6 114	265.83	2020.1
6	India	20	6.41	2 779	138.95	2020.6
7	Canada	18	5.77	3 273	181.83	2020.6
8	Saudi Arabia	16	5.13	1 729	108.06	2020.2
9	Singapore	14	4.49	3 216	229.71	2020.1
10	Italy	14	4.49	2 251	160.79	2020.1



Figure 5.10 Collaboration network among major countries in the engineering research front of “oil and gas with wind-light-heat-storage multi-energy integrated development and utilization”

Table 5.16 Institutions with the greatest output of core papers on “oil and gas with wind-light-heat-storage multi-energy integrated development and utilization”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	16	5.13	2 972	185.75	2020.3
2	Tsinghua University	9	2.88	1 654	183.78	2019.7
3	National University of Singapore	9	2.88	1 547	171.89	2020.1
4	Swiss Federal Institute of Technology Zurich	7	2.24	1 240	177.14	2020.9
5	Tianjin University	7	2.24	915	130.71	2019.4
6	University of Cambridge	6	1.92	1 979	329.83	2020.2
7	Lawrence Berkeley National Laboratory	6	1.92	1 063	177.17	2019.2
8	University of California, Berkeley	6	1.92	988	164.67	2019.0
9	Massachusetts Institute of Technology	6	1.92	896	149.33	2021.0
10	Colorado School of Mines	5	1.60	2 786	557.20	2019.8

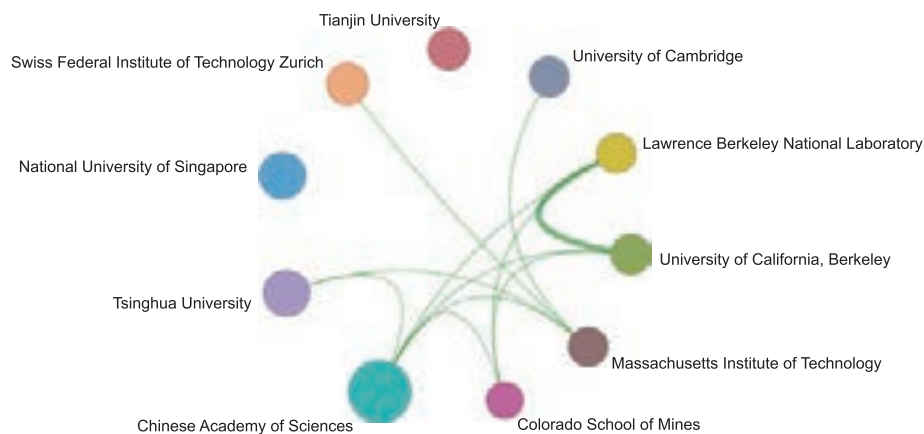


Figure 5.11 Collaboration network among major institutions in the engineering research front of “oil and gas with wind-light-heat-storage multi-energy integrated development and utilization”

Changes will also be made in production methods, process flows, and management systems, including adjustments from stable production to intermittent operations, such as intermittent pumping, injection, and gas lift. Through operational scheduling and decision-making methods, low-cost, large-scale, and high-efficiency consumption of green electricity can be achieved. The complementary adjustment capability of different types of energy storage will be expanded, reaching the coordinated optimization of electrical, thermal, and hydrogen storage, and realizing the comprehensive optimization of energy storage at oilfield sites.

The mechanisms and optimization methods of interaction between oil and gas, renewable energy (such as wind and solar), and heat accumulation within independent systems are gradually forming a synergistic mechanism and optimization method for oil and gas with wind-light-heat-storage integration. As information technology advances, the integrated development method of oil and gas with oil and gas with wind-light-heat-storage is evolving towards efficient simulation, rapid decision-making, and intelligent regulation. It is expected that by 2029, a feasibility project for the application of oil and gas with new energy will be developed, combining traditional oil and gas with new energy, and creating a diversified, wide-scale application model of energy storage technology. By 2034, collaborative optimization and control methods for multi-energy synergy in oil and gas production will be completed, forming a “low-carbon and intelligent” system for the smart extraction of new energy and oil and gas fields, geothermal energy extraction from abandoned wells, and comprehensive energy optimization, ensuring increased production and stable output of oil and gas fields, energy conservation, emission reduction, and green low-carbon practices (Figure 5.12).

Table 5.17 Countries with the greatest output of citing papers on “oil and gas with wind-light-heat-storage multi-energy integrated development and utilization”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	2 864	46.23	2020.7
2	USA	813	13.12	2020.6
3	Australia	462	7.46	2020.8
4	UK	387	6.25	2020.9
5	India	320	5.17	2021.0
6	Germany	320	5.17	2020.6
7	Republic of Korea	270	4.36	2020.9
8	Japan	203	3.28	2020.5
9	Saudi Arabia	202	3.26	2021.1
10	Canada	179	2.89	2021.0

Table 5.18 Institutions with the greatest output of citing papers on “oil and gas with wind-light-heat-storage multi-energy integrated development and utilization”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	359	27.24	2020.7
2	Tsinghua University	139	10.55	2020.9
3	Tianjin University	124	9.41	2020.7
4	Zhengzhou University	103	7.81	2020.8
5	University of Science and Technology of China	101	7.66	2020.9
6	Nanyang Technological University	84	6.37	2020.6
7	The University of Queensland	84	6.37	2020.3
8	Shenzhen University	84	6.37	2020.9
9	National University of Singapore	82	6.22	2020.8
10	Zhejiang University	81	6.15	2020.8

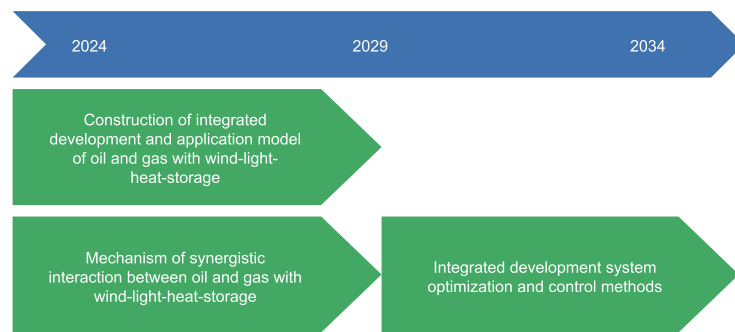


Figure 5.12 Roadmap of the engineering research front of “oil and gas with wind-light-heat-storage multi-energy integrated development and utilization”

5.2 Engineering development fronts

5.2.1 Trends in the Top 12 engineering development fronts

The Top 12 engineering development fronts assessed by the Energy and Mining Engineering Group are shown in Table 5.19. These fronts involve the fields of energy and electrical science, technology, and engineering; nuclear science, technology, and engineering; geological resource science, technology, and engineering; and mining science, technology, and engineering. Among these 12 engineering development fronts, “high energy density, long life and low-cost solid-state battery technology”, “research and development of devices and systems of heat storage and hydrogen storage”, and “development of high-power wide-range bidirectional charging technology and equipment” represent the engineering development front of energy and electrical science; “research and development of nuclear battery based on isotope power supply”, “source searching system based on nuclear unmanned aerial vehicle”, and “nuclear reactor DCS verification and validation method, device, and system” represent the engineering development front of nuclear science, technology, and engineering; “intelligent detection and recognition system while drilling under complex geological conditions”, “technology for identifying and locating favorable ore-forming spaces in the depth of granite-type uranium deposits”, and “Real-time online prediction system for shale gas well productivity” represent the engineering development front of geological resource science, technology, and engineering; “research and development of drilling technology and equipment in deep complex strata”, “co-mining technology for coalbed methane and coal resources”, and “integrated technology of CO₂ mineralization filling and storage” represent the engineering development front of mining science, technology, and engineering. The disclosure of core patents involved in each development front from 2018 to 2023 is presented in Table 5.20.

