IV Energy & Mining Engineering

1 Engineering research fronts

1.1 Development trends in the top 13 engineering research fronts

The top 13 engineering research fronts assessed by the Field Group of Energy & Mining Engineering are shown in Table 1.1.1. These fronts include the fields of energy and electrical science, technology, and engineering; nuclear science, technology, and engineering; geology resources science, technology, and engineering; mining science, technology, and engineering.

Among these top 13 research fronts, "renewable energy power generation and energy storage: energy-saving and environment-friendly technologies," "microgrids and smart distribution systems," "critical technical issues in advanced high-performance fuel cells," "in situ upgrading mechanism and key technologies for large-scale development of shale oil," "seepage mechanism and efficient development of unconventional oil and gas," and "deep space and deep sea nuclear reactors and power supply technology" are emerging ones. "Efficient and clean processing and transformation of coal," "3D seismic data analysis and reconstruction technology," and "fully intelligent integrated small modular reactor technology" are further developments of traditional research fields. "New-generation solar cells, including perovskite, perovskite/Si heterojunction tandem, $Cu_2ZnSnSe_4$ thin film, polymer, and quantum dot sensitized solar cells" is the subversive front. "Advanced nuclear energy technology: fusion-fission hybrid reactor technology," "key engineering technologies, equipment, and materials for the intelligentization of coal, oil, and gas exploitation," and "spatial distribution prediction of residual oil and gas resources based on big data and cognitive theory" are the fronts of interdisciplinary integration. The numbers of core papers published each year from 2012 to 2017 for each of the top 13 engineering research fronts are listed in Table 1.1.2.

(1) Advanced nuclear energy technology: fusion-fission hybrid reactor technology

The fusion-fission hybrid reactor (referred to as the hybrid reactor) is a nuclear energy technology that combines the advantages of, and overcomes the shortcomings of, fusion and fission. The main difference between a hybrid reactor and a pure fusion reactor is that the cladding contains fissile fuel. The fission fuel has better neutron proliferation ability and energy amplification capability than Be or Pb, which helps reduce the difficulty of fusion engineering. From the perspective of the enthalpy cycle, it is conducive to the achievement of self-sustainability and reduction of the initial amount of investment; from the perspective of energy balance, it can reduce the fusion power and reduce the radiation damage of high-energy neutrons on materials. Compared with a fission reactor, a hybrid reactor is a deep subcritical system driven by a fusion neutron source, which has outstanding safety performance, and can solve the problem of proliferation of fission fuel and metamorphism of transuranic element at the time of energy output. The main research directions of hybrid reactor include driver technology (including tokamak, laser inertial confinement fusion, and Z-pinch inertial confinement fusion), subcritical reactor technology (including pupa, proliferation, transmutation, and energy supply), and high-gain fusion target design technology (for inertial confinement fusion). The development trend of hybrid reactors is based on the recently achieved fusion parameters and draws on mature fission reactor technology to promote the early application of fusion energy and explore ways to solve the sustainable development of fissile energy.

(2) Renewable energy power generation and energy storage: energy-saving and environment-friendly technologies

As an effective way to solve the problems of energy utilization and environmental pollution in the world, a power generation system based on renewable energy is an inevitable choice and an effective measure for the sustainable development of energy utilization. Focusing on the efficient and clean utilization of renewable energy, technologies for renewable energy generation and energy storage are rapidly developing and attracting increasing attention worldwide.

Based on the current resource status and technological development level of renewable energy sources, the utilization of wind, solar, and hydropower is considered the most realistic and promising method to generate electricity.

Table 1.1.1 Top 13 engineering research fronts in energy and mining engineering

No	Engineering research front	Core papers	Citations	Citations per paper	Mean year	Percentage of consistently-cited papers	Patent-cited papers
1	Advanced nuclear energy technology: fusion-fission hybrid reactor technology	802	35 451	44.20	2013.43	–	–
2	Renewable energy power generation and energy storage: energy-saving and environment-friendly technologies	687	37 042	53.92	2013.76	–	–
3	Key engineering technologies, equipment, and materials for the intelligentization of coal, oil, and gas exploitation	75	146	1.95	2014.75	–	–
4	Microgrids and smart distribution systems	10	130	13.00	2016.60	50.0%	0.00
5	Critical technical issues in advanced high-performance fuel cells	595	30 669	51.54	2013.27	–	–
6	Efficient and clean processing and conversion of coal	810	36 477	45.03	2013.46	–	–
7	In situ upgrading mechanism and key technologies for large-scale development of shale oil	75	452	6.03	2015.20	–	–
8	3D seismic data analysis and reconstruction technology	37	403	10.89	2016.49	0.0%	0.00
9	Spatial distribution prediction of residual oil and gas resources based on big data and cognitive theory	147	1 507	10.25	2014.88	–	–
10	Seepage mechanism and efficient development of unconventional oil and gas	1 100	9 872	8.97	2015.16	–	–
11	Fully intelligent integrated small modular reactor technology	573	25 436	44.39	2013.52	–	–
12	Deep space and deep sea nuclear reactors and power supply technology	97	1 117	11.52	2014.43	–	–
13	New-generation solar cells, including perovskite, perovskite/Si heterojunction tandem, $Cu_2ZnSnSe_4$ thin film, polymer, and quantum dot sensitized solar cells	120	6 395	53.29	2015.85	22.5%	0.00

Table 1.1.2 Annual number of core papers published for each of the top 13 engineering research fronts in energy and mining engineering

No.	Engineering research front	2012	2013	2014	2015	2016	2017
1	Advanced nuclear energy technology: fusion-fission hybrid reactor technology	253	188	192	108	52	9
2	Renewable energy power generation and energy storage: energy-saving and environment-friendly technologies	150	173	161	117	69	17
3	Key engineering technologies, equipment, and materials for the intelligentization of coal, oil, and gas exploitation	6	15	12	16	11	15
4	Microgrids and smart distribution systems	0	0	0	0	4	6
5	Critical technical issues in advanced high-performance fuel cells	201	165	126	75	25	3
6	Efficient and clean processing and conversion of coal	230	213	193	115	57	2
7	In situ upgrading mechanism and key technologies for large-scale development of shale oil	5	8	9	14	23	16
8	3D seismic data analysis and reconstruction technology	0	0	0	1	17	19
9	Spatial distribution prediction of residual oil and gas resources based on big data and cognitive theory	11	22	25	32	30	27
10	Seepage mechanism and efficient development of unconventional oil and gas	96	116	137	206	256	289
11	Fully intelligent integrated small modular reactor technology	164	145	124	89	46	5
12	Deep space and deep sea nuclear reactors and power supply technology	13	22	16	15	18	13
13	New-generation solar cells, including perovskite, perovskite/Si heterojunction tandem, $Cu_2ZnSnSe_4$ thin film, polymer, and quantum dot sensitized solar cells	1	2	7	28	48	34

Renewable energy generation technologies can be classified into two types: single and hybrid energy generation systems. A single renewable energy system is relatively independent of other power systems and is susceptible to the limitations of the renewable energy source itself. Hybrid renewable energy systems are mainly classified into two categories: the first one is a combination of several renewable energy sources such as wind, solar, and hydropower to complement each other, which can overcome the discontinuous and unstable supply of a single type of renewable source; the second one is a combination of renewable energy with existing fossil fuels in a hybrid power generation system.

Energy storage is a kind of technology that stores electricity when electricity demand is low and discharges it when electricity demand is high to enable better integration of wind power, hydro, solar, and other renewable energy sources with the grid. From the perspective of storage media, there are some energy storage technologies, including mechanical, electrical, electrochemical, thermal, and chemical energy storage.

Current studies are mainly focused on renewable energy materials, components and thermal cycle characteristics of new energy systems, maximum use of renewable energy and minimum use of natural gas in the region, balance between multi-energy supply and demand across a full range, planning of large-scale energy storage facility and coordination with renewable energy systems, and optimization of energy flow based on energy storage and management.

