IV. Energy and Mining Engineering

1 Engineering research fronts

1.1 Trends in top 12 engineering research fronts

The top 12 engineering research fronts assessed by the Energy and Mining Engineering Group are shown in Table 1.1.1. These fronts involves the fields of energy and electrical science, technology, and engineering; nuclear science, technology, and engineering; geology resources science, technology, and engineering; and mining science, technology, and engineering.

Among these top 12 research fronts, emerging research fronts include "multivariate and high-density energy storage methods coupled with renewable energy," "research on photoelectrochemical-photocatalytic hydrogen production from water splitting," "research on methods of coupling big data and artificial intelligence (AI) in the smart grid," "all-solid-state lithium ion batteries with high energy density and fast charging," and "application of big data technologies and methods in oil-gas field geology–engineering–surface integration." "Characteristics, prevention, and mitigation of severe accidents in nuclear power stations," "critical metal mineralization and enrichment mechanisms," "ultra-high-temperature and high-pressure drilling fluids," and "multiphysics-coupling disaster-causing mechanisms in deep metal mining processes" are further developments of traditional research fields. "AI applied to reservoir prediction mechanisms," and "concepts of safe, highly efficient, and intelligent extraction of coal, oil, and gas" are the fronts of interdisciplinary integration. "Research on damage mechanisms and verification of advanced nuclear fuel and related materials" is both an emerging front and a subversive front.

The number of core papers published annually from 2013 to 2018 for the top 12 engineering research fronts is listed in Table 1.1.2.

Table 1.1.1 Top 12 engineering research fronts in energy and mining engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Multivariate and high-density energy storage methods coupled with renewable energy	210	8856	42.17	2015.9
2	Research on damage mechanisms and verification of advanced nuclear fuel and related materials	106	1064	10.04	2016.8
3	AI applied to reservoir prediction mechanisms	44	244	5.55	2015.8
4	Concepts of safe, highly efficient, and intelligent extraction of coal, oil, and gas	17	62	3.65	2016.2
5	Research on photoelectrochemical-photocatalytic hydrogen production from water splitting	25	1023	40.92	2017.6
6	Research on methods of coupling big data and AI in the smart grid	397	3180	8.01	2016.1
7	All-solid-state lithium ion batteries with high energy density and fast charging	73	3806	52.14	2016.3
8	Characteristics, prevention, and mitigation of severe accidents in nuclear power stations	209	7518	35.97	2014.3
9	Application of big data technologies and methods in oil-gas field geology–engineering–surface integration	11	185	16.82	2015.8
10	Critical metal mineralization and enrichment mechanisms	243	6785	27.92	2014.6
11	Ultra-high-temperature and high-pressure drilling fluids	111	1005	9.05	2016.0
12	Multiphysics-coupling disaster-causing mechanisms in deep metal mining processes	142	762	5.37	2015.8

Table 1.1.2 Annual number of core papers published for the top 12 engineering research fronts in energy and mining engineering

No.	Engineering research front	2013	2014	2015	2016	2017	2018
1	Multivariate and high-density energy storage methods coupled with renewable energy	30	17	31	38	49	45
2	Research on damage mechanisms and verification of advanced nuclear fuel and related materials	0	5	15	15	31	40
3	AI applied to reservoir prediction mechanisms	8	8	2	5	9	12
4	Concepts of safe, highly efficient, and intelligent extraction of coal, oil, and gas	2	3	0	1	6	5
5	Research on photoelectrochemical-photocatalytic hydrogen production from water splitting	0	0	0	2	7	16
6	Research on methods of coupling big data and AI in the smart grid	23	40	74	85	80	95
7	All-solid-state lithium ion batteries with high energy density and fast charging	6	7	9	11	14	26
8	Characteristics, prevention, and mitigation of severe accidents in nuclear power stations	66	62	41	32	7	1
9	Application of big data technologies and methods in oil-gas field geology–engineering–surface integration	1	0	2	6	1	1
10	Critical metal mineralization and enrichment mechanisms	63	63	54	42	17	4
11	Ultra-high-temperature and high-pressure drilling fluids	14	15	13	17	18	34
12	Multiphysics-coupling disaster-causing mechanisms in deep metal mining processes	26	18	18	20	23	37

(1) Multivariate and high-density energy storage methods coupled with renewable energy

Efficient and large-scale utilization of renewable energies, such as hydro, wind, solar, biomass, and geothermal energies, is the inevitable choice and important guarantee for sustainable development of global energy and environment. As far as resources and technology development are concerned, wind, solar, and hydro energies have the greatest prospects for development, and power generation is the most effective way to use them. However, a notable disadvantage of wind and solar power generation is that the output power is directly affected by environmental and climatic factors, resulting in features of randomness, intermittence, and fluctuation. Ensuring the continuous and stable output of qualified power from the power generation system is the basis and key for large-scale connection of renewable energy to the power grid. Constructing a renewable energy system that combines wind, solar, hydro, and thermal energies with energy storage units is an essential way to solve this problem, and is the trend of global power development.

Energy storage technology is an energy utilization technology that absorbs and stores energy for a period of time and then releases it in a controlled manner. It can be divided into five types: mechanical energy storage, electrical energy storage, electrochemical energy storage, thermal energy storage, and chemical energy storage. High-density energy storage, in terms of both high energy density and high power density, is the key to large-scale and efficient utilization of renewable energy, which is also a research hotspot of energy storage technology.

The emerging frontiers include low-cost, high-performance, single-type, and high-density energy storage methods; multivariate and high-density energy storage methods that are complementary to each other and coupled with renewable energy; multivariate, high-density energy storage methods that meet the different needs of renewable energy generation, transmission, distribution, and use; and renewable energy power supply systems based on the complementary coupling of wind, solar, hydro, and thermal energies.

(2) Research on damage mechanisms and verification of advanced nuclear fuel and related materials

Nuclear fuel contains most of the radioactive materials and its containment is the first line of defense against the release of radioactive materials in nuclear power plants. Therefore, while the international community is developing advanced nuclear fuels, it is also vigorously conducting research on the damage mechanisms of nuclear fuels and related materials. At present, the research on the damage mechanisms of the current pressurized water reactor (PWR) fuel is primarily focused on the interaction between the fuel and the cladding during power transients; the instability caused by oxidation of the cladding, the fuel fragmentation, dispersal and relocation behavior in a large water loss accident; and the performance degradation of spent fuel cladding in dry storage. To explain the fuel and material behavior from a macroscopic viewpoint, numerous research institutions have conducted various microscopic studies in materials science to master the material behavior of different materials under a variety of corrosive environments, neutron irradiation, temperature fields, and stress fields. Combined with molecular dynamics methods, the damage mechanisms of advanced nuclear fuel and related materials are predicted, evaluated, and verified.

(3) AI applied to reservoir prediction mechanisms

AI has begun to enter into the petroleum field. Applying AI to reservoir prediction can solve various bottlenecks and problems in oilfield exploration and development. However, the application of AI in the petroleum industry is still in its infancy. The forecasting mechanism aims to store and analyze the massive data obtained during reservoir prediction, such as geological data, geomechanical data, reservoir data, engineering data, and economic data, among others, and use big data analysis techniques for high-precision geological modeling and high-efficiency numerical simulation to accurately describe the underground reservoir. Ultimately, all data is integrated on a unified platform, and reservoir prediction is performed from both data and model levels to facilitate reasonable scientific decisions. In short, with the innovation and technological advances of the times, only by combining the traditional petroleum engineering technical knowledge with AI, and realizing the strategic integration of creativity and creative thinking, can we actively adapt to and promote the future development of the petroleum industry.

(4) Concepts of safe, highly efficient, and intelligent extraction of coal, oil, and gas

Intelligent perception, intelligent decision-making, and automatic control (execution) are the three elements of intelligent mining. Intelligent mining differs from general automatic mining in that the equipment has the functions of autonomous learning and decision-making, and has the abilities of self-perception, self-control, and self-correction. Only the intelligent and fully-mechanized mining system of this kind can completely respond to the changes of production environment, realize the real sense of intelligent mining, and realize the goal of unattended remote mining under constrained conditions.

The key technologies of intelligent coal mining include intelligent mining of thin seams and extremely thin seams, intelligent mining of large and extremely-large mining heights of thick seams, and intelligent mining of fully mechanized top coal caving in extra-thick seams. The development trend is to comprehensively promote the intelligent technology of fully mechanized mining in the future, realize the goal of limited unmanned mining, and achieve the goal of unattended robotic fluidized mining.

As the oil and gas exploration and development industry gradually turns its attention to the complex oil and gas resources (including unconventional, low-permeability, ultra-deep, deep-water oil and gas), there appears a series of new problems and challenges in the extraction of oil and gas in terms of safety, economy, and efficiency. Therefore, there is an urgent need to accelerate the cross-border integration of big data, AI, information engineering, underground control engineering, and establishment of a sound theoretical system of safe, efficient, and intelligent development. The eventual aim is to achieve advanced detection, closed-loop regulation, real-time warning, and intelligent decision-making, further promote the safe and economical extraction of oil and gas resources, and provide important support for achieving the major breakthroughs of complex oil and gas extraction in China.

The concepts of safe, highly efficient, and intelligent extraction of oil and gas involve reservoir characterization, downhole condition perception, closed-loop parameter control, and intelligent decision-making for choice of extraction scheme.

The reservoir characterization describes and evaluates the oil and gas flow characteristics in the reservoir during the entire production process and provides a basic reference for oil and gas exploitation regulation. The principal research trends of reservoir characterization include the detailed characterization of reservoir elements, dynamic three-dimensional (3D) geological modeling, and real-time correction of geological models and reconstruction theory.

The downhole condition perception identifies and diagnoses downhole conditions and offers early warning of risks, which then provides important support for safe extraction of oil and gas. The research trends related to downhole condition perception include the response mechanisms of underground monitoring equipment, automatic diagnosis of downhole risks, and early warning concepts.

The closed-loop parameter control is primarily intended to transmit downhole data to the ground, and then issue control instructions to the downhole equipment to adjust the parameters based on the dynamic analysis by a ground-based expert system. In this way, the bidirectional transmission of information is established, and the closed-loop real-time control is achieved, which can establish an important foundation for the economical and efficient production of oil and gas. The foremost research trends of closed-loop parameter control include the bidirectional high-efficiency transmission of massive datasets and closed-loop optimization theory applied to the downhole control parameters.

The intelligent decision-making necessary to devise extraction schemes utilizes the big data from oil and gas fields and then optimizes the extraction scheme for the oil and gas fields by using AI. The key research trends of intelligent decision-making include the dynamic optimization of oil and gas extraction schemes using big data and AI techniques, combined with the concepts of intelligent flow, integration, and self-purification of massive data during long-term extraction.

(5) Research on photoelectrochemical-photocatalytic hydrogen production from water splitting

When a semiconductor photocatalyst is irradiated with light, the electrons located on the valence band undergo a transition due to the external light energy. Photogenerated electrons and holes will be generated simultaneously in the semiconductor. Water could then be split into hydrogen and oxygen by the photogenerated electrons and holes, respectively. This catalytic reaction is the so-called photocatalytic hydrogen production reaction. The efficiency of hydrogen production could also be promoted by applying an external bias, whose reaction is called the photoelectrochemical or photoelectrocatalytic hydrogen production reaction. Photocatalysis and photoelectrocatalysis have a great potential for future sustainable solar hydrogen production.

The fundamental limitations to improving the photocatalytic and photoelectrochemical hydrogen production efficiency include the limitation on the efficiency of light absorption, photo-generated carrier separation efficiency, and catalytic reaction kinetics. At present, the research mainly focuses on development of the strategy for regulating the energy bandgap, construction of heterogeneous structures and crystal planet, and modification of photo cathode/anode semiconductor material. The search for high-efficiency photocatalysts and the development of new low-cost and stable catalytic material and reaction systems have also become a research hotspot. Recently, selection of matched catalysts for photocatalytic hydrogen production and degradation of contaminants in water have also attracted wide attention.

(6) Research on methods of coupling big data and AI in the smart grid

Big data is a dataset consisting of extremely large volumes of numerous data types having complex structures. Big data uses data analysis as the core, covering data preprocessing, fusion, storage, and processing. It has the characteristics of high volume, quick response, wide variety, and low value density. Broadly defined, AI is a smart machine that can react in a way that mimics human intelligence. Deep learning, a form of machine learning, is a method to realize AI. The coupling of big data and AI to the smart grid is a deep integration of data, autonomous knowledge learning, and application scenarios, which is an effective way to cope with the increasing complexity and uncertainty of the grid.

The current research directions include renewable energy generation power forecasting considering time-space correlation; automatic mining and extracting key features of grid stability assessment and emergency control; intelligent analysis and decision making of the power grid; intelligent diagnosis and identification of power grid faults; massive load data classification and prediction; and analysis of the power consumers’ behavior.

The emerging fronts are the development and construction of more advanced and intelligent analysis methods and platforms, and the application of the methods and platforms to deeper and more core fields. In the development of analysis methods and construction of platforms, stress should be placed on the introduction of mature, efficient, and advanced methods of big data analysis and AI, and the integration of existing analytics platforms to gradually build an integrated AI system platform for processing tasks in the power grid field. In field applications, emphasis should be placed on appropriate modification of AI methods in combination with the requirements of the power grid, enhancement of the applicability of the algorithm to increase the coupling depth, and the extension of the application to core areas such as grid security and stability analysis and control, and grid dispatching operations, to increase coupling breadth.

(7) All-solid-state lithium ion batteries with high energy density and fast charging

All-solid-state lithium ion batteries (ASSLIBs) are considered to be one of the most important next generation technologies for energy storage, especially for portable electronic devices and electric vehicle (EV) applications. ASSLIBs have many advantages over commercial lithium ion batteries having liquid organic electrolytes; such advantages include improved safety and reliability, higher volumetric energy densities, wider operating temperatures, higher charging/discharging rates, and simpler battery design. Therefore, ASSLIBs have attracted increasing attention in recent years and are being pursued by many world-leading EV manufacturers such as Toyota, Renault, Nissan, BMW, and Tesla.