(1) High energy density, long life, and low-cost solid-state battery technology

Solid-state batteries utilize solid-state electrolytes instead of the liquid electrolytes and separators used in traditional batteries, offering larger energy density, longer cycle life, and improved safety. Further improving the energy density of solid-state batteries increases the endurance mileage of electric vehicles, and further supports the development of electric heavy-duty trucks and electric aircraft. Specifically, solid-state batteries with an energy density of 400 W·h/kg and a stable cycle life of 2 000 cycles can increase the endurance mileage of electric vehicles to 1 000 kilometers, which is fundamental for the popularization of pure electric vehicles. In addition, the aforementioned solid-state battery can also power a two-seater light aircraft for thousands of flights, representing a key technology for emergence of the low-altitude economy. Solid-state batteries can significantly reduce the weight of aircrafts and increase their thrust-to-weight ratio, realizing the revolution of modern transportation electrification. However, the energy density and cycle life of solid-state batteries are influenced by interface instability, lithium dendrite growth,

Table 5.19 Top 12 engineering development fronts in energy and mining engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	High energy density, long life, and low-cost solid-state battery technology	328	648	1.98	2021.2
2	Research and development of nuclear battery based on isotope power supply	554	1 028	1.86	2020.8
3	Intelligent detection and recognition system while drilling under complex geological conditions	1 070	9 413	8.80	2020.7
4	Research and development of drilling technology and equipment in deep complex strata	199	4 026	20.23	2019.8
5	Research and development of devices and systems of heat storage and hydrogen storage	552	655	1.19	2021.9
6	Development of high-power wide-range bidirectional charging technology and equipment	812	2 078	2.56	2020.3
7	Source searching system based on nuclear unmanned aerial vehicle	638	5 917	9.27	2020.2
8	Nuclear reactor DCS verification and validation method, device, and system	203	1 199	5.91	2019.9
9	Technology for identifying and locating favorable ore-forming spaces in the depth of granite-type uranium deposits	580	8 062	13.90	2020.0
10	Real-time online prediction system for shale gas well productivity	421	4 720	11.21	2020.1
11	Co-mining technology for coalbed methane and coal resources	73	1 138	15.59	2019.9
12	Integrated technology of CO ₂ mineralization filling and storage	508	1 198	2.36	2020.8

Table 5.20 Annual number of core patents published for the Top 12 engineering development fronts in energy and mining engineering

No.	Engineering development front	2018	2019	2020	2021	2022	2023
1	High energy density, long life, and low-cost solid-state battery technology	28	35	39	54	85	87
2	Research and development of nuclear battery based on isotope power supply	77	84	67	97	121	108
3	Intelligent detection and recognition system while drilling under complex geological conditions	111	143	225	197	284	110
4	Research and development of drilling technology and equipment in deep complex strata	40	53	38	38	25	5
5	Research and development of devices and systems of heat storage and hydrogen storage	20	17	40	86	138	251
6	Development of high-power wide-range bidirectional charging technology and equipment	155	181	118	118	117	123
7	Source searching system based on nuclear unmanned aerial vehicle	107	124	132	114	122	39
8	Nuclear reactor DCS verification and validation method, device, and system	45	52	40	25	30	11
9	Technology for identifying and locating favorable ore-forming spaces in the depth of granite-type uranium deposits	104	127	137	98	97	17
10	Real-time online prediction system for shale gas well productivity	96	91	59	61	59	55
11	Co-mining technology for coalbed methane and coal resources	16	10	23	12	11	1
12	Integrated technology of CO ₂ mineralization filling and storage	70	66	72	111	84	105

and electrolyte degradation. In addition, the synthesis process of solid-state electrolytes is complex and has a low yield. Solid-state electrolytes generally cost USD 190/kg, which is considerably higher than the commercialization threshold of USD 50/kg. Through intrinsic material modification and manufacturing process optimization, the energy density and the cycle life of solid-state batteries can be further improved, and the synthesis cost can be reduced. The modification of intrinsic materials mainly develops from the directions of positive and negative electrode material modification, electrolyte structure design, and *in situ* solid electrolyte passivation layer formation. The main development directions for electrolyte development and manufacturing process optimization are film deposition process, mass production technology, and ultrafast and precise synthesis technology. Among them, the ultrafast and precision synthesis technology can realize the precise synthesis of multi-component and even high-entropy solid-state electrolytes in just a few seconds, which can not only efficiently screen and explore electrolyte materials with specific target components, but also realize the accurate and uniform synthesis of multiple elements in single pure phase materials, which is an important trend in the future development and industrial synthesis of solid-state battery materials.

(2) Research and development of nuclear battery based on isotope power supply

Isotope power supply is a nuclear energy device that converts the decay energy into electric energy by using the static or dynamic energy conversion technology based on the heat or radiation particles generated by the decay of radioactive isotopes. Isotope power supply has advantages such as long life, high energy density, high reliability, strong environmental adaptability, self-support and maintenance-free, etc. It is an ideal choice for long-term power supply in extreme special environments, and has been applied in space exploration, deep-sea and polar exploration, and power security in extremely remote areas. The technical direction of isotope power supply mainly focuses on the research of temperature difference power supply, photovoltaic power supply, photovoltaic power supply, and dynamic Stirling power supply. Among them, the temperature difference power supply has the highest reliability and technical maturity, making it widely used; photovoltaic power supply is considered the most promising for miniaturization and integration with microelectromechanical systems (MEMSs), although its power and power density still need improvement; dynamic Stirling power supply has a high system efficiency, but issues concerning the reliability and lifespan of moving parts need to be addressed. In the future, aiming at the multi-domain spectral application needs of space, deep sea, and wireless networks, the development of isotope power supplies will focus on four aspects: the use of modular heat source structures to improve the safety and multi-task adaptability of thermal power supplies; the development of high-efficiency thermoelectric materials and devices to enhance the conversion efficiency and economy of thermoelectric power supplies; the breakthrough in the semiconductor chip design and stack integration technology to improve the power level, conversion efficiency, and power density of photovoltaic power supplies; and the optimization of the design and processes of free piston to solve the reliability and lifespan of dynamic Stirling power supplies.

(3) Intelligent detection and recognition system while drilling under complex geological conditions

The intelligent detection and recognition system while drilling is an advanced drilling technology designed for complex geological conditions, aimed at improving the accuracy of formation identification and operational efficiency during the drilling process. This system integrates various theories and technologies such as geology, control engineering, mechanical mechanics, data analysis, and intelligent algorithms. Through real-time monitoring and analysis of various parameters during the drilling process, it achieves intelligent detection and accurate identification of geological structures, formation lithology, oil and gas properties, and other characteristics.

The main technical directions include while drilling measurement, while drilling logging, while drilling acoustic logging, while drilling seismic, and other while drilling measurement technologies, as well as the use of advanced intelligent algorithms to process and analyze the collected data. Through these technologies, the system can obtain various physical parameters underground in real time, such as temperature, pressure, resistivity, acoustic velocity, etc., providing key information for formation evaluation and drilling decisions.