(3) Key engineering technologies, equipment, and materials for the intelligentization of coal, oil, and gas exploitation

The intelligent extraction of coal, oil, and gas is based on massive data collection, and integrates intelligent environmental perception, intelligent equipment control, self-sustaining operation, intelligent analysis and feedback, etc. Its objective is to achieve unmanned coal mining operation and self-adjustment of oil and gas production. The intelligent extraction of coal, oil, and gas is an integration of environmental perception, intelligent decision, and automatic control. The related five sub-disciplines are engineering perception, digital mine, mine Internet of Things, big data and cloud computing, and equipment automation. The future developments of coal mining intelligentization are: ① Intelligent exploration, which refers to the automatic search and measurement of unknown mining spaces—e.g., coal-rock boundary location, coal gangue detection, and advanced detection; ② Intelligent navigation, which refers to the utilization of computer technology, photoelectric technology, and navigation technology for the automatic positioning of equipment and operator; ③ Intelligent manipulation, which refers to the integration of intelligent equipment and automatic scheduling; it features multiple technologies including longwall shearer memory cutting, hydraulic support automation, coal flow balance of conveying system, hydraulic system generalization, coal mining face visualization, remote control, 3D virtual reality, and one-key start and stop. Intelligentization of oil and gas exploitation involves intelligent well drilling, intelligent well completion, and intelligent production. Intelligent well drilling is essential for well completion and production. The active involvement of multiple technologies such as big data, artificial intelligence, closed loop control, and precise guidance will effectively avoid drilling risk and increase drilling rate. Intelligent well completion requires real-time monitoring and control, which can be achieved through advanced sensing technology, communication technology, equipment automation, big data, and artificial intelligence. Intelligent production is the big-data-based management and optimization of an oil and gas field during its life period. Intelligentization of oil and gas exploitation can be primarily approached through the cooperative work between multiple sub-disciplines, and requires the integration of data, equipment, and operation. The intelligentization of oil and gas field requires considering big data as the foundation. The development plan must be determined using intelligent analysis. The real-time optimization requires intelligent adjustment. Therefore, the integration of intelligent data collection, communication, analysis, and equipment manipulation is necessary and is the direction of future development. Moreover, the deep integration of equipment and material with artificial intelligence can monitor the real-time state of an oil and gas field, thereby enhancing recovery and supporting the data collection, staged fracturing, layered production, and data mining.

(4) Microgrids and smart distribution systems

Microgrids and smart distribution systems are composed of distributed generation units, energy storage system, energy conversion equipment, monitoring and protection devices, and loads. They are autonomous systems with self-control and energy management. They are flexible in operation and control, and can seamlessly access various AC and DC equipment and can work in multiple modes such as grid-tied and off-grid. Therefore, it greatly improves the power system capability to integrate distributed energy sources, improves system operation efficiency, and ensures continuous and reliable power supply of critical loads. In recent years, comprehensive planning and design, multi-time scale energy management, optimized operation, high-performance hybrid simulation, and new power electronic equipment and control have gradually attracted significant attention. In addition, with the continuous improvement of technologies such as big data, artificial intelligence, and new energy storage, the future microgrids and smart distribution systems will be more open and flexible to achieve integration and interaction with other types of energy systems such as cold, heat, and transportation systems.

(5) Critical technical issues in advanced high-performance fuel cells

A fuel cell directly converts the chemical energy in fuels and oxidants into electrical energy via an electrochemical reaction, and possesses the advantages of being high-efficiency, and pollution- and noise-free, etc. Very recently, significant improvements have been achieved in hydrogen proton-exchange membrane fuel cell (PEMFC) technologies, thus greatly promoting the global industrialization of fuel cell electric vehicles. So far, the specific power, efficiency, and cold start of automotive fuel cells have already technically satisfied commercialized requirements. However, there remains an urgent need to further improve the service life and greatly lower the cost of fuel cell stacks. Correspondingly, four key research interests should be pursued, including the synthesis of highly active and stable ultra-low/low platinum oxygen reduction reaction electrocatalysts and their mass production; fabrication of high-performance and durable ultra-low/low platinum membrane electrode assemblies and their mass production; development of high-performance anti-corrosion coatings for metallic bipolar plates; improvement of mass transport and water management in the cathodes. When breakthroughs are obtained in the aforementioned aspects, it is expected that the cell performance of PEMFCs will be greatly enhanced, the cost will be significantly reduced, and independent intellectual property rights on these key materials and components will also be attained.

(6) Efficient and clean processing and conversion of coal

The efficient utilization of coal is based on the needs of the end-user. Clean processed coal can be used as a fuel or a raw material. Efficient utilization of coal includes efficient combustion and efficient conversion. The cleaning of coal is designed to improve the quality of raw coal in order to fulfill the needs of users, so as to provide efficient matching and stable coal products for their efficient utilization. The clean transformation of coal is the use of coal as a raw material. It can be classified into gaseous, liquid, and solid fuels, or into chemical products and carbon materials with special uses.

The main task for the efficient utilization of coal is to improve its consumption structure. At present, scientific research is focused on the in situ conversion of coal, which is beneficial to cleaning secondary energy sources (electricity, fuel gas, and fuel oil). This includes the strengthening of deep processing to obtain chemical raw materials or products (gaseous, liquid, or solid). The main task of clean coal processing is to improve the quality of merchantable coal. The current research focuses on the development of new coal dressing technologies, especially for high-efficiency ash reduction, desulphurization, and dry coal preparation technology, focusing on the washing of steam coal. Coal conversion technology includes all kinds of chemical transformations of coal besides combustion. Scientific research focuses on five coal conversion technologies: coal gasification, coal liquefaction, coal-to-natural gas, coal-to-chemicals, and the pyrolysis of low-rank coal.

Considering the current situation of coal utilization technology and the rising requirements of environment, future coal-efficient processes, with clean processing and transformation, will involve the combination of high-efficiency combustion of coal, power generation technology, coal-fired pollutant control technology, high-efficiency coal-fired generator set and circulating fluidized bed combustion technology, and integrated coal gasification technology, based on coal gasification technology. The development of capture and seal-up technology for the safekeeping of CO_2, and oxygen-enriched combustion separation of CO_2, will be emphasized.

(7) In situ upgrading mechanism and key technologies for large-scale development of shale oil

In situ transformation of shale oil is a physical and chemical process of transforming unconverted organic matter and retained hydrocarbon in organic-rich shale into light hydrocarbon by using in situ heating technology, which can be referred to as "underground refinery." The basic principle of the technology is to heat the shale formation to generate high-quality petroleum and natural gas, which exists in a gaseous state under high-temperature conditions in the underground, thus greatly improving the fluidity. The shale will produce micro-fractures and high pressure during the in situ transformation process, and form an artificial seepage system to increase the seepage capacity. The high-quality petroleum produced via the in situ transformation of shale oil can reach the aviation kerosene level after simple processing, which significantly saves the cost of crude-oil refining, and the residues are stored underground, which can reduce environmental pollution, eliminate hydrofracture, save water resources, and reduce carbon dioxide emissions by comprehensively utilizing new energy sources such as wind and solar energy. At present, the technology is potentially feasible for industrial application, but it has not yet reached the industrialization level. Therefore, we should increase the support and investment for the technology, and develop in situ transformation technology suitable for continental organic-rich shale oil in China. Promoting the industrialization process of this technology is crucial for significantly reducing the external dependence of national crude oil and guaranteeing energy security.

(8) 3D seismic data analysis and reconstruction technology

In seismic data acquisition, owing to the influence of actual environment (such as mountains, rivers, and buildings) and financial constraints, the collected original data are often irregular, and consequently, the effect of subsequent processing (such as offset, multiple wave suppression, and seismic imaging) is not ideal. As an important step in seismic data processing, 3D seismic data analysis and reconstruction can effectively solve this problem. The main research direction of this technology is how to improve the regularity of field-derived data to enhance noise immunity and imaging accuracy. At present, the main research trends focus on the seismic channel interpolation method of F-K domain for sparse seismic data and the unsteady seismic data reconstruction method for irregular missing data, including data reconstructions based on predictive filtering, mathematical transformation, and wave equations. The current development trend is to apply these core technologies to the detection of weak microseismic signals, improvement of the signal-to-noise ratio, oil and gas detection, high-precision hydraulic fracturing monitoring, and full-waveform inversion of logging constraints.