Solid electrolyte materials are the key to ASSLIBs. The major problem that hinders the development of ASSLIBs to date has been associated to the relatively low ionic conductivity of the solid electrolyte as well as the poor solid/solid contact at the electrolyte/electrode interface. The properties of a good solid electrolyte material must meet several requirements apart from high Li-ion conductivity. These include low activation energy for Li^+ migration, negligible electronic conductivity (to avoid an internal short circuit), good chemical and electrochemical stability against electrode materials, good thermal stability, excellent mechanical properties, simple fabrication processes, and low cost. To date, there are a variety of material choices for solid electrolyte materials such as oxides, sulfides, hydrides, halides, borates or phosphates, thin films, and polymers. However, none of them can meet all of the essential requirements. Breakthrough discoveries of solid-state electrolyte materials with superior properties are in urgent demand.

ASSLIBs are the ultimate solution to achieving a high energy density and fast charging rate for lithium ion batteries. For its commercialization, great efforts are still to be made in key materials, structure designs, and fabrication techniques.

(8) Characteristics, prevention, and mitigation of severe accidents in nuclear power stations

A serious accident at a nuclear power plant refers to an accident in which the severity of the accident exceeds the design-basis accident (DBA) circumstances and causes the core to deteriorate significantly or even melt, and the failure of corresponding safety facilities may cause a large amount of radioactive material to be released, which is part of the nuclear power plant’s beyond-design-basis accident. The accident process is divided into core melt disintegration, pressure vessel failure, and containment failure.

The PWR nuclear power plant depends on the three barriers to prevent nuclear fission products from leaking, namely, the fuel cladding, the primary circuit pressure boundary, and the containment. When serious accidents such as core melting occur, the mitigation and treatment of accidents primarily focus on lessening the core damage and ensuring the function of the third barrier (i.e., the containment) to reduce the release of radioactive materials into the environment.

In the design of comprehensive accident mitigation measures for nuclear power plants, it is necessary to consider the serious core damage that is actually eliminated. Accident conditions typically include direct containment heating, large-scale steam explosion, hydrogen explosion, containment heat loss, and melt–concrete interaction.

Study should first be conducted on the core melting mechanism. Accident prevention and mitigation engineering techniques, including the in-throw melt retention technology, core melt traps, and hydrogen elimination technology, should be optimized and improved by conducting research on the processes and phenomena of core melt migration in the reactor and migration outside the reactor. Research should then be conducted on the integrity of containment, including containment failure probability calculation, source removal and other preventive and mitigation measures, as well as response to containment isolation failure, containment bypass, early failure of containment, and other accident sequences that lead to failure of containment. Finally, the elimination of large-scale releases should be verified by deterministic and probabilistic methods and the development of severe accident analysis methods and software.

(9) Application of big data technologies and methods in oil-gas field geology–engineering–surface integration

In oil and gas exploration and development, the "sweet spots" have been gradually reduced, forcing major oil companies to reduce costs and increase efficiency. However, big data, to some extent, can compensate for the theoretical defects. The big data application technologies and methods in oil-gas field geology–engineering–surface integration are thus proposed in this context. Based on the big data methods combined with pattern recognition technology, multi-scale data mining is performed on a large number of actual operational and historical data such as drilling, logging, oil testing, fracturing acidification, and ground testing to improve economic and social benefits. Through research and integration of geological, engineering, ground, and other full-process data; big data collection, processing, and storage; as well as cloud computing, exchange, and sharing, the big data application technology will ultimately be applied to strategic analysis and decision-making. That is to say, through the establishment of an integrated database, the existing mature data mining methods are used for regular analysis, dimensional analysis, correlation analysis, and empirical correlation statistical regression to guide the actual oilfield production practice. At the same time, the applications require a new management model to have a greater decision-making power, insight, and process optimization capabilities. In short, this is an essential technology for scientific exploration and development of oil and gas fields. It can transform data into information faster and more efficiently, quickly discover oil and gas, and reduce production costs. It will bring new vitality to major oil and gas fields and promote the informationization and intelligent development of oil and gas field development.

(10) Critical metal mineralization and enrichment mechanisms

Critical metals, namely strategic metals, including rare trace elements, rare earth elements, dispersed rare elements, and platinum group elements, are the raw materials essential for development of modern advanced manufacturing, low-carbon clean energy technologies and other growing industries. China is well-endowed with a variety of critical metals. For example, China has supplied 95% of the total rare earth elements, 84% of the total tungsten, and 53% of the total scandium resource to satisfy global demands in the past years. However, other critical metals, such as manganese, niobium, beryllium, nickel, cobalt, chromium, and platinum group elements, are relatively scarce but crucially needed, which may increase the risks of bottlenecks in the establishment of advanced manufacturing and growing industries in China.

Most developed western countries have recently been dedicated to unraveling significant factors that lead to enrichment mechanisms and mineralized characterization of strategically critical metals, and encouraging their domestic mining companies to launch exploration projects targeted at critical metal resources. The mineralization of critical metals is characterized by dispersion, low-grade, small tonnage, and challenge in geometallurgy. Some critical metals can be produced on a relatively large scale, but they commonly occur as by-products in extraordinarily small quantities from base metal refining. The mineralization of critical metals is typically uncontinuous and it is difficult to delimit their orebodies. Furthermore, the ore genesis and accumulation mechanism of critical metals remain unclear. Therefore, new theories and deposit models for mineralization of critical metals are urgently needed. It is recommended that scientific research be strengthened to reveal the enrichment processes and mineralization mechanisms related to low-abundance critical metals, to elucidate the microscale occurrence modes and macroscale distribution patterns of critical metal elements, and to define the vital, coupled geological and physiochemical (-biological) factors controlling the mineralization of critical metals. All of the proposed research works aim to discover new types of critical metal ore deposits and increase the resource reservoirs, to maintain a stable supply of critical raw materials that are needed to achieve the strategic plan of "Made in China 2025."

(11) Ultra-high-temperature and high-pressure drilling fluids

Drilling fluid is the lifeblood of drilling engineering, providing important support for removing bottom cuttings, cooling drilling tools, and controlling formation pressure during drilling. Its performance is the key to successful drilling. At present, as energy demand increases year-by-year, deep exploration and development, especially deep and ultra-deep oil and gas, marine oil and gas, and new energy sources such as dry hot rock geothermal resources, have become inevitable. The ultra-high-temperature and high-pressure environment in the well poses severe challenges to the performance of the drilling fluid. This environment may even lead to complete destruction of the drilling fluid system and rapid deterioration of performance, resulting in various complex downhole accidents. Therefore, it is urgent to study ultra-high-temperature and high-pressure drilling fluids to optimize the high-temperature and high-pressure resistance of drilling fluids. As a result, it is necessary to establish ultra-high-temperature and high-pressure water-based drilling fluids, ultra-high-temperature and high-pressure oil-based drilling fluids, and ultra-high-temperature and high-pressure synthetic-based drilling fluid systems to ensure safe and efficient drilling of deep formations. Among them, the research of ultra-high-temperature and high-pressure water-based drilling fluids includes the development of new monomer synthesis and conversion techniques; development of salt-resistant high-temperature and high-pressure fluid loss reducers, viscosity reducers, inhibitors, lubricants, plugging agents, and well-wall stabilizers; and the development of anti-high-temperature thickeners and high-temperature and high-pressure fluid loss reducers. Research on ultra-high-temperature and high-pressure oil-based drilling fluids includes development of oil-based drilling fluid treatment agents such as ultra-high-temperature and high-efficiency emulsifiers, tackifiers, fluid loss additive, and flocculants; development of high-performance adhesives and surfactants; development of new reversible emulsification drilling fluid systems; and rheology control methods for forming a system. Research on ultra-high-temperature and high-pressure synthetic-based drilling fluid includes research and development of new low-cost synthetic base materials, development of emulsifiers, flow modifiers, tackifiers, and flocculants for synthetic-based drilling fluids.

(12) Multiphysics-coupling disaster-causing mechanisms in deep metal mining processes

Deep metal mining faces the complex environment of the “three highs” and “one disturbance,” i.e., high ground stress, high osmotic pressure, high temperature, and strong mining disturbance. This research front aims to explore the multi-field coupling regulation of stress field, seepage field, temperature field, and chemistry field of deep metal mining, revealing gestation, evolution, and occurrence mechanisms of deep metal explosions such as deep rock burst and soft rock deformation under the multi-field coupling condition to lay the foundation for the advanced prediction and regulation of deep metal mine disasters.

Research and development areas include deep high-efficiency stress, seepage, temperature, chemical, and other multi-field environmental identification sensors and rapid detection methods to accurately identify the multi-field coupling environment of deep mining; multi-field coupling mechanics test systems, and discovery of the multi-field coupling rock mechanics behaviors; multi-field environmental intelligence inversion and dynamic monitoring analysis technology, deduction of the multi-field environment in the mining area by limited test data; investigation of the mechanisms of multi-field coupling disasters in deep mining; and development of numerical simulation software for mining disasters under multi-field coupling to develop the rock mass control concepts and the technology of multi-field coupled environmental conditions.

Based on existing research bases, the development in the future will focus on key research fields, i.e., “accurate intelligent identification technology under deep multi-field coupled environment,” “deep multi-field coupling mechanics test system,” “multi-field environmental intelligent deduction and dynamic monitoring analysis technology,” and “multi-field coupling disaster mechanism and rock mass control technology in deep mining,” to achieve innovative theoretical development and equipment-level breakthrough.

1.2 Interpretations for four key engineering research fronts

1.2.1 Multivariate and high-density energy storage methods coupled with renewable energy

(1) Conceptual explanation and key technologies

The efficient and large-scale utilization of renewable energies include hydro, wind, solar, biomass, and geothermal energies is the inevitable choice and important guarantee for the sustainable development of global energy and environment. As far as resources and technology development are concerned, wind, solar, and hydro energies have the best prospects for development, and power generation is the most realistic and prospective way to use them. However, a notable disadvantage of wind and solar power generation is that the output power is directly affected by environmental and climatic factors and, thus, exhibits great fluctuation, randomness, and intermittent behaviors. Such unqualified power cannot be directly connected to the grid on a large scale.

Energy storage technology is an energy utilization technology that absorbs and stores energy for a period of time and then releases it in a controlled way. According to the different storage media, energy storage technologies can be divided into five categories of mechanical, electrical, electrochemical, thermal, and chemical energy storage. Mechanical energy storage includes pump water, compressed air, and flywheel energy storage. Electrical energy storage generally includes supercapacitor and superconductor energy storage. Electrochemical energy storage refers to the energy storage using all kinds of batteries. Thermal energy storage stores electricity in the form of sensible, phase change, or chemical heat in the medium in a thermal insulation container, and then converts the stored heat into power or uses it as a thermal source. Chemical energy storage refers to the use of electricity to produce hydrogen or synthetic gas, ammonia, and other secondary energy carriers. Energy storage density is used to measure the energy storage capacity of energy storage equipment per unit mass or volume, which is also divided into energy density and power density. The former corresponds to the amount of energy stored, while the latter corresponds to the speed of energy storage and release. High-density energy storage with high energy density and high power density is the key to large-scale and efficient utilization of renewable energy. The associated research directions include the development of a single type of energy storage method with a high-density energy performance, and the development of multivariate energy storage systems using a combination of multiple energy storage methods.

(2) Development status and future development trends

The technologies of renewable energy power generation and energy storage are developing rapidly worldwide. By the end of 2018, the total installed capacity of renewable energy power generation in the world had reached 2351 gigawatts (GW), including 1172 GW of hydropower, 564 GW of wind, 480 GW of solar energy, 121 GW of biomass, and 539 GW of geothermal energy. The cumulative in-service installed capacity of energy storage worldwide was 180.9 GW, an increase of 3% over the previous year, of which the pump water storage was 170.7 GW, accounting for 94%. The electrochemistry energy storage reached 4.89 GW, an increase of 66.3% over 2017. Among the electrochemistry energy storage, lithium ion batteries accounted for 86% of the total installed capacity, followed by sodium-sulfur batteries and lead-acid batteries, both accounting for 6%. In 2018, the installed capacity of renewable energy in the world was amounted to 171 GW, a year-on-year growth of 7.9%, of which 94 GW was solar energy, accounting for the largest proportion, while 49 GW and 21 GW was wind power and hydropower, respectively. Two-thirds of the world's new electricity generation came from renewable energies. The newly-added in-service installed capacity of energy storage in the world was 5.5 GW, of which the largest was electrochemical energy storage, with a growth rate of 288% compared with the previous year.

China is the country with the fastest development of renewable energy power generation and energy storage technologies. By the end of 2018, the cumulative installed capacity of renewable energies had reached 729 GW, accounting for 38.4% of the total installed capacity of the country, of which hydropower reached 352 GW, accounting for 18.5% of the total installed capacity, wind power reached 184 GW, accounting for 9.7%, and photovoltaic power reached 174 GW, accounting for 9%. The cumulative installed capacity of in-service energy storage projects in China was 31.2 GW, an increase of 8% over the previous year, of which pump water energy storage was approximately 30 GW, accounting for 96% of the total installed capacity. The next largest two were electrochemical storage and molten salt storage, with a capacity of 1.01 GW and 0.22 GW and an increase of 159% and 1000%, respectively. In 2018, the newly-installed capacity of photovoltaic power was 44.26 GW, while the newly-added in-service installed capacity of the energy storage was 2.3 GW, of which electrochemical energy storage was the largest, with a number of 0.6 GW, an increase of 414% over 2017.