In the future, new technologies such as artificial intelligence, big data, and the Internet of Things will be continuously introduced to improve the speed and accuracy of data processing and enhance the intelligence level of the system. Technological innovation will

focus on improving the adaptability of the system to complex geological environments, solving problems such as low recognition accuracy, slow data transmission and processing speeds in existing technologies. In addition, with the overall development of the intelligent drilling technology, the research and application of hardware facilities such as intelligent drilling rigs, intelligent drill bits, and intelligent drill rods will further promote the improvement of intelligent detection and recognition systems while drilling.

(4) Research and development of drilling technology and equipment in deep complex strata

The research and development of drilling equipment and technology in deep complex strata at depths of over 10 000 meters refers to the development and application of a series of advanced drilling technologies and equipment to overcome extreme conditions such as high temperatures, high pressures, and complex formations, in order to achieve efficient and precise drilling goals. The scientific exploration of ultra-deep oil and gas resources is an important task in implementing the national “Four Deep” detection plan and helps in capturing the forefront of deep formation technology innovation. The “Taco-1 Well” in the Tarim Oilfield is the first well in China with a vertical depth exceeding 10 000 meters, whose drilling has overcome numerous challenges including ultra-high pressure, ultra-high temperature, and extreme loads, leading to the development of core technologies for safe and efficient drilling and completion of ultra-deep wells. The main technical directions include: ultra-deep well drilling equipment; optimization and expansion of well structures at extreme depths; efficient rock-breaking and drilling acceleration technologies; high-temperature resistant drilling and completion fluids; drilling fluid friction reduction technologies; high-temperature and high-pressure cementing technologies; and technologies for controlling and addressing complex conditions. The development trends include enhancing the integration of geological engineering to improve detection accuracy in complex geological environments; increasing the intelligence and modularity of deep formation drilling equipment for real-time diagnosis, prediction, and control; developing high-performance materials resistant to high temperatures, high pressures, and corrosion to enhance durability under extreme conditions; and innovating drilling acceleration methods and tools to improve rock-breaking efficiency.

(5) Research and development of devices and systems of heat storage and hydrogen storage

Thermochemical energy storage is a technology that stores and releases heat through reversible gas-solid chemical reactions. The reversible chemical reaction between the alloy and hydrogen is also a solid-state hydrogen storage technology. Magnesium-based metal/titanium-based metal alloys react with hydrogen to form metal hydrides for hydrogen storage and the release of heat. The hydrides are then heated and undergo decomposition reactions to release hydrogen gas. Therefore, it can be regarded as a technology that integrates thermochemical heat storage and solid-state hydrogen storage.

Current research often separates thermochemical heat storage from solid-state hydrogen storage and utilizes them separately. However, the processes of storing and releasing hydrogen are constrained by the processes of storing and releasing heat and heat transfer, which affect each other. Moreover, the magnitude of the heat of the chemical reaction has a significant impact on the energy storage efficiency of solid-state hydrogen storage. In the future, if the processes of storing and releasing hydrogen and heat are considered together to achieve combined hydrogen and heat supply, it could be an effective method to improve energy utilization efficiency.

The design optimization of devices and systems is an important challenge in this technology, which requires comprehensive consideration of factors such as high heat transfer performance, high system utilization efficiency, and reaction cycle stability for system integration. It requires collaborative consideration from multiple disciplines such as chemistry, heat transfer, thermodynamics, and mechanical design. These technologies are poised to bring new breakthroughs to the fields of hydrogen and heat storage.

(6) Development of high-power wide-range bidirectional charging technology and equipment

The high-power wide-range bidirectional charging technology refers to the bidirectional direct current (DC) /alternating current (AC) conversion between electric vehicles (EVs) and the power grid, which relies on the application of high-power bidirectional charging piles. For the high-power bidirectional charging piles, the AC input and output voltages of the power grid are commonly single-phase 220 V or three-phase 380 V, while the DC input and output voltages of EVs range from 200 V to 1 000 V, with a bidirectional power of up to 240 kW. The high-power wide-range bidirectional charging technology enhances the utilization efficiency of energy

and the flexibility and economy of EVs, which also increases the interaction between EVs and the power grid.

The main research topics in this field include: the bidirectional AC/DC and DC/DC conversion technology; the improvement of bidirectional charging power and voltage range; voltage resistance, insulation and heat dissipation technologies; the integrated management technology of bidirectional charging; the bidirectional charging metering technology; communication protocols among EVs, bidirectional charging piles and the power grid; and the optimization of bidirectional charging strategies, etc.

The research prospects include: investigating the high-efficiency high-power bidirectional AC/DC converter; improving the heat dissipation efficiency, reliability and service life of charging piles by utilizing the liquid cooling technology, which also downsizes the charging guns; and constructing the bidirectional charging energy management platform to achieve the information exchange and coordinated regulation among EVs, charging piles, and the power grid.

(7) Source searching system based on nuclear unmanned aerial vehicle

With the increasingly mature commercial use of unmanned aerial vehicles, the use of unmanned aerial vehicles equipped with radiation monitors for radiation monitoring or radioactive source search can achieve efficient search for radioactive sources in radiation accidents and reduce the risk of radiation exposure of source seekers. Unmanned aerial vehicles can be applied to nuclear accident pollution monitoring, radiation site investigation, and radioactive source search and other fields. Based on the good maneuverability of small unmanned rotorcraft, the real-time monitoring of large-scale environmental radioactivity is realized by combining nuclear detection, signal processing, GPS positioning, wireless communication and other technologies, and the data interaction between the airborne monitoring system and the ground control station is realized through the wireless data transmission module. The upper computer software obtains the measurement data in real time and processes it to display the radiation hot spot map of the current measurement environment. The core equipment and technology of the system include radiation detection equipment, which can simultaneously measure environmental dose rate and energy spectrum. For example, the source finding iterative algorithm is used to accurately locate the radioactive source. The Kriging interpolation algorithm is used to map the dose rate and outline the hot spots in the radioactive environment, which is of great significance for the search of radioactive sources and the detection for radioactive leaks.

(8) Nuclear reactor DCS verification and validation method, device, and system

Distributed control system (DCS) is a multilevel computer system composed of process control level and process monitoring level, linked by a communication network. As the central nervous system of a nuclear power plant, the distributed control system is divided into the safety-level distributed control system and the non-safety-level distributed control system. Its function is to monitor various parameters of the operation of the nuclear power plant in real time, including the protection and control of the nuclear reactor, which plays a very important role in ensuring the safe, reliable, and stable operation of the nuclear power plant. According to the requirements of HAF, the verification and validation of the safety-level distributed control system are necessary steps to ensure the security and reliability of the software. The design feature of the verification simulation platform is to adopt advanced and mature digital monitoring system configuration software with good openness, establish a simulation model that can accurately simulate the dynamic operational characteristics of the controlled system, and provide necessary real-time operational feedback for the control system to form a control closed loop. These simulation models include relevant physical reactor models, electrical models, thermal hydraulic models, and control simulation models. Through the integration of instrument control main control room human-machine interface design, logic diagram, and simulation diagram control system functions, a simulation platform can be independently designed to dynamically and real-time simulate and modify basic physical phenomena and dynamic processes of nuclear power plants according to verification requirements.