(9) Spatial distribution prediction of residual oil and gas resources based on big data and cognitive theory

Technologies for predicting remaining hydrocarbon resources aim to satisfy the following two characteristics. First, the distribution of the remaining conventional hydrocarbon resources is disperse and subtle. Second, the distribution of unconventional hydrocarbon resources is heterogeneous. They are important supplements and extensions of traditional resource assessment methods. The traditional studies on the distribution of remaining resources have been conducted from the perspective of resource management, i.e., the systematic management of hydrocarbon resource-play-target. The new technologies for predicting remaining hydrocarbon resources can realize the space localization of remaining resources and visualization of exploration risks. Big data and cognitive theory offer conditions for these technologies. Big data refer to the collection of data that cannot be captured, managed, and processed with conventional software and tools within a certain period of time. They are massive, high-growing, and diversified information assets, which require new processing modes to achieve stronger decision-making power, insight ability, and process optimization. Cognitive theory is related to the internal processing of organism learning, such as the acquisition and memory of information, knowledge, and experience, the realization of insight, the interrelation of concepts and terms, and the various psychological theories of resolving problems. With the deepening of hydrocarbon exploration and development, petroleum industry accumulates data related to mass hydrocarbon production, such as statistical data of exploration and development, geophysical data of earthquakes and well-logging, wireline-log and well-testing data, and lab data related to geology research. Based on the quantitative evaluation of hydrocarbon resources through traditional methods such as genetic method, statistical method, and analogy method, the development trends of future technologies for the prediction of hydrocarbon resources include the prediction of distribution of hydrocarbon resources, clarification of resource distribution law, and determination of favorable hydrocarbon accumulation zones or specific locations. All these actions should be undertaken according to cognitive theory during the exploration geological processing and development geological processing of big data.

(10) Seepage mechanism and efficient development of unconventional oil and gas

The seepage mechanism of unconventional oil and gas mainly involves the flow characteristics of oil and gas in nanoscale pores and micro cracks. It can be used to analyze the production dynamics in the reservoir and provide important support for the accurate description and evaluation of the unconventional oil and gas reservoirs. However, the geological characteristics of unconventional oil and gas reservoirs are complex, and the development of nanoscale pore oil and gas is difficult. There is an urgent need to improve the development efficiency of unconventional oil and gas, and realize major breakthroughs in the field of unconventional oil and gas. This mainly involves the research direction of reservoir reconstruction, production control, and automation exploitation.

China’s shale gas, shale oil, tight gas, tight oil, coal-bed methane, heavy oil, and other unconventional oil and gas resources are abundant, which are important strategic replacement resources. However, as the reservoirs are complex and the related theory and technology are not mature, it is difficult to realize economic and effective exploitation through conventional means. There is an urgent need to study the seepage mechanism and provide a scientific basis for the regulation and real-time optimization of the unconventional oil and gas production. Therefore, regarding the microscopic percolation characteristics of unconventional oil and gas, the attention degree of non-Darcy percolation, multiphase seepage, and multi-scale percolation will be hot topics in the future. Furthermore, the research on high-efficiency technology, such as waterless fracturing, multilevel fracturing, synchronous fracturing, partial fracturing and combined exploitation, “multi-layer and multi well type” mixed well network mining, and “factory” exploitation, has become the future development trend. It can significantly reduce the cost of mining and improve the recovery of oil and gas.

(11) Fully intelligent integrated small modular reactor technology

Since the International Atomic Energy Agency (IAEA) announced in June 2004 that it has launched an innovative small- and medium-sized reactor (SMR) development program featuring integrated technology and modular technology, the total number of participating member states has reached 30. More than 45 innovative SMR concepts have become hotspots in international research and development. Small nuclear reactors generally refer to reactors with a single stack of thermal power below 1000 MW (300 MW), with carbon-free emissions, small capacity, flexible site selection, low construction investment, short construction period, and system equipment that can be assembled at the factory. It is easy to transport and can be upgraded and economically improved through modular design. From the perspective of the modular small-stack technical solutions that have been proposed at home and abroad, there are various types of reactors such as pressurized water reactors (PWRs), high-temperature gas-cooled heat reactors, high-temperature gas-cooled fast reactors, lead-bismuth-cooled fast reactors, and molten salt reactors. The modular small reactor that can be deployed in the short-term, without exception, follows the integrated PWR route, and its design and development progress far exceeds those of other reactor types, which is mainly due to the good PWR technology and industrial foundation built over several decades. Research and development features of international main small-sized reactor models are that based on the recently promoted integrated PWR model, design measures to eliminate large loss-of-coolant accidents or projectile accidents are adopted, and design optimization is adopted to improve economy; marine modularity or circuit type of PWR adopts inherent safety features and passive safety system, draws on the experience of nuclear icebreakers and submarines, and adopts standardized design, and batch production and loading to enhance market competitiveness. The small-sized reactor belongs to military and civilian dual-use technology, which can be used as military power, applied to ship power and border defense construction, and can also be used in national economic construction fields (such as residential power supply, icebreaker, urban heating, industrial process heating, and seawater desalination). It has broad application prospects in the military and civilian fields.

(12) Deep space and deep sea nuclear reactors and power supply technology

Deep space and deep sea contain rich strategic resources.

They are new and valuable territories for the sustainable development of human beings in the 21st century. Their strategic position in national development and international competition is becoming increasingly prominent. Along with the continuous improvement of various deep-space and deep-sea technological capabilities, the issue of energy and power has gradually become a bottleneck for the further improvement of the performance of various deep-sea equipment, and must be rectified. Compared with conventional energy sources, nuclear reactor power sources have the natural advantages of high energy density, no air requirement, and long running time. They can fundamentally solve the shortcomings of deep-sea equipment and become the best choice for future deep-sea energy. The main technologies include: ① Heat-pipe-cooled reactor technology: In contrast to the traditional loop cooling reactor, the heat of this reactor is removed through the heat pipe, which has the advantages of being simple, safe, and reliable, and avoiding single point failure. It is very suitable as the preferred stack type for the power supply unit of a deep-sea small nuclear reactor; ② Free piston Stirling generator technology: regenerative thermal power generation technology, through the linear motor to output electrical energy. It has many advantages such as long life, high reliability, high conversion efficiency, no pollution, and low noise. It is widely used in space power, solar thermal power generation, small-scale cogeneration, portable power supply, biomass power generation system, etc.; ③ Reactor fully autonomous operation technology: the fully autonomous operation of a reactor indicates that it relies on its own physical thermal feedback and instrument control system to adjust and realize automatic operation. It does not require personnel to monitor and intervene online, and can automatically respond to fluctuations in working conditions. It has the advantage of long-term stable maintenance-free operation; ④ Reactor safety technology: special research on the safety technology of deep-sea nuclear reactors, focusing on the safety features, accident mechanisms, and threats of nuclear proliferation that are unique to deep-sea nuclear reactors.

(13) New-generation solar cells, including perovskite, perovskite/Si heterojunction tandem, $Cu_2ZnSnSe_4$ thin film, polymer, and quantum dot sensitized solar cells

Perovskite materials are a class of compounds that have a special molecular structure (ABX_3) and originate from calcium titanium oxide mineral ($CaTiO_3$). Perovskite materials have the advantages of high absorption coefficient, sharp absorption edge, and large adjustable bandgap, and hence, the efficiency of perovskite solar cells has been enhanced from 3.8% to 22.7% in only seven years. At present, scientific research in this regard mainly focuses on efficiency, stability, and large-scale industrialization. Among the research topics, inorganic substitution of organic and tin elements to replace lead elements is the most effective method to solve the stability and toxicity problems of perovskites, and has gradually become a new research trend. Furthermore, the unique crystal structure and photoelectric properties of perovskite materials are very suitable for monolithic solar cells. Perovskite/silicon monolithic solar cell technology utilizes different bandgap materials to absorb photons of different energies, thus fully utilizing sunlight, and is expected to become an emerging technology that breaks the efficiency limit of silicon solar cells. The current research and development of this technology focuses on optimizing material preparation processes and reducing parasitic absorption and reflection losses. In only three years, the efficiency of perovskite/silicon monolithic solar cells has increased from 13.7% to 25.2%, which is close to the highest efficiency of silicon cells. Perovskite/silicon monolithic solar cell technology will become a research hotspot in both academia and industry.

$Cu_2ZnSnSe_4$ thin film, polymer, and quantum dot sensitized solar cells are other types of novel solar cells studied in recent years. Compared with the CuInGaSe thin film, $Cu_2ZnSnSe_4$ has an energy gap closer to the ideal bandgap for solar cells. Moreover, it has abundant sources, is non-toxic and inexpensive, and is expected to achieve higher conversion efficiency. The main focus of related research is to raise its efficiency by improving the fabrication method and application of doping. The representative advances include achieving efficiency of 12.3% using metal precursors and 8.7% using a co-evaporation method (reached 10.4% subsequently, certified). The polymer solar cell is a type of solar cell based on organic semiconductors. It can be easily fabricated as large-area flexible solar cells via a spray method. So far, it could achieve efficiency higher than 13% (single junction) and close to 15% (tandem cell). The typical functional layers are a polymer electron donor layer and a fullerene electron acceptor layer. The recent research hotspots include the development of non-fullerene acceptor-based solar cells, optimization of the electron donor via chemical treatment (for instance, chlorization), and fabrication of tandem solar cells by combining different electron donor layers so as to increase the full spectrum absorption. A quantum dot sensitized solar cell is a type of photo-electrochemical solar cell not based on junction structures such as p-n junction and heterojunction. It uses semiconductor quantum dots (can be compound semiconductors such as PbS and CdSe or single semiconductors such as Si) adsorbed on photo-anodes (normally nanostructured oxide semiconductors such as porous TiO_2 and nanowire arrays of ZnO) as a light absorber and realizes electron–hole separation through carrier exchange between them and the oxidation/reduction ion pair in the solid or liquid electrolyte in contact with them. Bandgap modulation can be easily realized through the content and size control of the quantum dot to create spectrum-matched solar cells. Furthermore, it does not require good interfacial condition and very high purity of precursors, which are important to achieve high efficiency with low cost. Recently, a record efficiency of 4.72% has been achieved in the PbS/TiO_2 system doped with Hg, whereas an efficiency of 8.0% has been realized in the In_2S_3+$CuInS_2$/TiO_2 system.