Constructing a power generation system that couples wind, solar, hydro, and thermal energies with energy storage units is an important way to solve the problem of discontinuity and instability of renewable energy generation. In recent years, China has successfully launched several demonstration applications of centralized renewable energy grid connection technologies. In Qinghai Province, the world's largest water–solar complementary photovoltaic power station was established. An 850 megawatt (MW) photovoltaic power station was connected to a hydropower station as a "virtual hydropower unit." The photovoltaic power is smoothly and steadily transferred to the power grid through the rapid regulation of the hydro-turbine units. In Jilin Province, one wind farm realized the fast tracking of the changes of curtailed wind power by means of an energy storage system equipped with regenerative electric boilers, and another wind farm demonstrated the integrated operation of wind power and energy storage systems.

Generally speaking, up to the present, only pump water energy storage and compressed air energy storage are relatively mature among the large-scale energy storage technologies in China and worldwide, but they are restricted by geographical conditions. In-service compressed air storage also burns fossil fuels to provide the heat source. Other energy storage technologies are still at the stage of demonstration and laboratory research. Breakthroughs are needed in their reliability, service life, cost, and application adaptability. These technologies are still not qualified for wide popularization and application in the power grid, restricting the efficient and large-scale utilization of renewable energy. Coupling the renewable energy generation technology with multivariate high-density energy storage can not only make possible the large-scale access of renewable energy to power grid, but also meet the urgent demand of flexible peak shaving required by the smart grid.

The emerging fronts include low-cost, high-performance, single-type, high-density energy storage methods; multivariate and high-density energy storage methods that are complementary to each other and coupled with renewable energy; multivariate and high-density energy storage methods that meet the different needs of power generation, transmission, distribution, and usage stages of renewable energy; and renewable energy power supply systems based on complementary coupling of wind, solar, hydro, and thermal energies.

(3) Comparison and cooperation analysis based on major countries/regions and institutions

As shown in Table 1.2.1, China, the USA, India, and the UK are the countries with the largest number of core papers published in this research direction, with China and the USA ranking first and second, publishing 39.05% and 20.95% of the core papers, respectively. The proportion of core papers published by India and the UK is 9.05% each.

As shown in Table 1.2.2, the Chinese Academy of Sciences, Shanghai Jiao Tong University, the University of Chinese Academy of Sciences, the Universiti Malaysia Pahang, and Tsinghua University are the organizations with the largest number of core papers published in this research direction, the number of core papers being 11, 7, 6, 5, and 5, respectively.

As shown in Figure 1.2.1, China, the USA, the UK, Australia, and Spain are the countries that pay more attention to this engineering research front. China has the largest number of core papers published, and the major countries that cooperate with China in publishing core papers are the USA, the UK, Australia, and Japan. The USA has the second largest number of core papers published, and it cooperates with China, Spain, Australia, and Canada in publishing core papers.

As depicted in Figure 1.2.2, in this research direction the Chinese Academy of Sciences has close cooperation with the University

Table 1.2.1 Countries or regions with the greatest output of core papers on “multivariate and high-density energy storage methods coupled with renewable energy”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	82	39.05%	1929	21.78%	23.52
2	USA	44	20.95%	4388	49.55%	99.73
3	India	19	9.05%	476	5.37%	25.05
4	UK	19	9.05%	681	7.69%	35.84
5	Australia	16	7.62%	1001	11.30%	62.56
6	Germany	12	5.71%	337	3.81%	28.08
7	Canada	11	5.24%	212	2.39%	19.27
8	Spain	10	4.76%	367	4.14%	36.70
9	South Korea	9	4.29%	125	1.41%	13.89
10	Japan	7	3.33%	113	1.28%	16.14

Table 1.2.2 Institutions with the greatest output of core papers on “multivariate and high-density energy storage methods coupled with renewable energy”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Chinese Acad Sci	11	5.24%	219	2.47%	19.91
2	Shanghai Jiao Tong Univ	7	3.33%	63	0.71%	9.00
3	Univ Chinese Acad Sci	6	2.86%	110	1.24%	18.33
4	Univ Malaysia Pahang	5	2.38%	136	1.54%	27.20
5	Tsinghua Univ	5	2.38%	83	0.94%	16.60
6	Indian Inst Technol	4	1.90%	112	1.26%	28.00
7	Univ Wollongong	4	1.90%	85	0.96%	21.25
8	Pacific NW Natl Lab	3	1.43%	692	7.81%	230.67
9	MIT	3	1.43%	572	6.46%	190.67
10	Stanford Univ	3	1.43%	753	8.50%	251.00

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of “multivariate and high-density energy storage methods coupled with renewable energy”

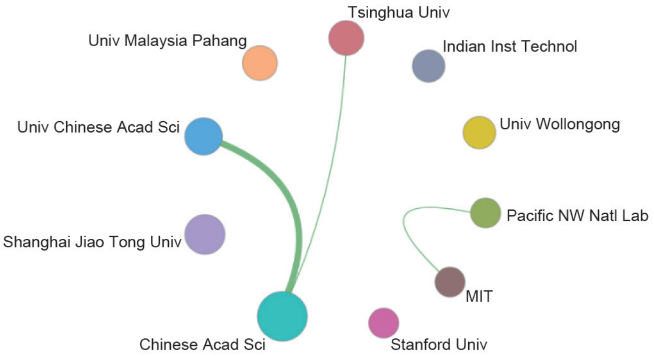

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “multivariate and high-density energy storage methods coupled with renewable energy”

of the Chinese Academy of Sciences, and has cooperation with Tsinghua University. Massachusetts Institute of Technology (MIT) and the Pacific NW National Laboratory also have some cooperation.

Table 1.2.3 shows that the country with the greatest number of citing papers is China, with a percentage of 45.38%, followed by the USA, with a percentage of 17.98%. Germany and South Korea also cite more than 5% of core papers.

In Table 1.2.4, the institution with the greatest number of citing papers is the Chinese Academy of Sciences, with a percentage of 27.65%, followed by the University of the Chinese Academy of Sciences, with a percentage of 10.28%, Tsinghua University and China University of Science and Technology, with a percentage of 9.51% and 8.11%, respectively.

The above data analysis indicates that China and the USA are at the forefront in the number and citation of core papers in the engineering research front of multivariate high-density energy storage methods coupled with renewable energy. The number and citation of the core papers of the Chinese Academy of Sciences and several Chinese universities are of the highest in the world.

1.2.2 Research on damage mechanisms and verification of advanced nuclear fuel and related materials

Nuclear fuel contains most of the radioactive materials and is the first line of defense against the release of radioactive materials. Therefore, while the international community is developing advanced nuclear fuels, it is also vigorously

Table 1.2.3 Countries or regions with the greatest output of citing papers on “multivariate and high-density energy storage methods coupled with renewable energy”

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	4173	45.38%	2017.3
2	USA	1653	17.98%	2016.8
3	Germany	631	6.86%	2016.9
4	South Korea	558	6.07%	2017.0
5	Australia	417	4.53%	2017.2
6	UK	342	3.72%	2017.0
7	India	342	3.72%	2017.5
8	Japan	336	3.65%	2016.9
9	Singapore	273	2.97%	2016.9
10	Canada	249	2.71%	2016.9

Table 1.2.4 Institutions with the greatest output of citing papers on “multivariate and high-density energy storage methods coupled with renewable energy”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Acad Sci	573	27.65%	2017.2
2	Univ Chinese Acad Sci	213	10.28%	2017.5
3	Tsinghua Univ	197	9.51%	2017.1
4	Univ Sci & Technol China	168	8.11%	2017.4
5	Univ Munster	159	7.67%	2016.4
6	Huazhong Univ Sci & Technol	137	6.61%	2017.0
7	Nanyang Technol Univ	135	6.52%	2016.9
8	Cent S Univ	133	6.42%	2017.3
9	Forschungszentrum Julich	128	6.18%	2017.5
10	Tianjin Univ	117	5.65%	2017.3

conducting research on the damage mechanisms of nuclear fuels and related materials.

At present, according to the existing engineering experience and material irradiation behavior, it is possible to better predict and evaluate the behavior of cladding corrosion, stress strain, and fission gas release of existing PWR fuel under stable operating conditions. The current research primarily focuses on the material damage and failure mechanism in transient and accident scenarios of nuclear power plants. Among them, the pellet-cladding interaction (PCI) in power transients involves the initial microcrack of cladding under the action of the corrosive fission gas atmosphere, which continuously expands due to the extrusion of fuel and causes the cladding to fail. In addition to the special concern on the instability oxidation of the cladding in a loss of coolant accident, attention should also be paid to the fragmentation, dispersal, and relocation of the fuel itself during the accident, which will have a profound impact on the consequences of the accident. In addition to the above-mentioned damage mechanisms and failure behaviors in the reactor, the material performance degradation mechanisms of spent fuel cladding during dry storage of PWRs, including hydride reorientation and delayed hydrogenation cracking, are closely related to safety of dry storage of spent fuel. Therefore, it is also the focus of research of the international community at present.

The analysis and mechanism of damage and failure behavior of advanced nuclear fuels and related materials are conducted in combination with macro-scale and micro-scale multi-scale research and analysis. Macroscopically, various types of experiments are performed, including various material performance tests, ion irradiation tests, and re-fabricated rod tests to obtain the behavior of materials in specific scenarios. Microscopically, various types of microstructure, morphology, and composition analysis tools, such as metallographic microscopes, scanning electron microscopes, and fluoroscopy electron microscopes, are used to study the internal characterization of defects, dislocations, phase transitions, and segregation, to explain the macroscopic material behavior.

To better carry out the unification of material behavior and mechanism at multi-scales, many countries have conducted research on the damage mechanisms of advanced nuclear fuel and related materials under irradiation conditions in the molecular dynamics field, and have established related models to predict the material irradiation behavior.

According to Table 1.2.5, the countries or regions with the largest number of core papers published in this research direction are the USA, China, and South Korea. Among them, the USA ranked first, having a proportion of core papers reaching 64.15%. The proportion of core papers of China exceeded 10%.

According to Table 1.2.6, the largest number of core papers published in this research direction are from Oak Ridge National Laboratory and Idaho National Laboratory, whose numbers of core papers published are both more than 10.

Table 1.2.5 Countries or regions with the greatest output of core papers on “research on damage mechanisms and verification of advanced nuclear fuel and related materials”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	68	64.15%	751	70.58%	11.04
2	China	12	11.32%	55	5.17%	4.58
3	South Korea	10	9.43%	150	14.10%	15.00
4	Sweden	6	5.66%	40	3.76%	6.67
5	UK	6	5.66%	38	3.57%	6.33
6	Japan	3	2.83%	44	4.14%	14.67
7	France	3	2.83%	24	2.26%	8.00
8	Germany	3	2.83%	20	1.88%	6.67
9	Czech Republic	3	2.83%	13	1.22%	4.33
10	Poland	2	1.89%	1	0.09%	0.50

Table 1.2.6 Institutions with the greatest output of core papers on “research on damage mechanisms and verification of advanced nuclear fuel and related materials”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Oak Ridge Natl Lab	22	20.75%	328	30.83%	14.91
2	Idaho Natl Lab	10	9.43%	88	8.27%	8.80
3	Penn State Univ	7	6.60%	124	11.65%	17.71
4	Los Alamos Natl Lab	7	6.60%	53	4.98%	7.57
5	MIT	7	6.60%	47	4.42%	6.71
6	Korea Atom Energy Res Inst	6	5.66%	131	12.31%	21.83
7	Westinghouse Elect Co	6	5.66%	108	10.15%	18.00
8	GE Global Res	6	5.66%	7	0.66%	1.17
9	Univ Wisconsin	4	3.77%	21	1.97%	5.25
10	Gen Atom Co	3	2.83%	96	9.02%	32.00

According to Figure 1.2.3, the USA, China, the UK, Germany, the Czech Republic, France, South Korea, and Sweden are more concerned about the cooperation between countries or regions in this field. China has many published papers, mainly in cooperation with the USA and Sweden.

According to Figure 1.2.4, the Oak Ridge National Laboratory, the Idaho National Laboratory, Pennsylvania State University, the Los Alamos National Laboratory, Westinghouse Electric Company, and the University Wisconsin have collaborated.

As given in Table 1.2.7, the country with the largest number of citing papers is the USA, with a proportion of 37.44%. China has a citing proportion of 26.99%, while South Korea has a citing proportion of 10.92%.

As shown in Table 1.2.8, Oak Ridge National Laboratory is the organization that produces the most of core papers, having a proportion of citing papers of 29.03%. The proportion of citing papers of the Korea Atomic Energy Research Institute is 10.26%.

The above data analysis indicates that the USA and China are leading producers of core papers in the field of nuclear fuels and related materials in terms of damage mechanisms and verification techniques. The number of citing papers of US research institutions is comparatively large.