(9) Technology for identifying and locating favorable ore-forming spaces in the depth of granite-type uranium deposits

Uranium is a strategic resource for both military and civilian use, which plays a significant role in national and energy security. Granite-type uranium deposits are essential industrial uranium resources in China. However, due to the limited prospecting depth, the explored depth of granite-type uranium deposits is mostly 500 m. In recent years, the prospecting depth has reached

1 000–1 200 m, while the prospecting depth of similar uranium deposits abroad exceeds 2 000 m. The main research directions for deep favorable metallogenic space identification and positioning technology of granite-type uranium deposits include the deep favorable metallogenic space plane and vertical positioning geological tracer technology, the deep geological structure and uranium metallogenic conditions geophysical detection technology, the multi-element metallogenic information comprehensive extraction technology, the three-dimensional geological-metallogenic-exploration model construction technology, and the deep uranium resources efficient, comprehensive prediction and evaluation technology, etc. This technological system has achieved remarkable results in prospecting several granite-type uranium deposits. In the Youdong area of the uranium ore field in the southern Zhuguang region, a thick industrial ore body was successfully found at a depth of 950 meters. The deepest industrial uranium deposit in China was found at a depth of 1 550 meters, refreshing the depth record of industrial uranium deposits in China. With the development and application of prospecting and prediction technologies such as big data and artificial intelligence, the main development trends of the deep favorable metallogenic space and positioning technology of granite-type uranium deposits in the future include the element-isotope geological identification technology for deep concealed ore bodies, the enhanced extraction technology for weak anomaly information in deep areas, the high-precision geophysical detection technology, the intelligent prospecting and prediction technology for deep uranium resources based on big data, and the four-dimensional modeling and prediction and evaluation technology for large-depth granite-type uranium deposits.

(10) Real-time online prediction system for shale gas well productivity

The real-time online prediction system for shale gas well productivity is a comprehensive system that integrates data acquisition, processing, analysis, and prediction functions. The system aims to establish a quantitative evaluation model by monitoring the production data of shale gas wells in real time and to quickly and accurately predict the production capacity of shale gas wells. This real-time online prediction can improve both efficiency and accuracy, providing an important basis for shale gas development.

The main technical directions include: ① establishing a target production dataset for shale gas wells, using neural network training to obtain a dynamic production prediction model, and determining the production of shale gas wells at the target time; ② developing an integrated shale gas well production capacity evaluation model using the Markov chain Monte Carlo intelligent historical fitting algorithm and the embedded discrete fracture technology coupled with a numerical simulator to predict shale gas well production capacity, taking into account fracture modeling, dynamic simulation, historical fitting, and production capacity prediction; ③ evaluating and predicting the production of shale gas wells by integrating geological, drilling, fracturing, and production data from the entire shale gas extraction cycle, and using machine learning, taking into account both geological and engineering factors.

The future development trend is to integrate advanced technologies such as machine learning and deep learning with statistical theoretical models to improve the accuracy and efficiency of shale gas well productivity prediction, and achieve dynamic and to phased evaluation and prediction.

(11) Co-mining technology for coalbed methane and coal resources

The co-extraction technology of coal-bed methane (CBM) and coal resources has emerged as a cutting-edge approach in the field of coal mining in recent years. This technology aims to achieve the efficient, economical, and environmentally friendly joint extraction of coalbed methane and coal, thereby enhancing resource utilization, reducing environmental impact, and contributing to the transformation of the energy structure. The primary research directions include the integration of extraction technologies, assessment of coalbed methane resources, analysis of hydrogeological impacts, intelligent monitoring and control technologies, and studies on economic viability and sustainability.

In the future, the co-extraction technology of coalbed methane and coal resources is expected to evolve towards greater intelligence, greenness, and systematization. In terms of intelligence, advancements in sensor technologies and data processing capabilities will lead to the more widespread adoption of intelligent monitoring and control systems, facilitating real-time monitoring and optimization of the extraction process. Regarding greenness, technological developments will place greater emphasis on environmental protection, striving to minimize ecological impacts during coalbed methane extraction and to prevent soil erosion and groundwater contamination. From a systematic perspective, there will be a push for interdisciplinary integration,

combining research findings from geology, engineering, environmental science, and other fields to develop a comprehensive framework for co-extraction technologies, thereby optimizing the integrated development and utilization of resources.

(12) Integrated technology of CO₂ mineralization filling and storage

The integrated technology of carbon dioxide (CO₂) mineralization backfilling and storage is an organic combination of the CO₂ storage technology and the backfill mining technology, to achieve large-scale utilization and storage of CO₂. This technology immobilizes CO₂ within the cement paste backfill material through mineralization reactions. It not only effectively reduces CO₂ emissions, enhances the strength of the backfill, and lowers filling costs, but also mitigates the environmental and spatial impacts of improper solid waste disposal. Additionally, it addresses issues such as strata movement and surface subsidence caused by mining activities. The technology primarily involves three key stages preparation of carbon-sequestering cement paste backfill materials, cement paste backfill slurry transportation, and the formation of cement paste backfill strength. The process includes sub-processes like mineralization reactions, cement paste backfill slurry transportation, and the diffusion of CO₂ within the cement paste backfill material. The main research directions for this technology include: ① study of three-phase (solid-liquid-gas) pipeline transportation; ② investigation of CO₂ mineralization mechanisms; ③ research on the mechanical properties of mineralized cement paste backfill; ④ development of CO₂ mineralization enhancement techniques; ⑤ preparation techniques for CO₂ backfill materials; ⑥ study of the physical-chemical synergistic mechanisms of CO₂ sequestration; ⑦ research on CO₂ backfilling mining methods. The core objectives of the integrated technology of CO₂ mineralization backfilling and storage are to increase CO₂ sequestration capacity and reduce backfilling costs, ultimately protecting the environment while saving costs.

5.2.2 Interpretations for four key engineering development fronts

5.2.2.1 High energy density, long life, and low-cost solid-state battery technology

Solid-state batteries use solid electrolytes instead of liquid electrolytes and separators used in traditional batteries, which provide the possibility for the use of lithium metal anodes, thereby greatly enhancing the energy density of lithium-ion batteries. The high energy density is a necessity to further increase the market penetration rate of electric vehicles and promote the electrification revolution of vehicles. Recently, the key factors affecting the energy density and cycle life of solid-state batteries are the instability of the electrode-electrolyte interface, the growth of lithium dendrites, and the degradation of the electrolyte with battery cycles, which also result in battery capacity attenuation and safety problems. In addition, the complex synthesis process, low yield, and high production cost of solid-state electrolytes have become major obstacles to the commercialization of solid-state batteries.

Intrinsic material modification and manufacturing process optimization can further improve the energy density, cycle life, and reduce the synthesis cost of solid-state batteries. The modification of intrinsic materials mainly develops in the directions of positive and negative electrode material modification, electrolyte structure design, and *in situ* interface passivation layer. To alleviate the interfacial side reactions, the electrode surface is modified by coating with conductive materials, doping with Si, C, and other elements, and reducing the particle size, which increases the lithium-ion diffusion rate and improves the energy density of solid-state batteries. Optimizing the directional and continuous interface channels of ion transport in the solid electrolyte, constructing a multilayer heterogeneous electrolyte structure, and doping Zn, F, and other elements to improve the electrochemical stability of the electrolyte are conducive to reducing the growth of lithium dendrites, decreasing the degradation of the electrolyte, and increasing the cycle life of the battery. By designing the *in situ* interface passivation layer rich in lithium fluoride and lithium nitride, the internal resistance of the battery can be reduced. This passivation layer could also alleviate the electrolyte degradation and suppress dendrite growth, improving the cycle performance and safety performance of the solid-state battery. However, due to the distinct coupling characteristics of chemical fields, electric fields, and force fields in the internal and interfacial electrochemical processes of solid-state batteries, it is difficult for a single design to include all the comprehensive parameters. Considering the multi-field coupling effect, the experimental environments and theoretical models of solid-state electrolytes under real working conditions are constructed, which can effectively reveal the failure and runaway mechanisms in their practical application and provide strong support for the design of

solid-state battery energy density and optimization of cycle life.