1.2 Interpretations for three key engineering research fronts

1.2.1 Advanced nuclear energy technology: fusion-fission hybrid reactor technology

(1) Conceptual explanation and key technologies

The fusion-fission hybrid reactor (referred to as the hybrid reactor) is a nuclear energy technology that combines the advantages of, and overcomes the shortcomings of, fusion and fission. The main difference between a hybrid reactor and a pure fusion reactor is that the cladding contains fissile fuel. The fission fuel has better neutron proliferation ability and energy amplification capability than Be or Pb, which helps reduce the difficulty of fusion engineering. From the perspective of the enthalpy cycle, it is conducive to the achievement of self-sustainability and reduction of the initial amount of investment; from the perspective of energy balance, it can reduce the fusion power and reduce the radiation damage of high-energy neutrons on materials. Compared with a fission reactor, a hybrid reactor is a deep subcritical system driven by a fusion neutron source, which has outstanding safety performance, and can solve the problem of proliferation of fission fuel and metamorphism of transuranic element at the time of energy output. The main research directions of hybrid reactor include driver technology (including tokamak, laser inertial confinement fusion, and Z-pinch inertial confinement fusion), subcritical reactor technology (including pupa, proliferation, transmutation, and energy supply), and high-gain fusion target design technology (for inertial confinement fusion). The development trend of hybrid reactors is based on the recently achieved fusion parameters and draws on mature fission reactor technology to promote the early application of fusion energy and explore ways to solve the sustainable development of fissile energy.

(2) Development status and future development trend

The research on hybrid reactors involves two major nuclear energy fields: fusion and fission. Based on the recently realized fusion technology and mature fission technology, the application of fusion energy and the sustainable development of fission energy are promoted.

The fusion field is divided into magnetic confinement fusion and inertial confinement fusion. In terms of magnetic confinement fusion, Tokamak research is in a leading position. China officially participated in the construction and research of the international thermonuclear experimental reactor (ITER) project; simultaneously, as a bridge between the ITER device and the fusion demonstration reactor (DEMO), China is independently designing and developing the China Fusion Engineering Experimental Reactor (CFETR) project. In terms of inertial confinement fusion, Z-pinch has more potential as an energy source and is likely to develop into a competitive fusion-fission hybrid energy (Z-FFR) scheme. The Z-FFR consists of a Z-pinch drive, energy target, and sub-critical energy cladding. The following focuses on the key technologies to be addressed by Z-FFR.

Z-pinch inertial confinement fusion covers multiple physical processes and complex physical effects such as magnetohydrodynamics, radiation transport, atomic physics, plasma microscopic instability, and transport mechanisms under strong pulsed magnetic fields. China has focused on the research of Z-pinch plasma implosion kinetics and its radiation source physics, and has obtained a wealth of research results. The research on the overall conceptual design of Z-FFR has made significant progress. However, there are few studies on key issues such as the relationship between current front and Z-pinch load parameters and implosion dynamics, Z-pinch plasma source calibration law and Z-pinch dynamic black cavity radiation field (temperature) calibration law, and Z-pinch inertia, and the energy conversion efficiency of several important physical processes in the process of constrained fusion.

The super-pulsed magnetic field is the most prominent feature of the Z-pinch process. Under this condition, plasma formation and magnetic Rayleigh–Taylor instability development have a decisive influence on the implosion process and implosion quality. Owing to the strong nonlinearity, the energy exchange between the electromagnetic energy of the load zone, the internal energy of the Z-pinch plasma, and the radiant energy is very complicated. The Spitzer resistivity does not accurately describe the characteristics of Z-pinch plasma resistivity, and its anomalous mechanism is unclear. The description and explanation of the generation process and physical mechanism of the radiation source are extremely important. A high-current device can provide a wider range of parameters for conducting Z-pinch plasma physics experiments.

The typical Z-pinch process has a cylindrical implosion feature, whereas the fusion target is a spherical implosion, and a suitable black cavity configuration is designed to effectively separate the loaded plasma Z-pinch process from the target implosion in time and space. This is the core issue of Z-pinch drive inertial confinement fusion. It is not feasible to carry out this experimental study on the existing devices in China. Compared with laser fusion, Z-pinch radiation source has a long time scale and large spatial scale, which makes it difficult to finely adjust the waveform. A new fusion target design is required to effectively compress the fuel and obtain higher energy gain.

The construction of a new-generation high-current pulse power experimental platform is beneficial to the experimental research and verification of the key physical problems of Z-pinch radiation source, black cavity, and target implosion, and other Z-pinch drive inertial confinement fusion processes. It is recommended to have national-level support for the construction of a Z-pinch drive with a peak current of 50–70 MA in 2018–2025 to achieve fusion ignition as soon as possible. Once the ignition target is achieved, the subsequent step is to start building Z-FFR. Z-FFR is equipped with a large ultra-high-power repetitive frequency driver, the preferred fast pulse linear transformer driver, with capacitor nominal energy storage $\leqslant$ 100 MJ, peak current 60–70 MA, rising edge 150–300 ns, and operating frequency 0.1 Hz; adopts the concept of “local overall ignition,” and designs high-gain fusion target pellets with energy gain Q $\geqslant$ 100; and designs natural uranium fission cladding to achieve self-sustaining energy amplification of 10–20 times and fission fuel proliferation.

(3) Analysis of comparisons and cooperation between countries/regions and institutions

According to Table 1.2.1, the countries with the largest number of core papers in this research direction are the USA, Germany, the UK, France, Japan, Italy, and China. Among them, the USA holds the first place, with more than 50% of core papers, and the proportion of core papers from Germany, the UK, France, Japan, Italy, and China exceeds 10%.

As evident from Table 1.2.2, the most core papers in this research direction are from Lawrence Livermore National Laboratory, University of Rochester, Los Alamos National Laboratory, Massachusetts Institute of Technology (MIT), General Atomics, Istituto Nazionale di Fisica Nucleare, Sandia National Laboratories, University of Oxford, and Chinese Academy of Sciences, with at least 20 papers each.

According to Figure 1.2.1, the USA, Japan, Germany, the UK, France, and China are more concerned about the cooperation between countries or regions in this field. China has published numerous papers, mainly in cooperation with USA, Japan, Germany, France, the UK, and Russia.

According to Figure 1.2.2, there is cooperation among Lawrence Livermore National Laboratory, MIT, General Atomics, Los Alamos National Laboratory, and University of Rochester.

In Table 1.2.3, the percentage of citing papers from the USA has reached 29.75%; the percentage of citing papers from China has reached 16.81%; and the percentage of citing paper from Germany exceeds 10%.

In Table 1.2.4, the institution that accounts for the highest output of core papers is Chinese Academy of Sciences, with nearly 20%. Lawrence Livermore National Laboratory accounts for more than 16% of the core papers.

According to the analysis of the above data, the core paper output and the number of quotations regarding fusion-fission hybrid reactors in the USA and China are among the highest in the world, and the number of core papers cited by Chinese institutions is large.

1.2.2 Renewable energy power generation and energy storage: energy-saving and environment-friendly technologies

(1) Concept description

As an effective way to solve the problems of energy utilization and environmental pollution in the world, an energy system based on renewable energy is an inevitable choice and an effective measure for the sustainable development of energy utilization. Focusing on the efficient and clean utilization of renewable energy, technologies for renewable energy generation and energy storage are rapidly developing and attracting increasing attention worldwide.

• Renewable energy generation system

Based on the current resource status and technological development level of renewable energy sources, the utilization of wind, solar, and hydropower is considered the most realistic and promising method to generate electricity.