1.2.3 AI applied to reservoir prediction mechanisms

The combination of AI and oilfield technologies may solve various bottlenecks and new problems in oilfield exploration and development. It is imperative to promote the transformation and application of the AI technology in old oilfields and oilfield industries. The greatest revelation of AI on reservoir prediction is that it can still produce significant prediction results by relying on massive data and deep

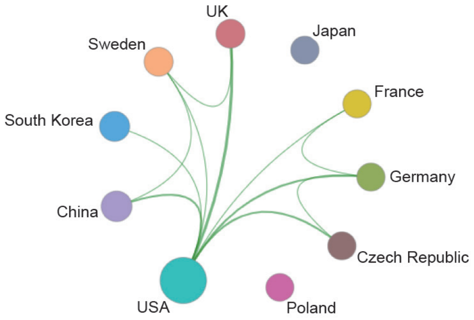

Figure 1.2.3 Collaboration network among major countries or regions in the engineering research front of "research on damage mechanisms and verification of advanced nuclear fuel and related materials"

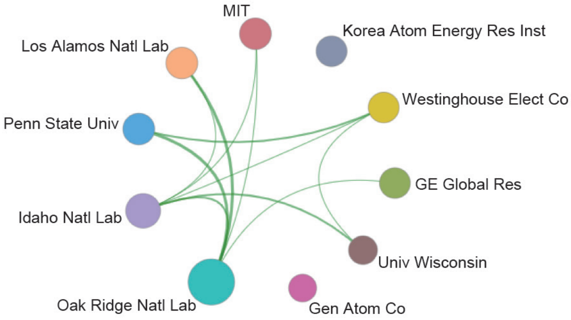

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "research on damage mechanisms and verification of advanced nuclear fuel and related materials"

Table 1.2.7 Countries or regions with the greatest output of citing papers on "research on damage mechanisms and verification of advanced nuclear fuel and related materials"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	USA	240	37.44%	2017.7
2	China	173	26.99%	2018.2
3	South Korea	70	10.92%	2017.6
4	UK	39	6.08%	2018.2
5	Germany	26	4.06%	2018.1
6	Sweden	22	3.43%	2017.9
7	Japan	21	3.28%	2018.0
8	Russia	18	2.81%	2018.3
9	France	13	2.03%	2018.4
10	Canada	11	1.72%	2018.4

Table 1.2.8 Institutions with the greatest output of citing papers on "research on damage mechanisms and verification of advanced nuclear fuel and related materials"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Oak Ridge Natl Lab	99	29.03%	2017.5
2	Korea Atom Energy Res Inst	35	10.26%	2017.5
3	Idaho Natl Lab	33	9.68%	2017.8
4	Los Alamos Natl Lab	31	9.09%	2018.2
5	Univ Wisconsin	25	7.33%	2017.8
6	Chinese Acad Sci	25	7.33%	2018.5
7	Univ Tennessee	21	6.16%	2018.1
8	Penn State Univ	19	5.57%	2017.6
9	Nucl Power Inst China	19	5.57%	2018.4
10	MIT	17	4.99%	2018.0

learning algorithms without clear reservoir patterns and laws. The reservoir prediction process involves a large amount of data, including geological data, geomechanical data, reservoir data, engineering data, economic data, and so on. However, the data scale and resolution are not uniform, the spatial density is large, the time and frequency are different, and most of the explanatory data are obtained indirectly with great uncertainty.

Big data techniques should be used for high-precision geological modeling and high-efficiency reservoir numerical simulation, while techniques such as unstructured grids and dynamic simulations should be used to describe the underground reservoirs more accurately. Ultimately, all the data is integrated on a unified platform to facilitate decision-making based on both data and models. Based on the quantitative and visual 3D model, all measurement data and constraints for the specific oil and gas field exploration and development life cycle are presented.

Based on the AI algorithms, the uncertainties of the model are reduced by continuously updating the model, driven by the abundant data, thus automatically facilitating making the most scientific and reasonable predictions and decisions based on full consideration of all data and laws. Based on a series of intelligent tools, equipment, and methods, deep learning and cognitive analysis of various data in the reservoir can help find oil and gas enrichment areas. However, the AI technology is still in its theoretical infancy stage for reservoir prediction applications. It is necessary to clarify the direction in strategic research and implement breakthroughs in key technologies. This is the key to realizing the enhancement of oil and gas exploration and development technology in China. It is hoped that this application will allow the big data and AI technologies to go hand-in-hand with the evolution of oil and gas exploration and development, thereby extracting more oil and gas resources underground to meet the country's growing energy needs.

Relevant papers in this area are published and cited primarily by Iran, Saudi Arabia, the USA, China, and other countries, as given in Tables 1.2.9 and 1.2.11. The foremost institutions include Petroleum University of Technology, King Fahd University of Petroleum and Minerals, Islamic Azad University, and the Technical College of Amirkabir University, as given in Tables 1.2.10 and 1.2.12. Australia has cooperated with the USA and Iran. Saudi Arabia has cooperated with Egypt and Malaysia; the Islamic Azad University, the Petroleum University of Technology, and the Southern Cross University have cooperated, as shown in Figures 1.2.5 and 1.2.6.

1.2.4 Concepts of safe, highly efficient, and intelligent extraction of coal, oil, and gas

(1) Concepts of safe, highly efficient, and intelligent extraction of coal

At present, the principals of safe, highly efficient, and intelligent extraction of coal are still in their infancy; they are entering the key stage of technological innovation and development. Therefore, it is necessary to research and develop key technologies such as integration of adaptive control and support systems for intelligent control of mining

Table 1.2.9 Countries or regions with the greatest output of core papers on “AI applied to reservoir prediction mechanisms”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Iran	19	43.18%	140	57.38%	7.37
2	Saudi Arabia	10	22.73%	57	23.36%	5.70
3	USA	5	11.36%	9	3.69%	1.80
4	Canada	4	9.09%	18	7.38%	4.50
5	Australia	4	9.09%	6	2.46%	1.50
6	China	3	6.82%	11	4.51%	3.67
7	Egypt	3	6.82%	18	7.38%	6.00
8	Algeria	2	4.55%	7	2.87%	3.50
9	France	2	4.55%	7	2.87%	3.50
10	Malaysia	1	2.27%	14	5.74%	14.00

Table 1.2.10 Institutions with the greatest output of core papers on “AI applied to reservoir prediction mechanisms”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Petr Univ Technol	9	20.45%	89	36.48%	9.89
2	King Fahd Univ Petr & Minerals	9	20.45%	56	22.95%	6.22
3	Islamic Azad Univ	7	15.91%	83	34.02%	11.86
4	Amirkabir Univ Technol	3	6.82%	35	14.34%	11.67
5	Univ Alberta	3	6.82%	12	4.92%	4.00
6	Southern Cross Univ	3	6.82%	5	2.05%	1.67
7	Univ Tehran	2	4.55%	20	8.20%	10.00
8	Nexen Energy ULC	2	4.55%	11	4.51%	5.50
9	Univ MHamed Bougara	2	4.55%	7	2.87%	3.50
10	Univ Rennes 1	2	4.55%	7	2.87%	3.50

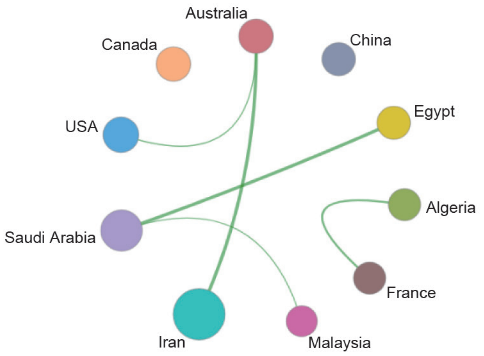

Figure 1.2.5 Collaboration network among major countries or regions in the engineering research front of “AI applied to reservoir prediction mechanisms”

height in surrounding rock, intelligent navigation for working face straightness, multi-information fusion and coordination of systems, intelligent advance support, and auxiliary operation. By realizing self-perception of environmental parameters for comprehensive mechanized equipment and self-regulation of mining behavior, the intelligent mining technology can be upgraded.

With the intelligent development of fully mechanized mining, its strategic position is becoming increasingly prominent. Intelligent mining is one of the core systems of an intelligent coal mine. Precise mining also requires few people or applies unattended remotely-controllable intelligent mining as

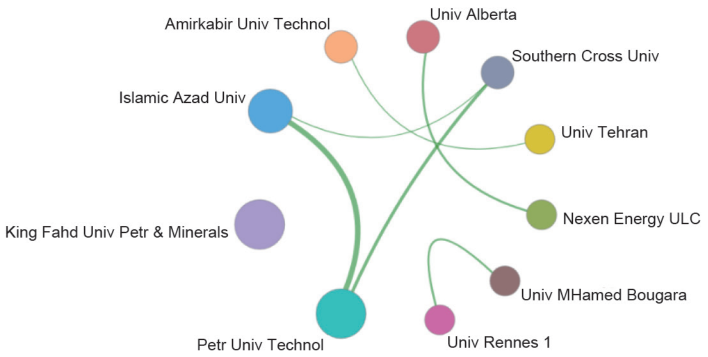

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "AI applied to reservoir prediction mechanisms"

Table 1.2.11 Countries or regions with the greatest output of citing papers on "AI applied to reservoir prediction mechanisms"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	Iran	76	31.93%	2016.8
2	China	40	16.81%	2017.6
3	Saudi Arabia	27	11.34%	2017.7
4	USA	20	8.40%	2017.4
5	Canada	19	7.98%	2017.5
6	Australia	16	6.72%	2015.9
7	India	11	4.62%	2017.2
8	France	8	3.36%	2016.6
9	South Korea	7	2.94%	2017.4
10	Malaysia	7	2.94%	2017.1

Table 1.2.12 Institutions with the greatest output of citing papers on "AI applied to reservoir prediction mechanisms"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Petr Univ Technol	31	21.83%	2015.7
2	King Fahd Univ Petr & Minerals	21	14.79%	2017.7
3	Amirkabir Univ Technol	19	13.38%	2017.6
4	Islamic Azad Univ	17	11.79%	2016.1
5	Univ Tehran	13	9.15%	2017.4
6	Shahrood Univ Technol	8	5.63%	2018.5
7	Southwest Petr Univ	8	5.63%	2017.4
8	So Cross Univ	7	4.93%	2015.4
9	Tsinghua Univ	6	4.23%	2017.3
10	China Univ Petr	6	4.23%	2017.7

an important support. At present, many coal enterprises grasp the new trend of technological development and vigorously upgrade mining technologies and equipment, which provides an important opportunity for the intelligent and fully mechanized mining technology. However, there also exist some practical problems such as an insufficient understanding of intelligent mining. The key research directions of safe, highly efficient, and intelligent extraction of coal include the "transparent mining" technology, intelligent coupling and adaptive control of a hydraulic support control group and surrounding rocks, intelligent height control of the shearer, the cooperative control technology based on multi-information fusion systems, and intelligent control of advanced support and auxiliary operation.

(2) Concepts of safe, highly efficient, and intelligent extraction of oil and gas

With the development of oil and gas exploration and development towards unconventional, low-permeability, ultra-deep, deep-water oil and gas, future oil and gas exploitation faces a series of difficulties and challenges in terms of safety, economy, and efficiency. Therefore, it is urgent to accelerate the cross-border integration of big data, AI, information engineering, and underground control engineering, and establish a sound theoretical system of safe, efficient, and intelligent development. The eventual aim is to achieve advanced detection, closed-loop regulation, real-time warning, and intelligent decision-making, further promote the safe and economical extraction of oil and gas resources, and provide an important support for achieving the major breakthroughs in complex oil and gas extraction in China.

The concepts of safe, highly efficient, and intelligent extraction of oil and gas primarily involve reservoir characterization, downhole condition perception, closed-loop parameter control, and intelligent decision-making for selection of extraction schemes. The reservoir characterization describes and evaluates the oil and gas flow characteristics in the reservoirs during the entire production process and provides a basic reference for oil and gas exploitation regulation. Currently, Texas A&M University has conducted research on multi-scale interpretation of oil and gas reservoirs based on geophysical data. Shell Oil Co. has built a 3D transparent reservoir that can be used for real-time interactive analysis. The downhole condition perception identifies and diagnoses downhole conditions, and offers early warning of risks, which can then provides crucial support for safe extraction of oil and gas. At present, British Petroleum (BP) has conducted a study on integrated risk control for safety of underground production. China's SINOPEC Corp. has established a relatively complete risk identification and hierarchical management mechanism.

The closed-loop parameter control is designed to transmit downhole data to the ground, and then issue control instructions to the downhole equipment to adjust the parameters based on the dynamic analysis by a ground-based expert system. In this way, the bidirectional transmission of information is established, and the closed-loop real-time control is achieved, which can lay an important foundation for the economical and efficient production of oil and gas. At present, Schlumberger, PetroChina, and other companies have proposed a relatively complete automatic regulation mechanism for oil and gas production equipment based on monitoring of real-time data such as downhole temperature, pressure, and flow velocity. The intelligent decision-making of extraction scheme for oil and gas fields utilizes the big data of oil and gas fields, and then optimizes the extraction scheme using AI, which provides key support for China's progress toward the smart oilfield. Currently, based on analysis of multi-dimensional massive data, Shell has realized the intelligent management of extraction schemes in hundreds of production and injection wells. However, China is still in its early stage of development in this research field.

The predominant research trends of reservoir characterization include the fine-grained characterization of reservoir elements, 3D dynamic geological modeling, real-time correction of the geological models, and the reconstruction theory. The key research trends of downhole condition perception include the response mechanisms of underground monitoring equipment, automatic diagnosis of downhole risks, and the associated early warning concepts. The primary research trends of closed-loop parameter control include the bidirectional high-efficiency transmission of massive data and the closed-loop optimization of downhole control parameters. The foremost research trends of intelligent decision-making include the dynamic optimization of extraction schemes of oil and gas based on big data and AI, and the concepts of intelligent flow, integration, and self-purification of massive data during long-term extraction.

(3) Comparison and cooperation between countries/regions and institutions

As seen in Table 1.2.13, the countries or regions with the largest number of core papers addressing intelligent extraction concepts are China, the USA, and Saudi Arabia. The proportion of core papers published in other countries is less than 10% while the proportion of core papers in China exceeds 50%. It is observed that the largest number of core papers published are from Xi'an Shiyou University with a ratio of more than 10%, while the output ratio of core papers of other institutions is approximately 6% as seen in Table 1.2.14.