The optimization of the manufacturing process mainly includes the improvement of the film formation process, large-scale production technology, and ultra-fast precision synthesis technology. The film-forming process is divided into the wet process and the dry process. Although the wet process is one of the most promising processes to achieve mass production of solid electrolyte membranes, it still needs further research and development. The large-scale production technology of electrolytes is still under exploration, where the high cost of raw materials and homogenized synthesis are urgent challenges that need to be overcome. The industry is expected to achieve small-scale production by 2025, while large-scale commercialization needs to wait until around 2030. The ultra-fast and precise synthesis technology can realize the ultra-fast synthesis of multi-component high-entropy solid-state electrolytes in just a few seconds, which can not only efficiently screen and explore electrolyte materials with specific target components but also realize the accurate and uniform synthesis of multiple elements in a single pure phase, which is an important trend in the future development and industrial synthesis of solid-state battery materials.

In the research front of “high energy density, long life, and low-cost solid-state battery technology”, China ranks first in the world with 149 patent disclosures, accounting for 45.43% of the number of patents published, followed by Japan, the USA, and Republic of Korea (Table 5.21). Among them, the USA has the most cooperation with Republic of Korea, while China has primarily established cooperation with the USA (Figure 5.13). The main output institutions of patent include Toyota Motor Corporation, Hyundai Motor Company, Kia Corporation, Panasonic Corporation, LG Chem Ltd., Nissan Motor Co., Ltd., Honda Motor Company, Beijing WELION New Energy Technology Co., Ltd., Samsung Electronics Co., Ltd., and BMW (Table 5.22). Among them, Hyundai Motor Company has the closest cooperation with Kia Corporation, with relatively little collaboration with other companies (Figure 5.14).

Figure 5.15 shows the roadmap of the front of “high energy density, long life, and low-cost solid-state battery technology”, which has broad development prospects in the fields of transportation electrification and energy storage systems. In the next 5–10 years, the key development directions of this field are the improvement of intrinsic material properties and large-scale manufacturing processes. Based on the modification of positive and negative electrode materials, electrolyte structure design, and *in situ* interface passivation layers, the energy density and cycle life of solid-state batteries could be further improved, with the realization of battery miniaturization and portability. Meanwhile, the large-scale mass production technology of electrolytes, the optimization of the film-forming process, and ultra-fast and precise synthesis technology are candidate methods to enhance the mass production process of solid-state batteries. These methods could also support the fields of energy and power by improving social and economic benefits.

Table 5.21 Countries with the greatest output of core patents on “high energy density, long life, and low-cost solid-state battery technology”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	149	45.43	200	30.86	1.34
2	Japan	61	18.60	220	33.95	3.61
3	USA	45	13.72	99	15.28	2.20
4	Republic of Korea	43	13.11	65	10.03	1.51
5	Germany	17	5.18	21	3.24	1.24
6	Belgium	5	1.52	14	2.16	2.80
7	UK	4	1.22	15	2.31	3.75
8	France	3	0.91	0	0.00	0.00
9	Netherlands	2	0.61	11	1.70	5.50
10	Spain	2	0.61	10	1.54	5.00

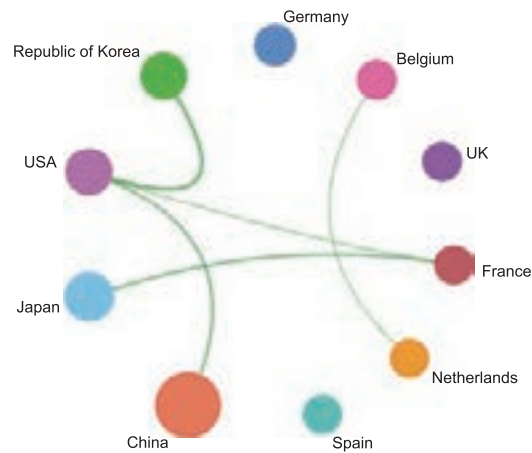


Figure 5.13 Collaboration network among major countries in the engineering development front of “high energy density, long life, and low-cost solid-state battery technology”

Table 5.22 Institutions with the greatest output of core patents on “high energy density, long life, and low-cost solid-state battery technology”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Toyota Motor Corporation	17	5.18	41	6.33	2.41
2	Hyundai Motor Company	15	4.57	47	7.25	3.13
3	Kia Corporation	14	4.27	33	5.09	2.36
4	Panasonic Corporation	11	3.35	76	11.73	6.91
5	LG Chem Ltd.	9	2.74	6	0.93	0.67
6	Nissan Motor Co., Ltd.	8	2.44	0	0.00	0.00
7	Honda Motor Company	7	2.13	17	2.62	2.43
8	Beijing WELION New Energy Technology Co., Ltd.	7	2.13	2	0.31	0.29
9	Samsung Electronics Co., Ltd.	7	2.13	1	0.15	0.14
10	BMW	6	1.83	10	1.54	1.67

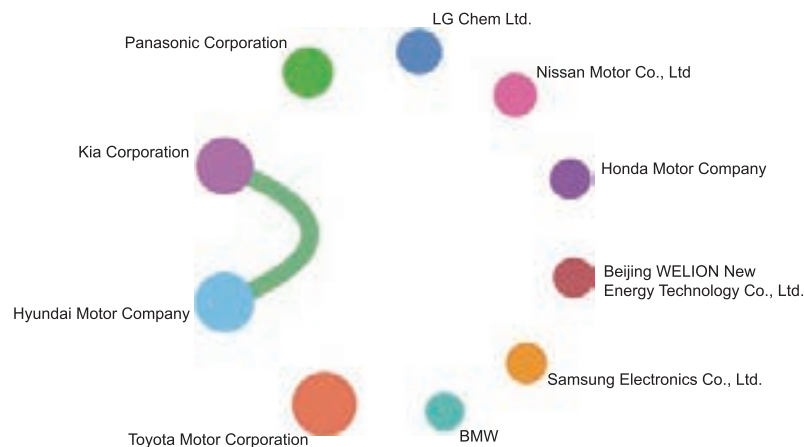


Figure 5.14 Collaboration network among major institutions in the engineering development front of “high energy density, long life, and low-cost solid-state battery technology”

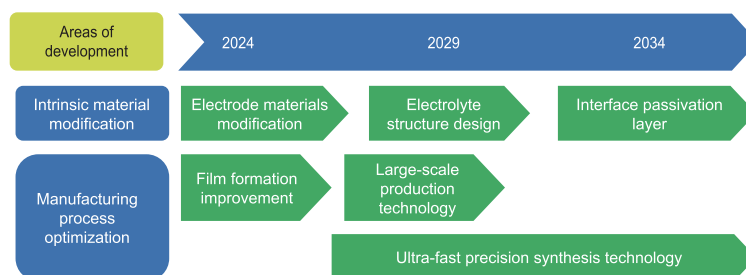


Figure 5.15 Roadmap of the engineering development front of “high energy density, long life, and low-cost solid-state battery technology”