Table 1.2.1 Countries or regions with the greatest output of core papers on the "advanced nuclear energy technology: fusion-fission hybrid reactor technology"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	434	54.11%	20 456	57.70%	47.13
2	Germany	130	16.21%	6 250	17.63%	48.08
3	UK	116	14.46%	6 518	18.39%	56.19
4	France	111	13.84%	5 468	15.42%	49.26
5	Japan	90	11.22%	5 166	14.57%	57.40
6	Italy	87	10.85%	4 316	12.17%	49.61
7	China	84	10.47%	3 326	9.38%	39.60
8	Spain	53	6.61%	2 359	6.65%	44.51
9	Russia	49	6.11%	2 234	6.30%	45.59
10	Switzerland	46	5.74%	2 647	7.47%	57.54

Table 1.2.2 Institutions with the greatest output of core papers on the "advanced nuclear energy technology: fusion-fission hybrid reactor technology"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Lawrence Livermore Natl Lab	116	14.46%	5 810	16.39%	50.09
2	Univ Rochester	74	9.23%	2 935	8.28%	39.66
3	Los Alamos Natl Lab	72	8.98%	3 661	10.33%	50.85
4	MIT	44	5.49%	2 674	7.54%	60.77
5	Gen Atom Co	41	5.11%	1 933	5.45%	47.15
6	Ist Nazl Fis Nucl	29	3.62%	1 116	3.15%	38.48
7	Sandia Natl Labs	25	3.12%	1 323	3.73%	52.92
8	Univ Oxford	21	2.62%	1 553	4.38%	73.95
9	Chinese Acad Sci	20	2.49%	988	2.79%	49.40
10	Univ Calif Berkeley	19	2.37%	1 568	4.42%	82.53

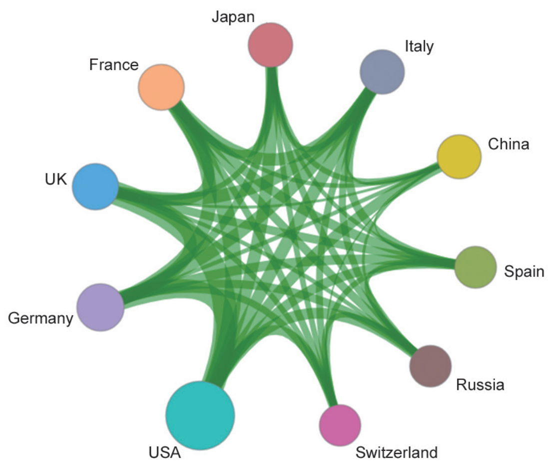

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of “advanced nuclear energy technology: fusion-fission hybrid reactor technology”

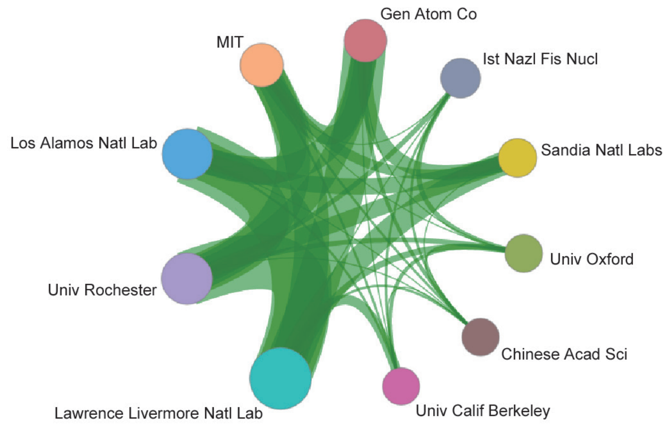

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “advanced nuclear energy technology: fusion-fission hybrid reactor technology”

Table 1.2.3 Countries or regions with the greatest output of citing papers on the “advanced nuclear energy technology: fusion-fission hybrid reactor technology”

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	USA	9 956	29.75%	2015.78
2	China	5 626	16.81%	2016.10
3	Germany	3 919	11.71%	2015.77
4	UK	2 873	8.58%	2015.85
5	France	2 542	7.59%	2015.70
6	Italy	2 480	7.41%	2015.77
7	Japan	2 267	6.77%	2015.81
8	Spain	1 418	4.24%	2015.88
9	Russia	1 207	3.61%	2015.71
10	Canada	1 183	3.53%	2015.81

Table 1.2.4 Institutions with the greatest output of citing papers on the “advanced nuclear energy technology: fusion-fission hybrid reactor technology”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Acad Sci	1 208	19.58%	2016.09
2	Lawrence Livermore Natl Lab	1 015	16.45%	2015.31
3	Univ Calif Berkeley	613	9.94%	2015.56
4	Los Alamos Natl Lab	591	9.58%	2015.51
5	Ist Nazl Fis Nucl	541	8.77%	2015.38
6	MIT	473	7.67%	2015.56
7	Univ Rochester	449	7.28%	2015.43
8	Russian Acad Sci	446	7.23%	2015.62
9	Univ Calif Los Angeles	419	6.79%	2016.03
10	CALTECH	415	6.73%	2015.63

Renewable energy generation technologies can be classified into two types: single and hybrid energy generation systems. A single energy generation system is relatively independent of other power systems and is susceptible to the limitations of the renewable energy source itself. Hybrid renewable energy power generation systems are mainly classified into two categories: the first one is a combination of several renewable energy sources such as wind, solar, and hydropower to complement each other, which can overcome the discontinuous and unstable supply of a single type of renewable source; the second one is a combination of renewable energy with existing fossil fuels (natural gas, biogas, biomass, geothermal, etc.) in a hybrid power generation system.

Guaranteeing a continuous, stable, and qualified power output is the key aspect of renewable energy generation. Current studies are focused on dynamic modeling and thermal cycle characteristics of energy system, maximum use of renewable energy and minimum use of natural gas in the region, balance between multi-energy supply and demand across a full range, and controlling system of energy storage and management.

The future development direction of renewable energy is a multi-energy complementary system composed of wind, solar, hydro, heat, and storage through a distributed renewable energy system and intelligent microgrid. Terminal integrated systems designed for multiple user-side needs such as electricity, heat, cold, and gas will be rapidly developed in China. Hybrid renewable energy power generation systems have been used in developed countries such as the United States and Europe.

• Advanced energy storage technology

An energy storage system operates by storing electricity when electricity demand is low and discharging when electricity demand is high to enable better integration of wind power, hydro, solar, and other renewable energy sources with the grid. The general concept of energy storage technology can be defined as a one-way or bi-direction storage between electricity and other types of energy such as heat, chemical, and mechanical energy.

From the perspective of storage media, energy storage technology includes mechanical, electrical, electrochemical, thermal, and chemical energy storage. Pump water storage, compressed air, and flywheel belong to the category of mechanical energy storage. Electric energy storage mainly includes supercapacitor and superconducting energy storage. Electrochemical energy storage mainly refers to batteries, such as lead-acid battery, lithium-ion battery, sodium sulfur battery, and liquid flow battery. Thermal energy could be stored through special media (such as phase change material) in a heat insulation container. The thermal energy can be converted into electricity when required or directly used. Chemical energy storage technology refers to the second utilization of hydrogen or natural gas from the electrolysis of water.

Pumped water storage is currently the most installed energy storage technology in the world, accounting for 98% of the total energy storage capacity. Moreover, compressed air energy storage, lead-acid, and lithium batteries have been developed rapidly in recent years, and have been the most competitive energy storage technologies in the world.

The key technologies of energy storage include planning of large-capacity energy storage and coordination with renewable energy systems, energy system optimization and management based on energy storage, and integrated design and coordination of energy storage and conversion devices.

(2) Development status and future development trend

• Renewable energy generation technologies

According to “Renewable 2018 Global Status Report,” published by Renewable Energy Policy Network for the 21st Century (REN21), renewable energy generation accounted for 70% of the net increase in global power generation in 2017, which is the largest increase in renewable energy generation in modern history.

At present, the increase in the global investment in renewable energy has exceeded two times the total investment in both fossil fuels and nuclear power generation. Owing to the increase in cost competitiveness, the proportion of renewable energy investment in the power industry in 2017 is more than 2/3, and the percentage of renewable energy in the power industry will continue to rise.