Based on Figure 1.2.7, the USA and Saudi Arabia focus more on cooperative research in this field. The USA has cooperated with China and France. Saudi Arabia has cooperated with Pakistan and Malaysia. No collaborative research has yet been conducted between other countries or regions. According to Figure 1.2.8, the Ocean University of China, National Laboratory for Marine Science & Technology (Qingdao), the SINOPEC Research Institute of Petroleum Exploration and Development, Shandong University, Shandong University of Science & Technology, and Shandong Zhengyuan Construction Engineering Co., Ltd. perform cooperative studies. Each institution has cooperated with the other four institutions. However, Xi'an Shiyou University, which has the largest number of core papers published, has not cooperated with any other institution.

According to Table 1.2.15, the countries or regions with the largest number of citing papers published are China, Saudi Arabia, Canada, and the UK. The proportion of citing papers in China is more than 30%, and the proportion of citing papers in

Table 1.2.13 Countries or regions with the greatest output of core papers on "concepts of safe, highly efficient, and intelligent extraction of coal, oil, and gas"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	10	58.82%	25	40.32%	2.50
2	USA	3	17.65%	11	17.74%	3.67
3	Saudi Arabia	2	11.76%	21	33.87%	10.50
4	Iran	1	5.88%	2	3.23%	2.00
5	France	1	5.88%	7	11.29%	7.00
6	Norway	1	5.88%	0	0.00%	0.00
7	Canada	1	5.88%	7	11.29%	7.00
8	Malaysia	1	5.88%	12	19.35%	12.00
9	Pakistan	1	5.88%	9	14.52%	9.00

Table 1.2.14 Institutions with the greatest output of core papers on "concepts of safe, highly efficient, and intelligent extraction of coal, oil, and gas"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Xi'an Shiyou Univ	2	11.76%	0	0.00%	0.00
2	Ocean Univ China	1	5.88%	1	1.61%	1.00
3	Qingdao Natl Lab Marine Sci & Technol	1	5.88%	1	1.61%	1.00
4	SINOPEC Res Inst Petr Explorat & Dev	1	5.88%	1	1.61%	1.00
5	Shandong Univ	1	5.88%	1	1.61%	1.00
6	Shandong Univ Sci & Technol	1	5.88%	1	1.61%	1.00
7	Shandong Zhengyuan Construct Eng	1	5.88%	1	1.61%	1.00
8	Univ Southern Calif	1	5.88%	0	0.00%	0.00
9	Birjand Univ Technol	1	5.88%	2	3.23%	2.00
10	Univ Tehran Med Sci	1	5.88%	2	3.23%	2.00

other countries is less than 10% except for Saudi Arabia. It can be seen that the institutions with the largest number of citing papers published are the King Fahd University of Petroleum and Minerals, the China University of Petroleum, the University of Alberta, and the Southwest Petroleum University, with the proportion of citing papers in these institutions being more than 10%, as listed in Table 1.2.16. The average citing dates are in 2017 and 2018.

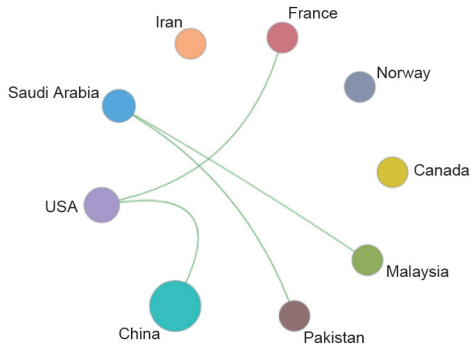

Figure 1.2.7 Collaboration network among major countries or regions in the engineering research front of "concepts of safe, highly efficient, and intelligent extraction of coal, oil, and gas"

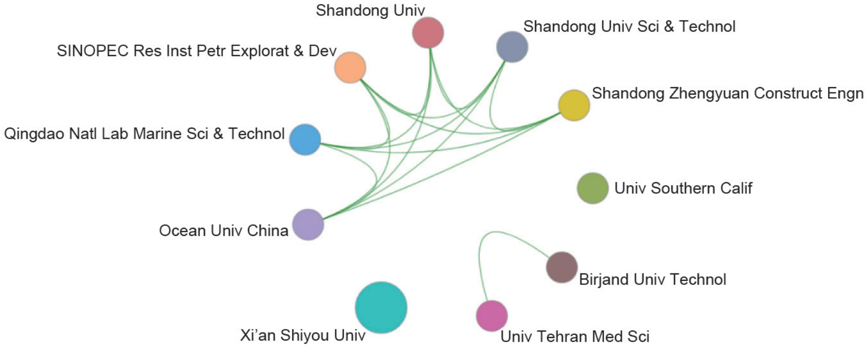

Figure 1.2.8 Collaboration network among major institutions in the engineering research front of "concepts of safe, highly efficient, and intelligent extraction of coal, oil, and gas"

Table 1.2.15 Countries or regions with the greatest output of citing papers on "concepts of safe, highly efficient, and intelligent extraction of coal, oil, and gas"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	23	32.39%	2018.1
2	Saudi Arabia	11	15.49%	2017.5
3	Canada	7	9.86%	2018.4
4	UK	7	9.86%	2018.0
5	USA	5	7.04%	2017.6
6	Malaysia	4	5.63%	2017.3
7	Iran	4	5.63%	2018.0
8	India	3	4.23%	2019.0
9	Tunisia	3	4.23%	2017.0
10	Egypt	2	2.82%	2018.5

Table 1.2.16 Institutions with the greatest output of citing papers on "concepts of safe, highly efficient, and intelligent extraction of coal, oil, and gas"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	King Fahd Univ Petr & Minerals	7	18.92%	2017.3
2	China Univ Petr	7	18.92%	2017.4
3	Univ Alberta	4	10.81%	2018.3
4	Southwest Petr Univ	4	10.81%	2018.5
5	China Univ Petr East China	3	8.11%	2018.7
6	Saudi Arabian Oil Co	2	5.41%	2017.0
7	Univ Malaysia Sarawak	2	5.41%	2017.0
8	Texas A&M Univ	2	5.41%	2018.0
9	Digital Res Ctr Sfax CRNS	2	5.41%	2017.0
10	Higher Inst Comp Sci & Multimedia Sfax	2	5.41%	2017.0

2 Engineering development fronts

2.1 Trends in top 12 engineering development fronts

The top 12 engineering development fronts assessed by the Energy and Mining Engineering Group are shown in Table 2.1.1. These fronts involve the fields of energy and electrical science, technology, and engineering; nuclear science, technology, and engineering; geology resources science, technology, and engineering; and mining science, technology, and engineering. Among these top 12 development fronts, "advanced technologies for EV/hybrid electric vehicle (HEV) and power batteries," "highly efficient coal conversion and ultra-low-emission control technologies," "technologies of hydrogen generation from renewable energy sources and integrated system of storage and transportation," and "technologies of intelligent, integrated, and small module floating reactors" are emerging fronts. "Fracture shape processing method and system based on microseismic monitoring," "seismic signal acquisition and processing technologies for marine seismic exploration," "research and development of new fracturing technologies, equipment, fracturing fluids, proppants, and additives," and "development of advanced warning systems for mining disasters in the deep metal mines" are the further developments of traditional existing research fields. "Nuclear high-temperature hydrogen production and helium turbine power generation technology" is the subversive front. "Technologies for safe, intelligent, and precise mining of coal" and "oilfield-integrated digital ecological management system based on wireless sensor networks" are the fronts of interdisciplinary integration. "Digitalized and intelligentized nuclear power plant and reactor technology" is both an emerging front and a subversive front. The numbers of core papers published each year from 2013 to 2018 for the top 12 engineering development fronts are listed in Table 2.1.2.

(1) Advanced technologies for EV/HEV and power batteries

Compared with traditional fuel vehicles, EV refers to a vehicle whose power energy system is composed of motors and power batteries. The HEV is a type of vehicle with a multi-power system combining engine and one or more electrical driving motors.

EVs have the advantages of low greenhouse gas emission, low energy consumption, and low noise. However, compared with traditional fuel vehicles, they generally have the shortcomings of a long charging time, a short effective driving range, and a short battery life. The HEV has the advantages of being both a fuel-operated vehicle and an EV. Compared with a fuel vehicle, the HEV has a lower fuel consumption and less pollution. Meanwhile, it has the advantages of fast charging and longer driving distance compared with the pure EV because of its dual energy storage. However, its structure is more complex and its cost is generally higher than the traditional fuel-operated vehicle.

The commonly used power batteries typically include lithium iron phosphate batteries and ternary lithium ion batteries. In recent years, the key research for the EV/HEV and power battery technology include the advanced powertrain, energy management, advanced auxiliary driving, automatic driving,

Table 2.1.1 Top 12 engineering development fronts in energy and mining engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Advanced technologies for EV/HEV and power batteries	290	11 923	41.11	2014.1
2	Nuclear high-temperature hydrogen production and helium turbine power generation technology	196	418	2.13	2015.0
3	Fracture shape processing method and system based on microseismic monitoring	69	861	12.48	2014.5
4	Technologies for safe, intelligent, and precise mining of coal	119	198	1.66	2016.3
5	Highly efficient coal conversion and ultra-low-emission control technologies	316	704	2.23	2015.5
6	Technologies of hydrogen generation from renewable energy sources and integrated system of storage and transportation	277	1 715	6.19	2014.7
7	Digitalized and intelligentized nuclear power plant and reactor technology	390	1 130	2.9	2014.9
8	Technologies of intelligent, integrated, small module floating reactors	160	556	3.48	2015.2
9	Oilfield-integrated digital ecological management system based on wireless sensor networks	237	2 968	12.52	2014.2
10	Seismic signal acquisition and processing technologies for marine seismic exploration	205	2 253	10.99	2014.3
11	Research and development of new fracturing technologies, equipment, fracturing fluids, proppants, and additives	225	3 872	17.21	2014.1
12	Development of advanced warning systems for mining disasters in the deep metal mines	38	31	0.82	2016.2

Table 2.1.2 Annual number of core patents published for the top 12 engineering development fronts in energy and mining engineering

No.	Engineering development front	2013	2014	2015	2016	2017	2018
1	Advanced technologies for EV/HEV and power batteries	124	69	53	33	11	0
2	Nuclear high-temperature hydrogen production and helium turbine power generation technology	20	16	12	28	49	32
3	Fracture shape processing method and system based on microseismic monitoring	16	21	17	11	4	0
4	Technologies for safe, intelligent, and precise mining of coal	9	6	11	28	31	31
5	Highly efficient coal conversion and ultra-low-emission control technologies	18	33	79	66	47	55
6	Technologies of hydrogen generation from renewable energy sources and integrated system of storage and transportation	25	23	35	48	40	48
7	Digitalized and intelligentized nuclear power plant and reactor technology	51	74	44	45	57	73
8	Technologies of intelligent, integrated, small module floating reactors	18	19	20	37	35	19
9	Oilfield-integrated digital ecological management system based on wireless sensor networks	88	71	37	32	9	0
10	Seismic signal acquisition and processing technologies for marine seismic exploration	67	65	31	31	11	0
11	Research and development of new fracturing technologies, equipment, fracturing fluids, proppants, and additives	78	79	44	20	4	0
12	Development of advanced warning systems for mining disasters in the deep metal mines	6	2	5	3	9	13

fast battery charging and life extension, battery material and electrochemical system, and battery model and management. In the future, depending on the advantages brought by the rapid development of AI, big data, intelligent transportation systems, and the fifth-generation (5G) wireless data transmission technology, EVs/HEVs and battery technology will be further developed. The research on new battery materials and electrochemical systems further improved the energy density, power density, safety, cycle life, charging performance, high/low temperature performance of power batteries. The development of a new generation of vehicle power batteries (such as solid-state lithium ion batteries, lithium air batteries, and lithium sulfur batteries) will continue to be the focus of research and development.

(2) Nuclear high-temperature hydrogen production and helium turbine power generation technology

Nuclear energy hydrogen production uses the heat generated by nuclear reactors as a primary energy source to produce hydrogen from hydrous-containing material—water or fossil fuels.

In the technical route for the production of hydrogen using nuclear energy, nuclear-heat-assisted hydrocarbon reforms and uses the process heat of a high temperature gas-cooled reactor (HTGR) to replace the heat source in the conventional technology, which can partially reduce the use of fossil fuels and correspondingly reduce some CO_2 emissions. The use of nuclear power to generate hydrogen by conventional electrolysis is a combination of mature technologies, but the efficiency of converting primary energy to hydrogen energy is low. In some scenarios where the PWR has an excess power generation capacity which should be dissipated or used in special applications, it can be used to realize energy storage or supply of hydrogen. To achieve efficient conversion of nuclear energy to hydrogen energy, the process heat provided by the reactor must be partially or fully utilized to reduce the efficiency loss during the thermo–electric conversion process. The mainstream nuclear hydrogen production technologies currently developed include thermochemical cycles (iodine sulfur cycle and mixed sulfur cycle) and high-temperature steam electrolysis.

The HTGR gas turbine direct-cycle power generation is based on the theory of the closed-type Brayden cycle. The gas turbine is combined with the modular high-temperature gas-cooled reactor (MHTGR), and the high-temperature gas generated by the HTGR is used to directly push the gas turbine to work and generate power. The efficiency of direct-cycle power generation by a helium turbine can be up to 50%.

(3) Fracture shape processing method and system based on microseismic monitoring

With the maturity of the theoretical research of microseismic monitoring technology, the current microseismic monitoring technology is widely used in the fracture exploration of hydraulic fracturing in low permeability oilfields, which can realize the monitoring of reservoir fractures and cracks, and the real-time monitoring of reservoir driving after water injection and gas injection. This technology has an important significance in oilfield exploration and development. The inversion method used in the traditional microseismic positioning consumes significant time and human resources, and the positioning accuracy cannot meet the requirements. Then, the fracture shape processing method and system based on microseismic monitoring emerged.