5.2.2.2 Research and development of nuclear battery based on isotope power supply

Compared with chemical and solar cells, isotope power supply has the advantages of high energy density, strong environmental adaptability, and self-sustainability without maintenance. It is the most promising power supply technology for space exploration, deep-sea and polar exploration, and wireless networks. Since its first application in 1961, the isotope power supply has been regarded as a disruptive technology by developed countries such as the USA, Russia, and the United Kingdom. For different application environments such as space, land, and underwater, a series and spectral temperature difference isotope power supply products have been developed in the last century. Notable examples include the “SNAP”, “HWM-RTG”, “GPHS-RTG”, and “MMRTG” plutonium-238 thermoelectric power supplies for space exploration in the USA, the “Penguin”, “Beta-M”, and “Senostav” strontium-90 thermoelectric power supplies for far-sea and polar weather monitoring and navigation in Russia, and the “RIPPLE” strontium-90 thermoelectric power supply for navigation beacons in the United Kingdom, with power coverages ranging from watts to hundreds of watts and efficiency increasing from 2% to 6.7%. In order to meet the power needs of deep space and deep-sea exploration in the new century, the USA has accelerated the development of next-generation isotope power sources, including structural optimization and improvement of modular heat sources (GPHS) to improve the safety of space applications; development of high temperature and high ZT value thermoelectric materials such as cobaltite, semi-Ha, and germanium silicon to improve the efficiency of the power system; development of efficient insulation structure and high emissivity coating to improve the thermal efficiency of the system; and the research, development, and testing of dynamic Stirling conversion power supplies. At the same time, for future wireless sensing network and MESM system integrated power supplies, both the USA and Russia have proposed research and development plans for micro tritium and nickel-63-volt power supplies.

At present, China, the USA, Japan, Russia, and Republic of Korea are the main forces in the international research and development of isotope power supplies (Table 5.23). Among them, China has developed rapidly in the past 10 years, and realized space applications in 2018, ranking first in the number of patents disclosed. The USA, which started the earliest and developed the most comprehensively, has the highest level of technology and maturity, ranking second in the number of patents disclosed. Russia has been slower due to its economic situation, ranking fourth in the number of patents disclosed. Due to its relevance to national strategic core technologies, countries follow the principle of independent development in the field of isotope power supply technology, and there are no reports of cooperation. The research and development of isotope power supply in China is mainly conducted by the China Institute of Atomic Energy (Table 5.24), and there are currently no reports of cooperation.

In the next 10 years, according to the needs of different scenarios, the development of isotope power supplies will continue to improve the power level, conversion efficiency, power density, and safety of the power supply as the focus of technological breakthroughs, and gradually improve the multi-task adaptability of isotope power supplies through modularization and standardization, thereby expanding their application range. Figure 5.16 shows the roadmap of the engineering development front of “research and development of nuclear battery based on isotope power supply”.

Table 5.23 Countries with the greatest output of core patents on “research and development of nuclear battery based on isotope power supply”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	471	85.02	873	84.92	1.85
2	USA	30	5.42	90	8.75	3.00
3	Japan	19	3.43	30	2.92	1.58
4	Russia	9	1.62	2	0.19	0.22
5	Republic of Korea	6	1.08	5	0.49	0.83
6	UK	3	0.54	15	1.46	5.00
7	Italy	3	0.54	7	0.68	2.33
8	France	2	0.36	0	0.00	0.00
9	India	2	0.36	0	0.00	0.00
10	Turkey	2	0.36	0	0.00	0.00

Table 5.24 Institutions with the greatest output of core patents on “research and development of nuclear battery based on isotope power supply”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China Institute of Atomic Energy	27	4.87	78	7.59	2.89
2	Xi'an Jiaotong University	12	2.17	82	7.98	6.83
3	Jilin University	10	1.81	19	1.85	1.90
4	Zhejiang University	7	1.26	4	0.39	0.57
5	Shandong Qilu Stem Cell Engineering Co., Ltd.	6	1.08	21	2.04	3.50
6	Yinfeng Biological Group Co., Ltd.	6	1.08	4	0.39	0.67
7	East China University of Technology	6	1.08	0	0.00	0.00
8	Anhui Guyi Biotechnology Co., Ltd.	5	0.90	15	1.46	3.00
9	Nanjing University of Aeronautics and Astronautics	5	0.90	13	1.26	2.60
10	Mitra RxDx, Inc.	5	0.90	7	0.68	1.40

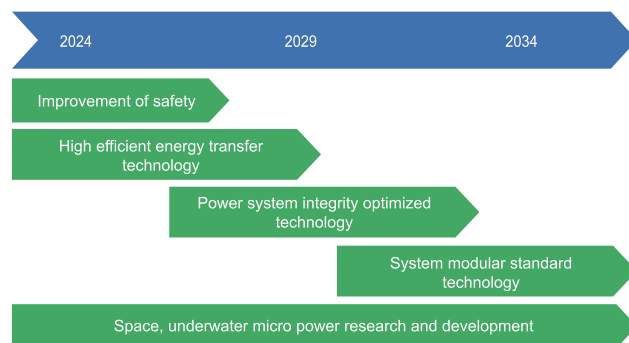


Figure 5.16 Roadmap of the engineering development front of “research and development of nuclear battery based on isotope power supply”

5.2.2.3 Intelligent detection and recognition system while drilling under complex geological conditions

The development of an intelligent detection and recognition system while drilling under complex geological conditions is a key technology in the exploration of underground resources such as oil, minerals, and coal. Especially in complex geological conditions where resource distribution is complex, this system can enhance exploration efficiency and accuracy, reduce drilling risks, and optimize development plans, which is of great significance for the exploration and development of underground resources.

The preliminary development of measurement while drilling (MWD) and logging while drilling (LWD) technologies can be traced back to the 1930s. The earliest LWD methods were based on electrical logging techniques, relying primarily on traditional measurement methods such as electromagnetic waves and acoustic waves. These systems had slow data transmission speeds and poor real-time performance. With the advancement of remote sensing instruments, various LWD technologies, such as acoustic logging and radioactive logging, have gradually developed. Progress in electronic and data processing technologies also significantly enhanced MWD and LWD techniques. After entering the 21st century, MWD systems that integrate wireless communication and high-precision sensors have become increasingly mature, providing more real-time and accurate geological data. In recent years, the rise of big data and machine learning has further propelled the development of intelligent drilling detection and identification systems. In complex geological conditions, machine learning algorithms have been employed to automatically identify geological features and optimize drilling paths. Although research and application in this field are still in their early stages, they have already demonstrated tremendous potential.

In the research front of “intelligent while-drilling detection and identification systems under complex geological conditions”, China ranks first in patent output, with 1 032 published patents, accounting for 96.45% of the total. Other countries have a share of less than 4%. The USA ranks second with 11 published patents, accounting for only 1.03% (Table 5.25). In terms of the main output institutions of patents in this field (Table 5.26), the top ten institutions are from China, among which China Railway Tunnel Group Co., Ltd., Shandong University, and China State Railway Group Co., Ltd. rank in the top three. There is international cooperation primarily among the USA, France, and Canada (Figure 5.17) in this field. There is institutional cooperation among Chinese entities, including China Railway Tunnel Group Co., Ltd., China State Railway Group Co., Ltd., and Dalian University of Technology (Figure 5.18).