According to the statistics provided by the National Energy Administration, in 2017, the renewable energy power generation capacity of China was 1.7 trillion kWh, with a year-on-year increase of 150 billion kWh; renewable energy has accounted for 26.4% of the total power generation, with a year-on-year increase of 0.7%. Among various renewable power sources, hydropower generation capacity was 1,194.5 billion kWh, with a year-on-year increase of 7%; wind power generation capacity was 305.7 billion kWh, with a year-on-year increase of 26.3%; photovoltaic power generation was 118.20 billion kWh, with a year-on-year increase of 78.6%; biomass power generation was 79.4 billion kWh, with a year-on-year increase of 22.7%. The annual abandonment of hydropower was 51.5 billion kWh. As the amount of incoming water was greater than that in the last year, the water utilization rate reached 96%; the amount of abandoned wind power was 41.9 billion kWh, and the abandoned wind rate was 12%, with a year-on-year decrease of 5.2%; the abandoned solar power was 7.3 billion kWh, and the abandoned rate was 6%, which is 4.3% lower than that in 2016. Thus, the proportion of renewable energy power generation in China has steadily increased.

At present, the research on renewable energy technologies mainly includes the following three aspects: advanced power generation technology, grid connection technology, and multi-energy complementary system of renewable energy.

For the advanced power generation technology of renewable energy, as the most important output characteristic of photovoltaic power generation is randomicity, tracking the maximum active output power point of photovoltaic power generation is one of the research priorities. As the maximum power point tracking requires high accuracy, rapidity, and stability, effective adjustment of active output is the key aspect of photovoltaic power generation. Wind power generation technologies are mainly classified into two categories: the first employs constant speed and constant frequency, mainly adopting active stall regulation or capable generator equipment; the second employs variable speed and constant frequency, mainly equipped with an asynchronous induction generator. Of the two categories, variable-speed and constant-frequency power generation can capture and utilize wind energy to the utmost extent, and the speed running range is relatively loose with the adjustment system more flexible.

In terms of grid connection technologies for renewable energy generation, renewable resources are affected by ambient temperature and weather factors, which result in relatively large fluctuations and intermittence. This characteristic could easily cause flashover or fluctuations in the grid voltage. Therefore, grid connection and consumption of renewable energy are key aspects for access to existing energy systems. ① Advanced inverter technology: Considering photovoltaic energy as an example, power grids and photovoltaic power plants are mainly connected by inverters. Therefore, inverters are required to be capable of expandable communication functions, controlling reactive power and active power, reducing active power rate, and achieving harmonic compensation. The inverters should guarantee the stability of power output quality and anti-interference ability. Moreover, the interaction between grid and energy sources should satisfy the requirements of the smart grid. ② Accurate and fast grid voltage signal locking technology is required for grid connection of renewable energy, which could accurately lock the phase of voltage under high-power asymmetric operation and voltage sampling fluctuations of grid. ③ System anti-interference technology: The island detection technology requires reliable anti-interference ability from the renewable energy system. Moreover, the low-voltage ride-through (LVRT) performance has become a necessary index for ensuring the safe and stable operation of a power system under the condition of large-scale new energy access. For a centralized wind power and photovoltaic station, LVRT is realized based on inverter control, and the command of island detection can be realized by using the energy from the transmission and transformation of electricity system. For a distributed wind power and photovoltaic station, island detection should be achieved through the control system, and signal command is given based on the energy management platform of the power distribution system.

As for a multi-energy complementary system of renewable energy, compared with traditional power grids, this kind of hybrid system typically has system complexity and uncertainty. ① Planning of system integration, including deterministic and uncertainty analysis: The deterministic analysis indicates that the wind, light, and other resource conditions and load requirements are derived from historical record data. Uncertainty analysis mainly refers to modeling of renewable energy and load variations based on probability statistics, considering several factors such as natural conditions and cold and heat loads of users. ② Comprehensive system modeling: Notably, the time scales and dynamic characteristics of the subsystems in the renewable energy complementary system are different. For example, grid power should be instantaneously balanced, and its dynamic characteristics should be described using differential-algebraic equations. Cold and heat conversion processes are the slowest and are usually expressed in dynamic processes by minute and hour. ③ Optimizations of system design: At present, the calculating methods used by researchers include power flow calculation based on Newton–Raphson method, lowest cost optimization of life cycle analysis, and multi-objective chaotic quantum genetic algorithm. To achieve the optimal use of energy and long-term economic operation, a renewable energy complementary system requires scientific system integration and energy management.

• Advanced energy storage technology

By the end of 2017, the cumulative installed capacity of energy storage projects in the world reached 175.4 GW, a year-on-year increase of 4%. The cumulative installed capacity of pumped water storage still accounted for the largest proportion, i.e., 96%, but with a decrease of 1 percentage point from the previous year. The cumulative installed capacity of electrochemical energy storage was the second largest, with a scale of 2926.6 MW, an increase of 45% from the previous year. The proportion of electrochemical energy storage was 1.7%, an increase of 0.5 percentage points over the previous year. Among the various types of electrochemical energy storage technologies, the cumulative installed capacity of lithium-ion batteries had the largest proportion, accounting for more than 75%.

In 2017, the installed capacity of newly added chemical storage projects in the world was 914.1 MW, a year-on-year increase of 23%. The planned installed capacity of the electrochemical energy storage project under construction is 3063.7 MW. It is expected that the global installed capacity of electrochemical energy storage will experience rapid growth in the short term.

By the end of 2017, the cumulative installed capacity of the energy storage projects of China has reached 28.9 GW, a year-on-year increase of 19%. In 2017, the total capacity of newly invested energy storage projects in China was 121 MW, involving three areas: centralized renewable energy grid connection, auxiliary services, and user-side projects. In the field of centralized renewable energy integration in 2017, the projects undertaken include Qinghai DC photovoltaic and energy storage demonstration project and Jilin wind thermoelectric hybrid energy storage project. The commercialization of solar energy storage is accelerated, and the application of combined electricity and heat storage has become a new research direction to reduce the electricity peaking of power systems and increase the consumption of renewable energy.

Although there are many different types of energy storage technologies, only pumped storage is relatively widely used in large-scale energy storage devices. However, owing to geographical constraints, the usage of pumped storage is very limited. Moreover, other energy storage methods are still in experimental or initial research stages, and the reliability, service life, manufacturing cost, and application capability of these energy storage devices must be improved. In general, the research on energy storage technology in China is still in its initial period and it is not suitable for comprehensive application to the power grid. Moreover, there are still several problems such as incomplete research institutions, uncertain economic benefits, and the lack of operational data support. At present, the key technical fields of energy storage technology research are mainly distributed in the following aspects.

The planning of energy storage systems includes the following fields: ① The wide-area layout of energy storage systems and cogeneration method for conventional power supply and renewable energy; the integration of an energy storage device of hundreds of megawatts in the power transmission and distribution processes of the new energy generation system; ② Research on the selection and configuration method of energy storage in new technology and power supply business mode; the convergence effect, operation mode, and controlling strategy of a distributed energy storage system in the power grid; ③ The policy requirements to realize market application of energy storage technology, including electricity price, market access institution, and electricity market mechanism, which could promote energy storage development; the coordinated operation mechanism of energy storage and other energy resources under various types of electricity market transactions.

As for the technologies of energy storage devices, current research mainly includes: ① The key material modification, low-cost preparation, energy density improvement, and industrialization technology of lithium ion, lead carbon, liquid flow, and other types of energy storage batteries under the current power system; high-security battery materials based on ionic liquid and solid electrolyte; low-cost and high-reliability membrane production technology of liquid flow battery; ② Development of supercapacitor, including porous graphene electrode and high-pressure electrolyte salt, electrolyte, and cellulose separator; ③ Research on air compressor and expander technology; study of high-efficiency and low-cost cold and heat storage technology; 4Research on next-generation energy storage technology, including high-specific-energy-density battery technology such as lithium sulfur and lithium air batteries; research on hydrogen production and storage equipment, and technologies of large-scale hydrogen energy storage device with low cost and high efficiency; research and development of heat and cold storage devices with high capacity and energy density; key materials of thermal phase change energy storage.

In terms of integration and applications of energy storage systems, studies in this field mainly include: ① System integration, controlling technology, and engineering demonstration of an energy storage and power station of hundreds of megawatts; ② Architecture of battery energy storage system including energy storage battery pack, battery management system, power conversion system, microgrid control center, and energy management system; research on cascade utilization and safety management techniques such as battery reorganization, integration, and heat grooming; ③ Development of energy storage converter based on new device, topology, and control method; control of energy storage converter, energy storage battery management, and energy monitoring and scheduling system; ④ System integration and engineering application technologies of hydrogen, phase change, and flywheel energy storage; integration and test technology of seawater pumped storage and cryogenic energy storage system.