Through model trial calculation and application of actual data, the system can effectively classify the microseismic events to obtain the shape and distribution of small cracks and micro cracks that form the fracture zone. Combined with time information, the development and extensions of each crack over time can be obtained. After that, the effect of hydraulic fracturing, the formation of the seaming system, and whether natural productivity can be improved can be further determined to achieve maximum development results. In short, this processing method and system can continuously collect and record the microseismic data in the fracturing process and realize real-time processing and visualization, effectively optimize the fracturing scheme, and provide reservoir resource evaluation and drilling position maps, achieving the purpose of increasing production and guiding oil and gas field development.

(4) Technologies for safe, intelligent, and precise mining of coal

By means of different technologies, including intelligent perception, intelligent control, the Internet of Things, cloud computing, and big data, intelligent and precise mining technology and equipment for mining safety are proposed as a new mining mode that integrates the intelligent mining technique requiring few or no workers (remote, unattended operations), providing the functions of risk identification, monitoring, and early warning. This mode is based on transparent spaces and geophysics as well as multi-field coupling to achieve spatiotemporal accuracy and efficiency.

At present, the main research directions are as follows: the innovation of geophysical sciences with transparent functions, a new type of intelligent perception, a multi-internet fusion transmission method and technical equipment, dynamic complex mining analysis of multi-field and multi-parameter information and fusion processing technologies, theoretical models on precise coal mining based on big data and cloud technology, multi-field-coupling composite disaster warning, remote-controlled intelligent coal mining technology and equipment requiring minimal crew, disaster communication, personnel orientation, disaster detection technology and equipment, and intelligent coal mine construction based on cloud technology, all of which provide a technological path for a mode of future mining that requires fewer workers, based on the Internet and scientific mining.

China has concentrated on safety mining that requires a minimal number of workers (ultimately unattended), and it will further accelerate the intensity of innovation for mining technology, with plans to fully implement a safe, intelligent, and precision mining mode by 2050 step by step, thus to upgrade current coal mining industry and eventually build a competitive energy sector.

(5) Highly efficient coal conversion and ultra-low-emission control technologies

There are two ways to realize coal conversion. The first is raw-material based conversion, i.e., to use coal as raw material to convert coal into high-value chemical products, chemical raw materials, or other forms of fuels through a coal chemical process. The second is fuel-based conversion, i.e., the use of coal as fuel to convert chemical energy into heat or electricity through combustion and other processes. Highly efficient conversion and ultra-low-emission control are required for the whole life cycle of coal utilization, including coal processing, coal conversion, and utilization of coal waste.

The emerging fronts in coal conversion include: 1) coal processing technologies, such as highly efficient dust reduction, desulfurization and water-saving coal preparation, and the new process of ultra-clean coal classification, with emphasis on the washing of steam coals for power generation; 2) advanced processes for raw-material-based coal conversion with high efficiency and ultra-low-emission, such as coal gasification, coal liquefaction, coal-to-natural gas, coal-to-chemicals, and low-rank coal pyrolysis; 3) fuel-based coal conversion technologies, including the “three-ultras” (ultra-high parameters, ultra-low-emissions, and ultra-supercritical) coal-fired boiler technology, advanced coal combustion technologies with in-furnace ultra-low-emission, highly flexible coal-fired power generation technology coupled with renewable energy and energy storage, low-cost and efficient flue gas purification technologies with zero secondary pollution, efficient and clean combustion of civic coals, high-reliability integrated coal gasification combined cycle technology, coal-based supercritical CO_2 combined cycle power generation technology, coal-based high-temperature fuel cell technology, oxygen-coal combustion technology, and other advanced CO_2 capture and storage technologies; and 4) coal waste utilization technologies, including harmless utilization of coal ash and desulfurization ash, and efficient regeneration and harmless disposal of SCR catalysts.

(6) Technologies of hydrogen generation from renewable energy sources and integrated system of storage and transportation

Hydrogen energy is widely considered to be the most promising energy in the future owing to its advantages of high energy density, wide sources, and zero emission. The combination of a hydrogen supplying system and the proton exchange membrane fuel cell techniques is the most potential alternative that may replace the conventional internal combustion engine power system for vehicles. However, over 95% of hydrogen currently comes from the production of fossil fuels. Therefore, it belongs to the secondary energy category which cannot be regarded as a complete clean energy source. Besides, the storage and transportation of hydrogen in an efficient and safe manner is also a bottleneck that restricts the application of hydrogen energy. Therefore, hydrogen production from renewable energies (such as wind, solar, and water energy) and integration of hydrogen storage and transportation can effectively solve these problems, which are embodied in the following two aspects:

1) Hydrogen production from renewable energies. In areas where wind energy and hydropower resources are abundant, a large amount of abandoned wind and hydropower resources that cannot be connected to the power grid can be transformed into the chemical energy of hydrogen by electrolysis of water. Similarly, in areas with abundant sunshine, solar energy can be also stored as hydrogen energy

through direct photocatalytic water splitting techniques combined with hydrogen production by photoelectric and photothermal effects.

2) Integration of hydrogen storage and transportation. Due to its natures of low energy density, low boiling point, and difficulty of compression, hydrogen storage and transportation have long been considered as the obstacle for applications of hydrogen energy. Compared with the traditional high-pressure gaseous hydrogen storage and low-temperature liquid hydrogen storage, solid-state hydrogen storage can achieve very high capacity and safety, which is a promising approach in the future. Especially in recent years, the developments of Mg-based hydrogen storage materials make it possible to store and transport hydrogen safely and efficiently with a hydrogen capacity of up to 7.6 wt%. Moreover, the material is inexpensive and easy to obtain. Building Mg-based hydrogen storage trailers has already been attempted in recent years and the hydrogen storage capacity of a single trailer can reach 1.2–1.5 t, which is 3–4 times of the traditional long tube hydrogen storage trailer. By producing hydrogen from renewable energies in energy-rich areas, the underutilized energy will be converted into the chemical energy of hydrogen which will then be delivered to the destinations safely and efficiently through the integrated hydrogen storage and transportation system. In this way, the "green" process of hydrogen production, large-scale storage, transportation, and application can be realized, which will be the only way toward future hydrogen utilization (Figure 2.1.1).

(7) Digitalized and intelligentized nuclear power plant and reactor technology

The rapid development of information technology has "digitalized" and "intellectualized" the design itself, and has made the digital system of nuclear power research and development, design, verification, manufacturing, construction, commissioning, and operation become the current fronts. By making the nuclear power cycle and the data of the entire industry chain be interactively shared on the digital platform, the efficiency and reliability of all aspects of nuclear power will be greatly improved, and the iterative upgrade of nuclear power technology will be further realized based on this platform.

The intelligent development of nuclear power is divided into three stages. The first stage is infrastructure construction. Intelligentization must be based on digitalization. From the adoption of the intelligent instrument and intelligent controller concepts to the nuclear power plant's full digital instrument control system, most of the nuclear power plants in China have been digitalized (with the exception of the few early nuclear power plants). The second stage is the establishment of an AI architecture, the use of "Internet+" to build big data systems, the development of digital nuclear

Figure 2.1.1 Hydrogen generation from renewable energy sources and the integrated system of storage and transportation

power plants, and the development of application of virtual reality (VR) technology. The digital nuclear power plants include two types: one is a virtual 3D digital nuclear power plant, for installation and maintenance, while the other is dynamic, displaying various parameters and status of the nuclear power plant in real time. The third stage of intelligent nuclear power is the development of nuclear power AI applications, including operational guidance, accident handling guidance, intelligent maintenance of nuclear power plant equipment systems, and application of robots or robotic system maintenance in high radioactive and unreachable areas. These three stages are not separated from each other, but are cross-developed, which makes the digitalization and informationization maturation occur step by step, gradually realizing intelligence. This is a hot spot in the international arena and a key work to occupy the dominant height of technology and science.

(8) Technologies of intelligent, integrated, small module floating reactors

The intelligent, integrated, modular, floating reactor technology generally refers to a reactor with the thermal power of a single unit being below 1000 MW (electric power 300 MW), with carbon-free emission, small capacity, flexible site selection, small construction investment, and short construction period. The equipment can be assembled and transported at the factory, and can be upgraded and economically improved through modular design. The small reactor belongs to military and civilian dual-use technology, which can be used not only as military power to be applied to ships and border defense construction, but also as residential power supply, icebreaker, urban heating, industrial process heating, and seawater desalination. It has broad application prospects both in military and civilian fields.

Breakthroughs should be made in the key design technologies, major test verification technologies, and key equipment improvement design and manufacturing technologies of small smart reactors, to form a group of advanced small smart reactor technologies with completely independent intellectual property rights. A comprehensive breakthrough should be made in modular design, inherent safety, intelligent control and economics, and the development of small reactor nuclear power technology for heating, power supply, cogeneration, seawater desalination, and special purposes. Specifically, key technologies for the overall design and layout of integrated reactors should be studied, including key technologies of long-life and boron-free core design, key technologies of modular design, key technologies of intelligent design, all-digital intelligent instrument control system, key technologies of multi-reactor control, key technologies for safety review; and key equipment such as the small shielded pump, the small steel containment, the DC steam generator, and the built-in steam regulator should be developed.

(9) Oilfield-integrated digital ecological management system based on wireless sensor networks

The oilfield-integrated digital ecological management system based on wireless sensor network concepts establishes a digital management platform for unified production management and comprehensive research in the whole oilfield by using innovative technology and management concepts, which can significantly improve real-time monitoring of the production process. A wireless sensor network combines the sensor technology, the embedded computing technology, the wireless communication technology, and the distributed information processing technology. It has the characteristics of a high degree of cross-disciplinary and high technology integration. It is the core and foundation of the technology of the Internet of Things. The hardware circuit of the wireless sensor network system is divided into data acquisition, routing node, gateway node, and monitoring center circuits. The software is composed of the wireless communication network software subsystem and the monitoring center management software subsystem. The various types of data collected by the wireless sensor network are transmitted to the control center through the wireless network and stored after corresponding software processing. The functions of automatic input of dynamic information, query, analysis, and mining of complex data are completed, and data report is automatically generated. The flexibility of the sensor acquisition node and the stable application of the network ensure the reliability of the oil well monitoring, contribute to the improvement of the operation efficiency of the oil well and the reduction of the network operation cost, and promote the automation and information development of oil field production.

(10) Seismic signal acquisition and processing technologies for marine seismic exploration

Marine seismic acquisition technology has been innovated and developed to meet the requirements of accurate imaging of seismic data under the new exploration situations as marine oil and gas exploration gradually shifts to deep oil and gas reservoirs, high-speed shielded oil and gas reservoirs, and oil and gas fields with complex structures. It has developed, in terms of mode, from planar source to multi-layer source and stereo source; in terms of receiving mode, from horizontal cable to upper and lower cable and oblique cable (variable depth cable), and from single pressure type detector cable to speed and pressure combination double detector cable; and in terms of marine 3D exploration, from narrow azimuth acquisition of linear routes to annular wide azimuth acquisition. The application of these new seismic acquisition techniques effectively overcomes the shortcomings of marine seismic exploration, increases the low-frequency energy of seismic original signals, broadens the seismic frequency band, improves the signal-to-noise ratio and imaging effect of deep effective reflection signals, and satisfies exploration and development of complex oil and gas fields. Meanwhile, since the noise contained in the seismic data collected during seismic exploration will increase, it needs to be digitally processed to extract useful information to provide reliable information for geological interpretation of seismic exploration, in which signal noise reduction is performed digitally. Signal denoising is, therefore, a particularly important step in processing; it is used to extract useful information from seismic data and improve the signal-to-noise ratio of seismic data.

(11) Research and development of new fracturing technologies, equipment, fracturing fluids, proppants, and additives

Fracturing is the key engineering means to achieve oil and gas production and improve economic efficiency. The fracturing process pumps the fracturing fluid into the oil and gas reservoir through the high-pressure device to produce cracks, and then uses the proppant to support the crack to form permanent cracks, thereby improving the reservoir permeability, providing important support for increasing production, and increasing efficiency. With the increasing complexity of oil and gas exploration and development, the challenges of traditional fracturing, such as low fracturing efficiency and unsatisfactory fracturing effect, seriously restrict the economical and efficient mining of complex oil and gas resources. It is urgent to explore the new fracturing technology, research frontier equipment, and develop high-performance proppants and additives with fracturing fluids to promote efficient mining of complex oil and gas resources. The new fracturing technologies can increase reservoir volume and fracture complex index; these new technologies include infinite fracturing, waterless fracturing, repeated fracturing, high-end fracturing, simultaneous fracturing, zipper fracturing, selective pressure crack, and factory fracturing. Advanced fracturing equipment can meet high pump pressure, low pollution, remote operation, cost reduction, and other purposes; examples of such equipment include the ultra-high pressure high-power fracturing units, high-power fracturing trucks, high-power fracturing pumps, fully soluble multi-stage fracturing systems, infinite-stage fracturing sliding sleeves, fully degradable fracturing bridge plugs, composite fracturing plugs, and so on. High-performance fracturing fluids and proppants can reduce reservoir pollution, reduce leakage, and have good suspension properties; examples of such fluids systems include high-temperature fracturing fluid systems, soft particle fracturing fluids, ultra-high temperature reservoir instant fracturing fluids, high-temperature viscoelastic surfactant based fracturing fluids, composite fracturing fluid systems, low-density proppants, and new functional environmental proppants.

(12) Development of advanced warning systems for mining disasters in the deep metal mines

For mining disasters of deep metal mines under complex multi-field environments, a set of early warning systems, including advanced acquisition of disaster-indicating signals, intelligent analysis of disaster incubation, advance warning of disaster occurrence, and dynamic avoidance of potential disasters, are to be developed to realize intelligent analysis and dynamic control of mining disaster information in deep metal mining, which will greatly improve the safety and efficiency of deep resource development.