In the next 5 to 10 years, the development of “intelligent detection and recognition system while drilling under complex geological conditions” will primarily focus on two areas (Figure 5.19):

1) Innovation in sensing technology: This will involve adopting new data transmission technologies, such as wired drill pipes, to ensure efficient well-to-surface data transmission in deep and ultra-deep wells. Additionally, the use of intelligent directional

Table 5.25 Countries with the greatest output of core patents on “intelligent detection and recognition system while drilling under complex geological conditions”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	1 032	96.45	8 688	92.30	8.42
2	USA	11	1.03	274	2.91	24.91
3	Japan	9	0.84	113	1.20	12.56
4	Republic of Korea	9	0.84	104	1.10	11.56
5	Canada	3	0.28	85	0.90	28.33
6	Australia	1	0.09	73	0.78	73.00
7	Iran	1	0.09	39	0.41	39.00
8	France	1	0.09	30	0.32	30.00
9	Netherlands	1	0.09	30	0.32	30.00
10	Sweden	1	0.09	19	0.20	19.00

Table 5.26 Institutions with the greatest output of core patents on “intelligent detection and recognition system while drilling under complex geological conditions”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China Railway Tunnel Group Co., Ltd.	21	1.96	137	1.46	6.52
2	Shandong University	18	1.68	137	1.46	7.61
3	China State Railway Group Co., Ltd.	17	1.59	65	0.69	3.82
4	China University of Mining and Technology-Beijing	11	1.03	69	0.73	6.27
5	Shenzhen Autel Technology Co., Ltd.	7	0.65	213	2.26	30.43
6	Shandong University of Science and Technology	7	0.65	161	1.71	23.00
7	Dalian University of Technology	7	0.65	59	0.63	8.43
8	China University of Geosciences (Wuhan)	7	0.65	56	0.59	8.00
9	China Petroleum and Chemical Corporation	6	0.56	87	0.92	14.50
10	AECC South Industry Co., Ltd.	6	0.56	68	0.72	11.33

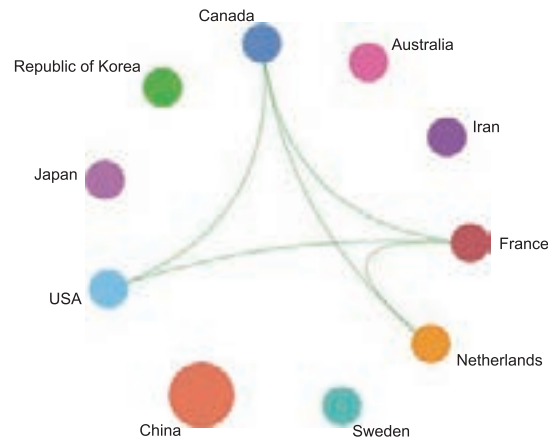


Figure 5.17 Collaboration network among major countries in the engineering development front of “intelligent detection and recognition system while drilling under complex geological conditions”

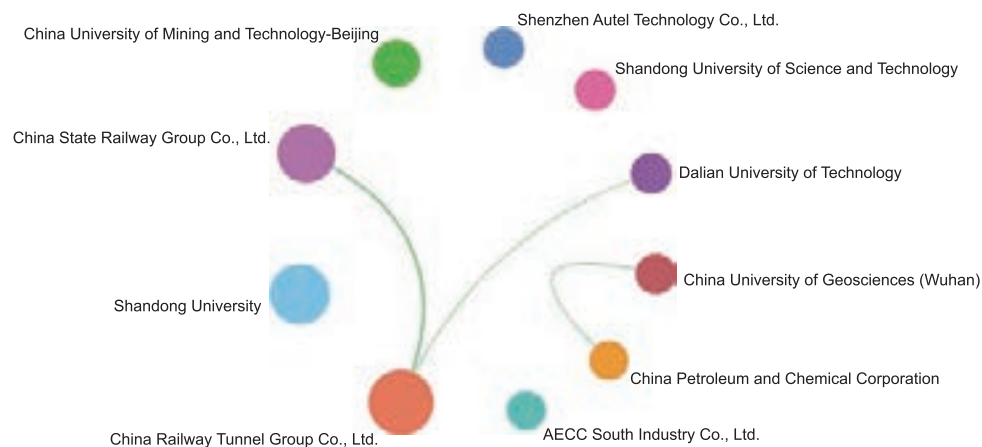


Figure 5.18 Collaboration network among major institutions in the engineering development front of “intelligent detection and recognition system while drilling under complex geological conditions”

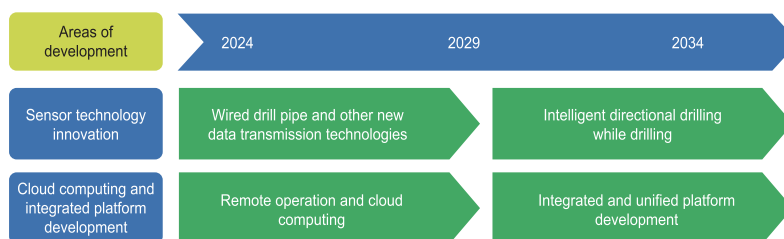


Figure 5.19 Roadmap of the engineering development front of “intelligent detection and recognition system while drilling under complex geological conditions”

drilling methods and artificial intelligence will be emphasized to enhance the level of drilling automation, enabling the system to make autonomous decisions and reducing reliance on data transmission and human experts.

2) Development of cloud computing and integrated platforms: With the advancement of the Internet of Things (IoT) and cloud computing, future intelligent while-drilling systems will enable remote operations and data processing. These systems will integrate geological data, drilling engineering, real-time monitoring, and intelligent identification to form a unified platform, simplifying drilling operations and increasing efficiency. All critical data and decision-support functions will be consolidated into a single interface, making the drilling process more streamlined and effective.

5.2.2.4 Research and development of drilling technology and equipment in deep complex strata

The research and development of drilling technology and equipment in deep complex strata at depths of over 10 000 meters is a highly challenging field of engineering technology, aimed at addressing the intricate geological environments found deep within the Earth’s crust. By developing and deploying a suite of cutting-edge drilling technologies and equipment, this endeavor aims to effectively overcome extreme conditions such as high temperatures, high pressures, and complex geological formations, thereby achieving efficient and precise drilling objectives.

The research and development of drilling technology and equipment in deep complex strata holds significant strategic importance across multiple dimensions, including resource extraction, technological innovation, and national energy security. The deep subsurface contains abundant reserves of hydrocarbons, minerals, and geothermal resources. It is estimated that 60% of the world’s newly discovered oil and gas reserves originate from deep formations. In China, 83% of deep oil and gas resources remain to be explored and developed. The development of ultra-deep drilling technology is crucial for mitigating China’s oil and gas resource shortages and ensuring the security and stability of China’s energy supply. Moreover, breakthroughs in this field will provide extensive research and application opportunities for the development of high-strength, high-temperature-resistant drilling materials and intelligent drilling systems.

In 2016, Xi Jinping, General Secretary of the Chinese Communist Party, proposed the strategic objective of “marching deep into the depth of the earth.” On May 30, 2023, the Tahe-1 well, with a planned depth of 11 100 meters, commenced drilling, tasked with the dual objectives of exploring geological structures and discovering hydrocarbon resources. In recent years, China has made significant strides in deep-earth resource exploration, consistently setting new depth records and demonstrating its strong capabilities in this arena. For instance, in the Tarim Oilfield, over 1 700 wells have been drilled to depths exceeding 6 000 meters, accounting for 80% of the total in China. On March 4, 2024, China National Petroleum Corporation (CNPC) drilled the Tahe-1 well in the heart of the Taklamakan Desert to a depth exceeding 10 000 meters, making it the deepest vertical well in Asia and further consolidating China’s leadership in ultra-deep drilling technology. At present, China has successfully developed a series of ultra-deep automated drilling rigs capable of operating at depths between 7 000 and 12 000 meters, as well as four-column rigs for 8 000 to 9 000-meter depths, which have demonstrated significant efficacy in practical applications. Additionally, the 52 MPa high-pressure drilling pump technology has matured and been widely deployed, while the development of the 70 MPa ultra-high-pressure drilling pump has also achieved success. Furthermore, prototype development or software development has

been completed in areas such as energy storage and energy management technology, drilling rig integrated control technology, intelligent decision-making and support technology, and low-pressure drilling fluid automation processing technology, and has entered the stage of industrial testing or small-scale application. The development of these technologies and equipment provides strong support for the sustainable development of deep well drilling technology in China.