Physical energy storage will still be dominant. According to China's National 13th Five-Year Plan, by the end of 2020, the cumulative installed capacity of pumped storage in China will be 40 GW. By the end of 2017, 28.49 GW has been completed, and the scale of projects under construction is 38.71 GW. It is expected that this target will be achieved by 2020.

Electrochemical energy storage will maintain steady growth. High-density distributed energy storage systems such as electric vehicles will fundamentally change the structure of the power grid. With the promotion and application of new energy vehicles, the performance and cost of battery systems have gradually become the main bottleneck delaying their rapid development. Future electrochemical energy storage will focus on battery systems with higher energy density, lower cost, better security, and longer lifetime.

Energy storage technology will be deeply integrated with renewable energy systems. Energy storage technology can achieve smooth power fluctuation, reduction of electric peaking, frequency modulation, and voltage regulation, and is considered an important means to achieve the large-scale integration of renewable energy systems to the power grid. With the development of smart microgrid and energy Internet, more flexible power-peaking resources will be developed to satisfy urgent demand, and the promotion of renewable energy grid connection will increase in the market.

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

According to Table 1.2.5, the countries with the largest output of core papers in this research direction are the USA, China, Iran, and India. Among them, the core papers from USA and China account for 26.78% and 19.51% respectively, and the core papers from India and Iran account for more than 6%.

As evident from Table 1.2.6, the organizations with the largest output of core papers in this research direction are MIT, Imperial College of Science, Technology and Medicine, University of Malaya, Chinese Academy of Sciences, and Huazhong University of Science and Technology—each of them with more than 10 core papers.

According to Figure 1.2.3, China, the USA, Australia, the UK, and Germany are more concerned about the cooperation between countries or regions in this field. Among them, China has a large number of published papers, mainly in cooperation with the USA, Australia, and the UK.

According to Figure 1.2.4, Imperial College of Science, Technology and Medicine has a cooperative relationship with University of Malaya in certain areas.

In Table 1.2.7, among the countries that cite the most core papers, China accounts for more than 33%, and the USA accounts for nearly 20%. The percentages of cited core papers from India, the UK, Iran, Spain, Australia, Germany, and Italy all exceed 5%.

In Table 1.2.8, the institution that cites the most core papers is the Chinese Academy of Sciences, whose citing proportion is nearly 25%. The proportion of cited core papers from Tsinghua University and North China Electric Power University is more than 10%.

According to the analysis of the above data, the USA and China are at the forefront of the world's core output and quotation for renewable power generation, and Chinese institutions have cited numerous core papers in recent years.

1.2.3 Key engineering technologies, equipment, and materials for the intelligentization of coal, oil, and gas exploitation

(1) Concepts of research fronts

Intelligent mining began in the 1980s with automated mining and telemining/distance mining. In 1992, Finland proposed the Intellimine program, and the concept of intelligent coal mining was introduced. At present, oil and gas exploitation in China urgently requires intelligent dynamic control using intelligent equipment and technology to reduce production costs and improve the production and recovery of oil and gas. Intelligent mining refers to the mining operation process without manual intervention, independently completed using

Table 1.2.5 Countries or regions with the greatest output of core papers on the "renewable energy power generation and energy storage: energy-saving and environment-friendly technologies"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	184	26.78%	9 997	26.99%	54.33
2	China	134	19.51%	7 261	19.60%	54.19
3	Iran	46	6.70%	1 908	5.15%	41.48
4	India	43	6.26%	2 382	6.43%	55.40
5	Spain	40	5.82%	2 172	5.86%	54.30
6	UK	39	5.68%	2 289	6.18%	58.69
7	Australia	39	5.68%	2 158	5.83%	55.33
8	Germany	33	4.80%	1 580	4.27%	47.88
9	Canada	33	4.80%	1 419	3.83%	43.00
10	Malaysia	26	3.78%	1 517	4.10%	58.35

Table 1.2.6 Institutions with the greatest output of core papers on the "renewable energy power generation and energy storage: energy-saving and environment-friendly technologies"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	MIT	15	2.18%	713	1.92%	47.53
2	Imperial Coll Sci Technol & Med	13	1.89%	798	2.15%	61.38
3	Univ Malaya	13	1.89%	643	1.74%	49.46
4	Chinese Acad Sci	12	1.75%	633	1.71%	52.75
5	Huazhong Univ Sci & Technol	12	1.75%	495	1.34%	41.25
6	Tech Univ Denmark	10	1.46%	717	1.94%	71.70
7	Indian Inst Technol	9	1.31%	491	1.33%	54.56
8	Univ New S Wales	9	1.31%	443	1.20%	49.22
9	King Fahd Univ Petr & Minerals	9	1.31%	440	1.19%	48.89
10	Univ Tehran	9	1.31%	368	0.99%	40.89

Figure 1.2.3 Collaboration network among major countries in the engineering research front of "renewable energy power generation and energy storage: energy-saving and environment-friendly technologies"

mining equipment through intelligent perception of mining environment, intelligent control of mining equipment, and autonomous cruising of mining operations. The intelligent mining of coal, oil, and gas is a revolutionary technology based on mechanized mining and automated mining, through the deep integration of informatization and industrialization to improve production efficiency and economic benefits.

(2) Fronts of engineering science branches

Key engineering technologies, equipment, and materials for intelligent coal mining. They are the deep integration of three technical units: environmental perception, intelligent decision, and automatic control, involving five branches of engineering science: engineering environmental perception, digital mining, mine Internet of things, big data and cloud computing, and automatic control. Engineering environment

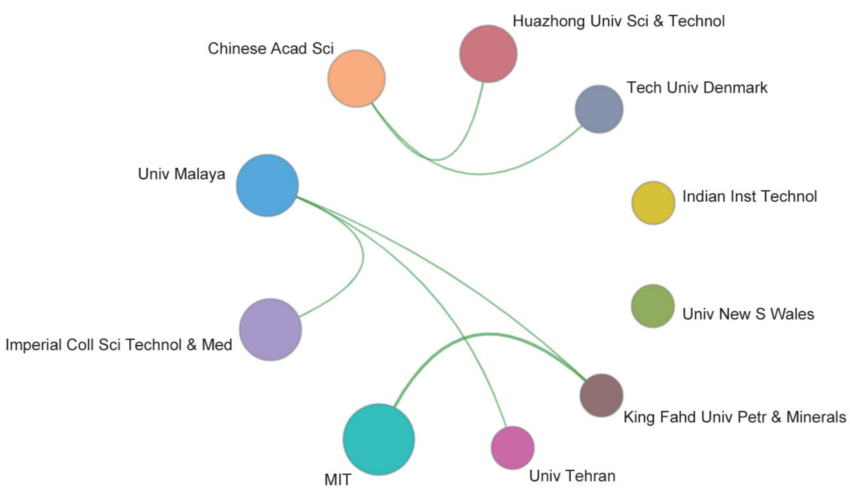

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "renewable energy power generation and energy storage: energy-saving and environment-friendly technologies"

Table 1.2.7 Countries or regions with the greatest output of citing papers on the "renewable energy power generation and energy storage: energy-saving and environment-friendly technologies"

No.	Country/Region	Citing core papers	Percentage of citing papers	Mean year
1	China	7 544	33.96%	2016.27
2	USA	4 244	19.11%	2015.90
3	India	1 920	8.64%	2016.21
4	UK	1 414	6.37%	2016.10
5	Iran	1 294	5.83%	2016.18
6	Spain	1 232	5.55%	2015.81
7	Australia	1 205	5.42%	2015.98
8	Germany	1 183	5.33%	2015.98
9	Italy	1 150	5.18%	2015.90
10	South Korea	1 027	4.62%	2016.11

Table 1.2.8 Institutions with the greatest output of citing papers on the “renewable energy power generation and energy storage: energy-saving and environment-friendly technologies”

No.	Institution	Citing core papers	Percentage of citing papers	Mean year
1	Chinese Acad Sci	870	24.47%	2016.11
2	Tsinghua Univ	417	11.73%	2016.27
3	North China Elect Power Univ	416	11.70%	2016.08
4	Univ Chinese Acad Sci	300	8.44%	2016.47
5	Xi’an Jiao Tong Univ	299	8.41%	2016.12
6	Nanyang Technol Univ	268	7.54%	2016.12
7	Huazhong Univ Sci & Technol	259	7.29%	2016.23
8	Shanghai Jiao Tong Univ	250	7.03%	2016.21
9	Islamic Azad Univ	243	6.84%	2015.81
10	Zhejiang Univ	233	6.55%	2016.14

perception is an automatic detection and transmission technology for underground equipment, personnel, and disasters. It aims to achieve automated meticulous monitoring of the whole mining process in underground complex geological conditions. In this field, Australia focuses on intelligent detection of coal seam geological structures based on thermal infrared imaging whereas China focuses on intelligent detection of the position and pose of mining equipment. The equipment level of intelligent mining in China is equivalent to that of foreign countries. Chinese mining machines have online awareness of fault parameters and operation parameters, shearer drum cutting memory program, and wireless remote control system, which realize a remote monitoring system of mining machines. Foreign mainstream hydraulic supports can achieve remote control and system fault diagnosis whereas the reliability of hydraulic support electro-hydraulic control systems in China still has a certain gap with foreign technology. At present, the intelligence of Chinese independent development conveyors is mainly reflected in soft start control, chain automatic tensioning, and monitoring of operating conditions. The intelligent integrated system of a fully mechanized mining face can realize intelligent integrated control and cooperative interlocking of mining machine, hydraulic support, conveyor, and other equipment in the mining face. Automatic control indicates that the mining machine can achieve self-regulation and autonomous cruising through pre-programming without manual intervention to complete the mining operation independently. In this field, Australia focuses on the development of mining machine memory cutting and autonomous navigation technology, whereas China focuses on remote control technology of mining equipment.