The research directions of the advanced warning systems include multi-dynamic monitoring and analysis concepts of mining ground pressure under a multi-field coupling environment of metal ore; time-delay characteristics and prediction methods of rock burst induced by deep strong unloading; dynamic picking and real-time prediction of deep disaster breeding evolution process models; deep mining information intelligence judgment and disaster warning based on big data; intelligent correlation mechanisms of deep mining disaster signals and types; and integrated intelligent systems of deep mining disaster spatial and temporal prediction and dynamic regulation.

Attention should be focused on "accurate and real-time picking of deep mining disaster information," "intelligent analysis of disaster signals and gestation processes," and "predictive and dynamic disposal of mining disasters under multi-field coupling," to realize advanced prediction, early-warning and advanced disposal of deep mining disasters, and further promote the safe, green, and efficient mining of deep mineral resources.

2.2 Interpretations for four key engineering development fronts

2.2.1 Advanced technologies for EV/HEV and power batteries

(1) Conceptual elaboration and key technologies

The EV/HEV is one of the most important components in the field of new energy vehicles. At present, the crisis of energy exhaustion and the pressure of environmental pollution have become a common global problem. The high efficiency and low pollution of EV/HEVs have brought new opportunities for their development. Various countries, including China, have intensified their research, development, and investment to master the core technologies in this field. The power system of the EV adopts a mode that combines battery power (high voltage) and a driving motor. Because of the high efficiency of the motor throughout its working range, EVs generally adopt the direct drive mode. Some EVs are equipped with gearboxes for multi-gear adjustment. The HEV has two sets of energy storage and drive systems, i.e., an internal combustion engine (fuel-based) and an electric motor (power consumption). Its structure is more complex and its modes are more diversified. According to the position of the motor relative to the traditional power system, the hybrid schemes can be divided into six categories: P0–P5.

The performance of power batteries has been greatly improved from the early lead-acid batteries to the nickel-hydrogen batteries and to the lithium batteries currently in use. At present, the commonly used power batteries are lithium ion batteries, consisting of lithium iron phosphate batteries and ternary material batteries.

(2) Current situation and future development trend

From 2013 to 2018, the sales of new energy vehicles in China were 17 600, 74 700, 331 000, 507 000, 777 000, and 1 256 000, respectively. In 2018, the production and sales of new energy vehicles in China were 1.27 million and 1.256 million, respectively, an increase of 59.9% and 61.7%, respectively, over the same period of the previous year. The production and sales of pure EVs were 986 000 and 984 000, respectively, an increase of 47.9% and 50.8% over the same period of the previous year. The production and sales of plug-in HEVs were 283 000 and 271 000, respectively, an increase of 122% and 118% over the same period of the previous year. According to the forecast, the domestic sales of new energy vehicles will exceed two million by 2020, and the annual growth rate of future sales will exceed 40%.

While steadily promoting the progress of traditional energy optimization and management, and power coupling with other research directions, the research focus of EV/HEVs is gradually shifting to advanced research directions such as intelligent networking, intelligent driving, and intelligent travel. Based on the concept of man–vehicle–road collaborative management, the optimization of vehicle power allocation, and enrichment of energy management, EV/HEVs can be integrated into the intelligent city network architecture for comprehensive control, and vehicle performance optimization should consider overall urban travel conditions rather than simply focus on single vehicle. Meanwhile, advanced assisted driving and automatic driving will become the development trend in the future based on networking and deep learning algorithms.

The research of power batteries focuses primarily on energy density, safety, and fast charging. Solid-state batteries are attracting increasing attention due to the advantages of their light weight (high energy density), thin size (less electrolyte/mass), safety, flexibility, wide electrochemical window, and long cycle life. In addition, the research on algorithms based on big data and machine learning also provides powerful support for the state prediction, parameter estimation, and dynamic management of power batteries.

(3) Comparison and cooperation among key countries/regions and institutions

As shown in Table 2.2.1, the countries or regions with the largest number of core patents published in this field are the USA, China, and Japan, with the USA accounting for 50%, and China and Japan accounting for 16.21% and 15.86%, respectively.

From Table 2.2.2, it can be observed that Ford Global Technologies LLC, Toyota Motor Corp., General Motors Corp.,

Table 2.2.1 Countries or regions with the greatest output of core patents on “advanced technologies for EV/HEV and power batteries”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	145	50.00%	6514	54.63%	44.92
2	China	47	16.21%	1290	10.82%	27.45
3	Japan	46	15.86%	1688	14.16%	36.70
4	South Korea	24	8.28%	1032	8.66%	43.00
5	Germany	13	4.48%	605	5.07%	46.54
6	Switzerland	6	2.07%	261	2.19%	43.50
7	Israel	5	1.72%	231	1.94%	46.20
8	UK	3	1.03%	96	0.81%	32.00
9	Canada	2	0.69%	122	1.02%	61.00
10	Sweden	2	0.69%	111	0.93%	55.50

Table 2.2.2 Institutions with the greatest output of core patents on “advanced technologies for EV/HEV and power batteries”

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	FORD	23	7.93%	808	6.78%	35.13
2	TOYT	12	4.14%	433	3.63%	36.08
3	GENK	10	3.45%	549	4.60%	54.90
4	HYMR	10	3.45%	403	3.38%	40.30
5	GOOG	9	3.10%	573	4.81%	63.67
6	QCOM	8	2.76%	446	3.74%	55.75
7	TESM	6	2.07%	418	3.51%	69.67
8	GLDS	6	2.07%	199	1.67%	33.17
9	GENE	6	2.07%	197	1.65%	32.83
10	BETT	5	1.72%	231	1.94%	46.20

FORD: Ford Global Technologies LLC; TOYT: Toyota Motor Corp.; GENK: General Motors Corp.; HYMR: Hyundai Motor Co., Ltd.; GOOG: Google Inc.; QCOM: Qualcomm Inc.; TESM: Tesla Motors Inc.; GLDS: LG Chem Ltd.; GENE: General Electric Co.; BETT: Better Place GmbH.

and Hyundai Motor Co., Ltd. are the institutions with the largest number of core patents published.

According to Figure 2.2.1, the USA, South Korea, Japan, Canada, Germany, Israel, and Switzerland pay more attention to the cooperation between countries or regions in this field. Among them, the USA has the largest number of cooperating countries or regions. It cooperates with South Korea, Japan, Canada, and Germany, while Israel and Switzerland cooperate with each other.

According to Figure 2.2.2, there only exists cooperation between Hyundai Motor Co., Ltd. and LG Chem Ltd. in all institutions.

2.2.2 Nuclear high-temperature hydrogen production and helium turbine power generation technology

(1) Nuclear high-temperature hydrogen production

Hydrogen is an important industrial raw material and an ideal secondary energy or energy carrier in the future. Hydrogen is used as a secondary energy source for storage and transportation, and can be used directly as a fuel. In addition to traditional ammonia synthesis, methanol synthesis, and petroleum refining, hydrogen can be used on a large scale in the fields of hydrogen metallurgy, coal liquefaction, and fuel cell vehicles.

Nuclear hydrogen production is an efficient and clean method for large-scale hydrogen production, which can play an

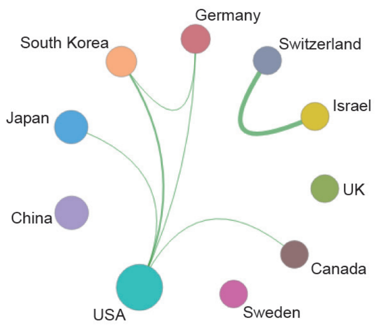

Figure 2.2.1 Collaboration network among major countries or regions in the engineering development front of "advanced technologies for EV/HEV and power batteries"

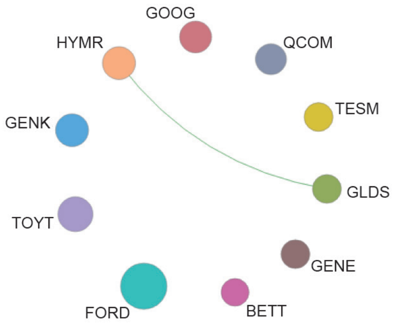

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of "advanced technologies for EV/HEV and power batteries"

important role in the large-scale supply of hydrogen in the future. The comprehensive utilization of HTGR technology (combined supply of hydrogen, electricity, and heat) with nuclear energy hydrogen production as the core will provide an important support for the technological revolution in many industrial sectors in China, and play a role in upgrading products, reducing pollution, and reducing carbon emissions.

The idea of nuclear hydrogen production began in the 1970s. After the oil crisis, there have been many studies related to thermochemical cycles. The international cooperation in nuclear energy hydrogen production has been active. At the Generation IV International Forum (GIF), the non-electrical use of nuclear energy such as hydrogen production, desalination, and heat utilization, were discussed, and a research and development plan for the use of nuclear energy to produce hydrogen was developed. A hydrogen project management department was set up for the HTGR system and the International Atomic Energy Agency (IAEA) have set up coordination projects related to the economics of nuclear energy hydrogen production. More than a dozen countries have participated in the evaluation of the nuclear energy hydrogen production technology.

It can be seen from the characteristics and advantages of nuclear energy hydrogen production technology that hydrogen production from HTGRs is suitable for centralized, large-scale, and emission-free applications of hydrogen. Therefore, the hydrogen production technology selected for coupling with the HTGR should also have these characteristics. Nuclear power generation–electrolysis is the most mature technology that can be used to produce hydrogen from small reactors for the consumption of residual nuclear power or in special scenarios. Nuclear-assisted fossil fuel reforming can use nuclear heat as an alternative heat source, saving some fossil fuels and partially reducing emissions. For example, if the HTGR process heat-assisted natural gas reforming technology is adopted to produce hydrogen, approximately 30% of natural gas can be saved to be used as a heat source, reducing CO_2 emissions by 30%. This technology can be used as a recent transition technology for nuclear energy hydrogen production, to further explore and promote the coupling between reactor and hydrogen production plant, nuclear hydrogen safety research and license application, and economic evaluation of the nuclear energy hydrogen production technology.

From a long-term perspective, thermochemical cycles and high-temperature steam electrolysis are promising nuclear energy hydrogen production technologies as they use high-temperature process heat of HTGR as a heat source, and water as a hydrogen-making raw material, and thus can completely eliminate carbon emissions from the hydrogen production process. The development of nuclear energy hydrogen production technology must consider the technical characteristics (including hydrogen production capacity, product hydrogen purity, end users, and waste management), cost (including hydrogen price, applicability of technical and economic evaluation assumptions, and research and development costs), and risks (technology development status and maturity, and research and development risk).

(2) Helium gas turbine direct-cycle power generation

The HTGR gas turbine direct-cycle power generation is based on the theory of the closed-type Brayden cycle. The gas turbine is combined with the MHTGR, and the high-temperature gas generated by the HTGR is used to directly push the gas turbine to work and generate power. The efficiency of direct-cycle power generation by the helium turbine can reach more than 50%.

The electric helium gas turbine compressor unit is the core component of the helium gas turbine direct-cycle power generation system. The turbocharged gas compressor unit under helium conditions has no successful precedent in the world, and the electromagnetic bearing is one of the key technologies in the helium turbine power generation system of the HTGR. Because the core outlet temperature of the HTGR can reach over 900 °C, the structure and materials, capable of withstanding high temperature and high pressure, for pressure shells and turbine blades are also one of the key technologies for gas turbine direct-cycle power generation of HTGRs.

At present, global research on this field is focused on the following projects. The gas turbine modular helium reactor (GT-MHR) program jointly developed by the USA and Russia and the gas turbine high temperature reactor (GTHTR300) project in Japan have a core outlet temperature of 850 °C, both of which adopt direct circulation by a closed helium turbine, whose turbine blades are made of nickel-based alloy without blade cooling. However, it has so far remained at the research design stage. The pebble bed modular reactor (PBMR) program of South Africa initially designed a direct circulation of the helium gas turbine with a core outlet temperature of 900 °C, and the project was terminated due to financial and other problems. The Tsinghua University in China uses the HTGR with gas turbine generator (HTR-10GT) project plan to conduct research on key technologies for commercial HTGRs for helium gas turbine power generation, including the design of the helium gas turbine power plants, the basic characteristics of helium gas turbines, engineering test research on large-scale plate-fin heat exchangers, and engineering test research on large-scale electromagnetic bearings. At present, the first domestic single-stage prototype test device for pneumatic air compressors has been established and many tests have been performed. The large heavy-duty flexible rotor electromagnetic bearing test rig for engineering verification tests has also been completed and engineering experiments are underway.

In the field of HTGRs, MHTGR with inherent safety is an advanced type of reactor, and the direct-cycle power generation of the helium gas turbine is an ideal energy conversion technology. The concept of ultra-high-temperature gas-cooled reactor, developed based on the MHTGR and helium gas turbine cycle, is considered by the international community to be one of the competitive candidates for the fourth-generation nuclear energy system. From a long-term perspective, with the development of ultra-high-temperature gas-cooled reactor technology and breakthroughs in key technologies and components for direct circulation of helium turbines, the direct-cycle power generation technology of the Xenon Turbine will be widely developed and applied, upon which, if the combined power generation method of helium direct turbine and steam turbine is adopted, the power generation efficiency can be further improved.

(3) Comparison and collaboration among major countries/regions and institutions

According to Table 2.2.3, the countries or regions with the largest number of core patents in this research direction are China, Japan, South Korea, the USA, France, Germany, and India. Among them, China holds the first place, at more than 75%.

It can be seen from Table 2.2.4 that the institutions with the largest number of core patents published in this research direction are Tsinghua University, Harbin Electric Co., Ltd., China National Nuclear Corporation, and China Huaneng Group Corp., and the number of core patents is 78.

According to Figure 2.2.3, there is rare cooperation among the major countries or regions, but the cooperation within the GIF organization is not included.