In the research front of “research and development of drilling technology and equipment in deep complex strata”, China and the USA are leading in the number of core patents published, with 122 and 54 patents respectively, accounting for 61.31% and 27.14% of the total. Other countries have published less than 6.00% of the related patents. China has the highest number of cited patents, accounting for 53.35% of total citations, while the USA accounts for 34.97%, and other countries have citation ratios of less than 7.00%. Australia has the highest citations per patent (Table 5.27). In terms of patent-producing institutions (Table 5.28), ExxonMobil Upstream Research Company, China University of Petroleum-Beijing, China Petroleum and Chemical Corporation, Southwest Petroleum University, Schlumberger Technology Corporation, and PetroChina Co., Ltd. are the leading contributors. Among them, institutions with citation rates exceeding 5.00% include ExxonMobil Upstream Research Company and Sinopec (Table

Table 5.27 Countries with the greatest output of core patents on “research and development of drilling technology and equipment in deep complex strata”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	122	61.31	2 148	53.35	17.61
2	USA	54	27.14	1 408	34.97	26.07
3	France	10	5.03	264	6.56	26.40
4	Saudi Arabia	8	4.02	108	2.68	13.50
5	Canada	7	3.52	194	4.82	27.71
6	Netherlands	7	3.52	194	4.82	27.71
7	Japan	5	2.51	93	2.31	18.60
8	Republic of Korea	4	2.01	48	1.19	12.00
9	Australia	3	1.51	84	2.09	28.00
10	Norway	2	1.01	55	1.37	27.50

Table 5.28 Institutions with the greatest output of core patents on “research and development of drilling technology and equipment in deep complex strata”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	ExxonMobil Upstream Research Company	19	9.55	518	12.87	27.26
2	China University of Petroleum-Beijing	12	6.03	277	6.08	23.08
3	China Petroleum and Chemical Corporation	10	5.03	206	5.12	20.60
4	Southwest Petroleum University	9	4.52	201	4.99	22.33
5	Schlumberger Technology Corporation	7	3.52	194	4.82	27.71
6	PetroChina Co., Ltd.	7	3.52	193	4.79	27.57
7	Halliburton Energy Services Incorporation	7	3.52	157	3.90	22.43
8	Gree Electric Appliances Incorporation of Zhuhai	7	3.52	112	2.78	16.00
9	Saudi Arabian Oil Company	7	3.52	90	2.24	12.86
10	University of Electronic Science and Technology of China	4	2.01	78	1.94	19.50

2.2.8). Countries with strong collaborative efforts in this domain include China, the USA, Saudi Arabia, the Netherlands, Canada, and France (Figure 5.20). There are institutional collaborations among PetroChina Co., Ltd., China Petroleum and Chemical Corporation, and China University of Petroleum-Beijing (Figure 5.21).

The research and development of drilling technology and equipment in deep complex strata is rapidly evolving toward diversification and intelligent systems to meet the escalating challenges of deep drilling. Over the next 5 to 10 years, the level of intelligence and modularity in deep drilling equipment is expected to significantly improve, with broader applications of real-time diagnostics, predictive analytics, and control technologies to effectively manage extreme geological challenges. Concurrently, to cope with the high-pressure and high-temperature environments of deep formations, the development and deployment of high-strength, high-temperature-resistant downhole power tools, measurement-while-drilling (MWD) systems, and vertical drilling systems will be a focal point. Furthermore, the research and development of drilling materials capable of withstanding high temperatures, pressures, and corrosion will be central, as their application will markedly enhance the durability and stability of equipment in extreme environments. Additionally, to improve drilling efficiency, the innovation of drilling acceleration methods and tools will continue to advance, thereby expediting rock-breaking processes and reducing overall drilling costs (Figure 5.22).

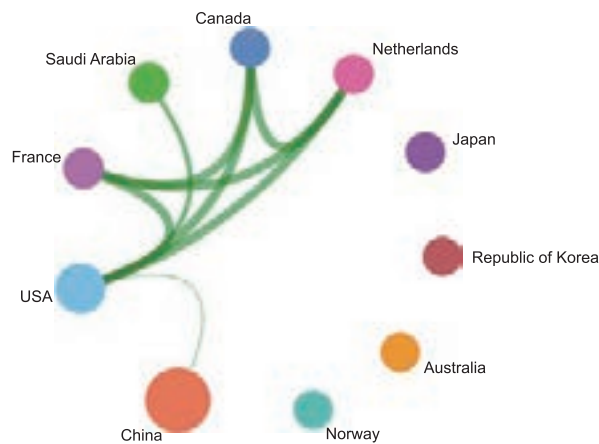


Figure 5.20 Collaboration network among major countries in the engineering development front of “research and development of drilling technology and equipment in deep complex strata”

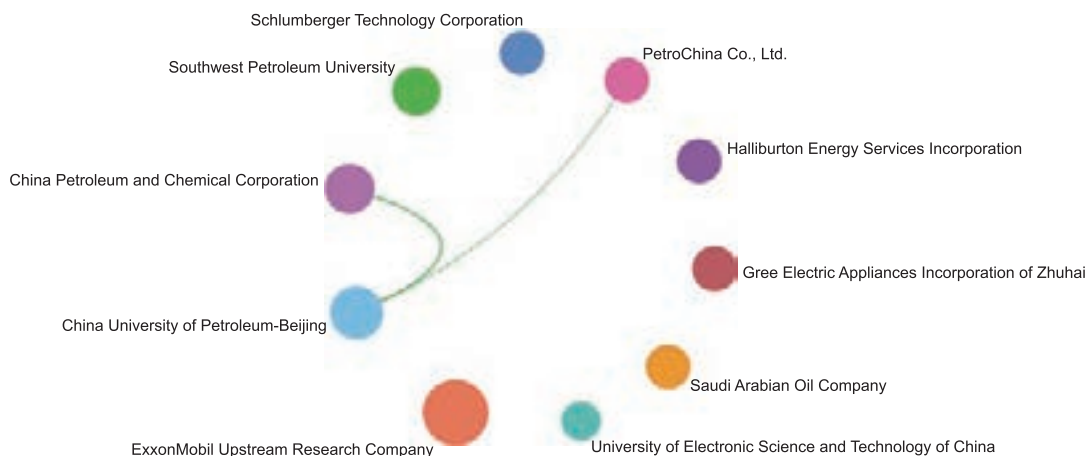


Figure 5.21 Collaboration network among major institutions in the engineering development front of “research and development of drilling technology and equipment in deep complex strata”

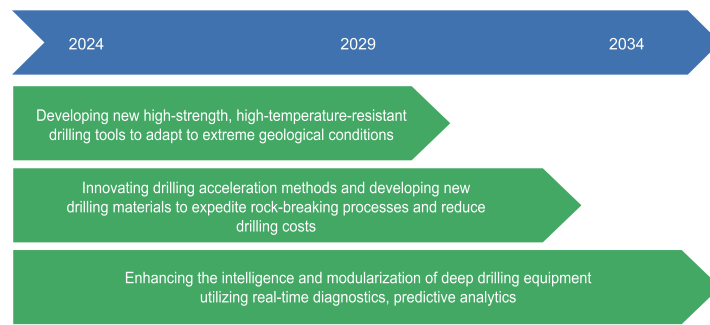


Figure 5.22 Roadmap of the engineering development front of “research and development of drilling technology and equipment in deep complex strata”

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