According to Figure 2.2.4, there is cooperation between Tsinghua University, China National Nuclear Corporation, and China Huaneng Group Corp.

According to the above data analysis, China, Japan, and South Korea are at the forefront of the core patent output for nuclear energy high-temperature hydrogen production technology.

2.2.3 Fracture shape processing method and system based on microseismic monitoring

Microseismic monitoring technology is an effective seismic method for monitoring fracture development in hydraulic fracturing. It is widely used in the development and planning of oil and gas fields. The fracture not only determines the water injection effect, but also controls the division of the strata and the injection–production well network. Moreover,

Table 2.2.3 Countries or regions with the greatest output of core patents on "nuclear high-temperature hydrogen production and helium turbine power generation technology"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	148	75.51%	181	43.30%	1.22
2	Japan	23	11.73%	94	22.49%	4.09
3	South Korea	12	6.12%	91	21.77%	7.58
4	USA	10	5.10%	44	10.53%	4.40
5	France	1	0.51%	8	1.91%	8.00
6	Germany	1	0.51%	0	0.00%	0.00
7	India	1	0.51%	0	0.00%	0.00

Table 2.2.4 Institutions with the greatest output of core patents on "nuclear high-temperature hydrogen production and helium turbine power generation technology"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	UYQI	36	18.37%	105	25.12%	2.92
2	HRBE	15	7.65%	5	1.20%	0.33
3	CNNU	14	7.14%	9	2.15%	0.64
4	CHHN	13	6.63%	9	2.15%	0.69
5	JAAT	7	3.57%	3	0.72%	0.43
6	USHS	7	3.57%	1	0.24%	0.14
7	KAER	5	2.55%	23	5.50%	4.60
8	SUZH	5	2.55%	0	0.00%	0.00
9	KOAD	4	2.04%	2	0.48%	0.50
10	XENE	4	2.04%	0	0.00%	0.00

UYQI: Tsinghua University; HRBE: Harbin Electric Co., Ltd.; CNNU: China National Nuclear Corporation; CHHN: China Huaneng Group Corp.; JAAT: Japan Atomic Energy Agency; USHS: Univ Shanghai Sci & Technology; KAER: Korea Atomic Energy Research Institute; SUZH: Suzhou Hailu Heavy Industry Co., Ltd.; KOAD: Korea Advanced Institute of Science & Technology; XENE: X-Energy LLC.

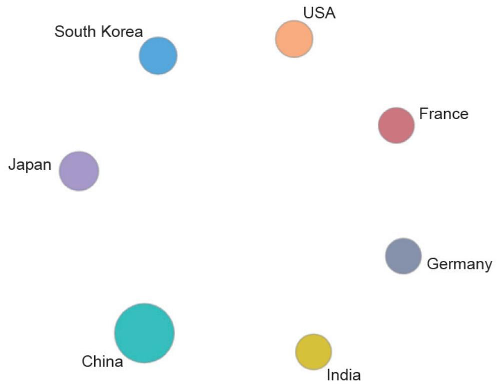

Figure 2.2.3 Collaboration network among major countries or regions in the engineering development front of "nuclear high-temperature hydrogen production and helium turbine power generation technology"

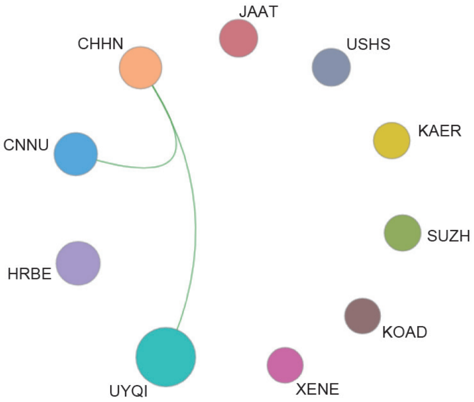

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of "nuclear high-temperature hydrogen production and helium turbine power generation technology"

it directly determines the quality of the oilfield development. However, there are still many problems in practical applications. It is very important to employ microseismic focus mechanism inversion, as well as fracture interpretation and imaging technology to provide effective information for reservoir description.

Research directions include using the data information of the target area to simulate the fracture propagation to obtain the shape distribution information of the fracture; using the microseismic monitoring data of the target area to invert the microseismic events caused by the fracturing to obtain the intensity range of the fracture; obtaining a fracturing phase distribution model according to the morphological distribution information and the intensity range; recovering the original signal according to the received signal of the detector by using each volume unit in the target data volume; and calculating the energy of each volume unit to form a four-dimensional imaging result, outputting the result, and obtaining a multi-scale fracture crack model through the fracturing phase distribution model. This technology not only reflects the shape and orientation of the fracture itself, but also considers the distribution range and intensity information of the microseismic inversion, which can more accurately characterize the spatial distribution of hydraulic fracturing cracks and reflect the changes of cracks at different times.

In summary, the fracture shape processing method and system based on microseismic monitoring can continuously collect and record the microseismic data in the fracturing process and realize real-time processing and visual interpretation, effectively optimize the fracturing scheme, and provide reservoir resource evaluation and drilling position to achieve a production increase and guide development of oil and gas field.

The foremost producing countries and regions of the core patents in this front are the USA, Canada, France, the Netherlands, and China (Table 2.2.5), and the main output institutions are Schlumberger Ltd., Halliburton Co., and Prad Research & Development Ltd. (Table 2.2.6). Cooperation and exchanges have taken place between these countries/regions and institutions (Figure 2.2.5 and Figure 2.2.6).

2.2.4 Technologies for safe, intelligent, and precise mining of coal

(1) Concept elaboration and significance

Precise coal mining is based on the coupling of transparent space geophysics and multi-physics fields, and is supported by the unattended mining technology (or requiring fewer people) and safety mining technologies, thereby the zero-death rate of coal mining workers can be realized. The critical approaches are “digitalized” and “informationized,” taking full consideration of coal mining disturbance, disaster inducement, mining-induced ecological environment destruction, and the like under different geological conditions, and forming a model of future mining through which precise and efficient intelligent mining and disaster prevention collaborate with each other. Moreover, the continuous mining and resource recovery can be in line with international advanced level. Precise coal mining is of great significance for improving coal mining safety and technology, for resource

Table 2.2.5 Countries or regions with the greatest output of core patents on “fracture shape processing method and system based on microseismic monitoring”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	57	82.61%	707	82.11%	12.40
2	Canada	13	18.84%	220	25.55%	16.92
3	France	10	14.49%	189	21.95%	18.90
4	Netherlands	10	14.49%	189	21.95%	18.90
5	China	5	7.25%	88	10.22%	17.60
6	Russia	2	2.90%	16	1.86%	8.00
7	UK	1	1.45%	28	3.25%	28.00
8	Germany	1	1.45%	9	1.05%	9.00

Table 2.2.6 Institutions with the greatest output of core patents on "fracture shape processing method and system based on microseismic monitoring"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	SLMB	20	28.99%	289	33.57%	14.45
2	HALL	16	23.19%	192	22.30%	12.00
3	PRAD	14	20.29%	255	29.62%	18.21
4	BAKO	5	7.25%	42	4.88%	8.40
5	UYPE	2	2.90%	45	5.23%	22.50
6	CARB	2	2.90%	39	4.53%	19.50
7	TEXA	2	2.90%	22	2.56%	11.00
8	LGNE	2	2.90%	19	2.21%	9.50
9	CONO	2	2.90%	18	2.09%	9.00
10	TATN	2	2.90%	16	1.86%	8.00

SLMB: Schlumberger Ltd.; HALL: Halliburton Co.; PRAD: Prad Research & Development Ltd.; BAKO: Baker Hughes Inc.; UYPE: China University of Petroleum; CARB: Carbo Ceramics Inc.; TEXA: University of Texas System; LGNE: Logined BV; CONO: Conocophillips Co.; TATN: TATNEFT.

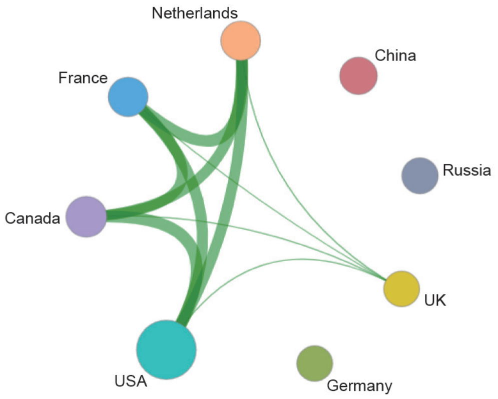

Figure 2.2.5 Collaboration network among major countries or regions in the engineering development front of "fracture shape processing method and system based on microseismic monitoring"

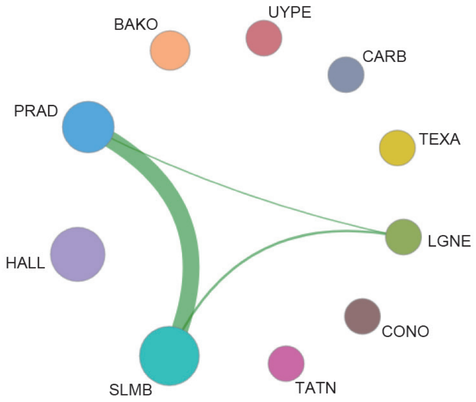

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of "fracture shape processing method and system based on microseismic monitoring"

exploitation efficiency, and for transition of the mining industry from a labor-intensive to technology-intensive industry characterized by advanced technology.

The following scientific problems need to be solved for precise and safe coal mining technology: digitized quantification of multi-field dynamic information in coal mining processes such as stress, strain, displacement, cracks, and seepage; collection, sensing, and transmission of multi-source information from working site and mining-induced disturbance zones; multi-source massive dynamic data evaluation and screening mechanisms based on big data cloud technology; multiphase and multi-field coupled disaster inducement theories and research based on big data; in-depth perception on precursor information of disaster and relevant intelligent simulation and control; early warning of mine disasters; and critical emergency rescue technology and equipment for coal mine disasters.

(2) Historical status and trend

Throughout the international mining history, the primary causes of mining disasters include unclear geological situations and disaster-causing mechanisms, unknown disaster threats, and unsolved key technological problems. Therefore, to fundamentally solve the problem of safe and efficient coal production in coal mines, the coal mining industry must evolve from a labor-intensive to a technology-intensive industry characterized by advanced technologies. Additionally, a path specified by intelligent, safe, and unattended mining or mining with fewer people should be followed. The strong momentum of the third industrial revolution and the rapid development of information-dominated technology have provided another opportunity and challenge for the transformation of mining industry from traditional empirical and qualitative decision-making to precise, quantitative, and intelligent decision-making. It is possible to realize scientific, intelligent, and unattended mining of coal, or mining with a reduced crew size.

(3) Comparison and collaboration among major countries/regions and institutions

In Table 2.2.7, it can be noticed that the core patents regarding precise and intelligent mining of coal are generally distributed in China and Australia, among which the percentage of China has surpassed 98% and the average indexing rate is much higher than that of Australia.

In Table 2.2.8, institutions with most patents with regard to precise and intelligent coal mining are China University of Mining and Technology, Beijing; China University of Mining and Technology, Xuzhou; and China Coal Technology and Engineering Group, whose percentage for core patents are all higher than 5%.

In Figure 2.2.7, it can be learned that countries focusing on this area are China and Australia.

In Figure 2.2.8, institutions that have collaborated are China Coal Technology and Engineering Group and Huaibei Mining (Group) Co., Ltd., as well as China University of Mining and Technology, Xuzhou, and China University of Mining and Technology, Beijing.

Table 2.2.7 Countries or regions with the greatest output of core patents on “technologies for safe, intelligent, and precise mining of coal”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	117	98.32%	198	100%	1.69
2	Australia	2	1.68%	0	0%	0.00

Table 2.2.8 Institutions with the greatest output of core patents on “technologies for safe, intelligent, and precise mining of coal”

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	UYMB	24	20.17%	13	6.57%	0.54
2	UYMT	8	6.72%	40	20.20%	5.00
3	CHLY	6	5.04%	23	11.62%	3.83
4	UYCQ	5	4.20%	27	13.64%	5.40
5	ULNT	5	4.20%	2	1.01%	0.40
6	UYXS	5	4.20%	2	1.01%	0.40
7	UYHP	4	3.36%	5	2.53%	1.25
8	UYLG	3	2.52%	16	8.08%	5.33
9	UNBS	3	2.52%	7	3.54%	2.33
10	HUAI	3	2.52%	3	1.52%	1.00

UYMB: China University of Mining and Technology, Beijing; UYMT: China University of Mining and Technology, Xuzhou; CHLY: China Coal Technology and Engineering Group; UYCQ: Chongqing University; ULNT: Liaoning Technical University; UYXS: Xi’an University of Science and Technology; UYHP: Henan Polytechnic University; UYLG: Anhui Science and Technology University; UNBS: University of Science and Technology Beijing; HUAI: Huaibei Mining (Group) Co., Ltd.

Figure 2.2.7 Collaboration network among major countries or regions in the engineering development front of “technologies for safe, intelligent, and precise mining of coal”

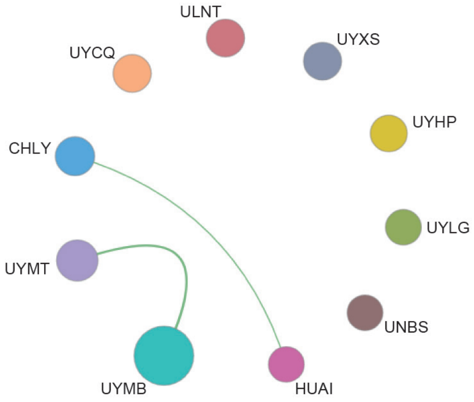

Figure 2.2.8 Collaboration network among major institutions in the engineering development front of “technologies for safe, intelligent, and precise mining of coal”

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