Key engineering technologies, equipment, and materials for digital mines and mine system network. Focusing on mine spatial data and models, it is a concentrated expression of spatial information technology, network technology, and visualization technology in the comprehensive application of mining enterprises. Its basic task is to provide data security and technical support for the visualization, refinement, and intelligent control of the whole process of mine production through unified space-time benchmarks, unified data standards, unified network structure, and unified integration platform. The main directions of the future of digital mines include mine spatial data warehouse and data update technology, mine data mining and knowledge discovery technology, true 3D solid modeling, and virtual mining technology. The mine system network consists of the perception layer, transport layer, analysis layer, and application layer. The mine sensor network is built on a high-speed network covering the mine ground surface and underground. The mine environment, equipment, and personnel are connected in real time through various sensors to the real-time monitoring, sensing, communication, and control of the environment, equipment health, and personnel safety posture. The future development of the mine system networks is focused on multi-network convergence transmission technology and multi-parameter information analysis and processing technology. As the scope of coverage of mine system networks becomes increasingly wider, the amount of generated data of the "human, machine, and physical" ternary worlds interacting and integrating in the information space and available on the Internet is also increasing, and the data are inherent. The extraction and utilization of value must be supported by ultra-large-scale and highly scalable cloud computing technology. Large data cloud computing technology for coal mines is still in its infancy. Moreover, it needs to focus on the development of unified technical standards and data modeling.

Key engineering technology, equipment, and materials for intelligent drilling. Intelligent drilling combines large data and artificial intelligence, and uses advanced detection, closed-loop control, and precision guidance, which can effectively avoid drilling risks, form high-quality wellbore, improve drilling speed and drilling ratio, and reduce drilling cost. It is the basis for the smooth development of well completion and production. Intelligent drilling uses the big data of the drilling process to adaptively optimize the drilling rock-breaking parameters and intelligently regulate the well trajectory by analyzing the real-time working conditions. The key engineering technology of intelligent drilling involves data bidirectional efficient transmission technology, closed-loop intelligent regulation technology, and intelligent drilling guidance technology. The drilling process generates massive data. To ensure the dynamic interaction between the ground control system and the downhole information, it is necessary to use an intelligent drill pipe and other equipment for more efficient data transmission. The use of intelligent analysis of drilling data, optimization of drilling parameters through signal feedback, and formation of closed-loop control of drilling information significantly improves the efficiency of drilling data processing, specifically involving unmanned drilling rigs, intelligent pressure control, integrated driller control, and other equipment. Intelligent guidance uses strata conditions and ground control commands to control the drilling speed of the drill bit for targeted directional drilling, specifically involving intelligent drill bits and other equipment. To improve the performance of tools under complex conditions, carbon fiber composites, high-entropy alloys, super steels, pure phase polycrystalline diamond, and other materials have received extensive attention at home and abroad. Furthermore, bionic drilling fluids and supramolecular polymer drilling fluids have been extensively studied at home and abroad as important carriers for wellbore drilling and smooth progress. Currently, Norway has applied highly flexible, executable multi-task unmanned rigs to the field. Baker Hughes' first TerrAdapt adaptive drill bit has dramatically reduced the frequency of downhole faults through automated controls. The British North Sea Babbage Oilfield used intelligent closed-loop control and intelligent drill pipe to efficiently transmit data through the intelligent drill pipe, which has increased the penetration rate by nearly 200%. Schlumberger, Baker Hughes, Weatherford, Halliburton, etc. have used intelligent steering technology for drilling sites.

Key technology, equipment, and materials for intelligent well completion. Intelligent well completion uses advanced sensing, transmission, and automatic control equipment, combined with large data, artificial intelligence, etc. It can monitor and control the production of oil and gas in real time including interlayer isolation, permanent monitoring, flow control, and sand control, and provide strong support for the intelligent production. The key technology of intelligent well completion is mainly related to oil-well inflow control and intelligent optimization of completion parameters. At present, an integrated well management control system integrates downhole monitoring, data transmission, and stratified flow control. It can realize reservoir information management, dynamic data sharing, and intelligent flow control. It is widely studied at home and abroad. It involves downhole sensors, downhole production controller, multi-channel packer, etc. At present, the Beck Hughes InCharge completion system can control up to 12 production layers using an electric hydraulic drive and achieve stepless throttling. The Schlumberger Manara well completion system can conduct data wireless transmission, multi-channel separation, and hierarchical monitoring. In addition, Halliburton and China National Petroleum Corporation (CNPC) launched SmartWell and EIC-Riped completion systems. Furthermore, the multi-function intelligent nano completion fluid system of nanomaterials and completion fluids can automatically identify and deal with complicated conditions or accidents in the downhole, which has become the trend of future development.

Key engineering technology, equipment, and materials for intelligent production. Intelligent production is the dynamic management and optimization of the whole life cycle of oil and gas field based on big data and trail learning. Intelligent production of oil and gas can be achieved using the effective integration of data, instruments and equipment, and field operation through the collaborative work of research branches. Intelligent production utilizes a sensing device to collect the downhole data, subsequently transmits it to the ground system for intelligent analysis and signal feedback, and carries out the control instruction through the ground and downhole equipment to continue the intelligent management and optimization to the well work condition. The key engineering technology of intelligent production involves the dynamic real-time four-dimensional interpretation technology of reservoir production, intelligent displacing technology to improve oil recovery, and intelligent analysis and utilization technology of multivariate massive data. The intelligent production of oil and gas mainly involves the intelligent monitoring of oil and gas fields, capturing the dynamic information of each link to provide the support for the real-time interpretation of oil and gas reservoir, and the intelligent analysis of gas and oil exploitation. Moreover, the massive data produced during the field operation must be analyzed intelligently using deep learning and data mining, which impose stringent requirements on the performance of big-data storage and computing equipment. The nano intelligent oil displacement agent has attracted increasing attention at home and abroad because it can remarkably improve the recovery rate of a low-permeability reservoir. To analyze the production dynamics of oil and gas reservoirs, Anadarko Petroleum is building a huge monitoring database based on microbial DNA in Delaware Basin. Oil reservoir robot, which has become a hot research topic globally, can monitor the temperature and pressure data under complex conditions, and Saudi Aramco has carried out active research in this field. Shell used big data and cloud computing to establish an oil field management system, which initially achieved automatic control of production. To improve oil recovery, CNPC and Sinopec Group have been actively exploring the improvement of oil recovery using intelligent fine water injection and an intelligent nano flooding agent. The Natural Resources Corp., Canada also carried out a pilot test to enhance the recovery rate of polymer nano microspheres. In addition, China has developed supercomputers rapidly and has reached the international advanced level, which lays an important foundation for the study of massive data storage, calculation, and analysis of oil and gas exploitation.

(3) Development status and future development trend

The development direction of intelligent mining is to achieve a real-time and intelligent full life cycle regulation of the coal and oil-gas production process, based on the dynamic information of the production process, relevant engineering technology, equipment, and material. At present, a significant amount of research has been carried out in the key fields of intelligent mining at home and abroad. However, the entire process of intelligent mining has not been realized. The following major breakthroughs must be achieved in the future.

Deep integration of engineering equipment, materials, and artificial intelligence. Efficient intelligent development of coal, oil, and gas is realized through effective data acquisition, hierarchical intelligent production, and data mining and intelligent analysis. Advanced computer, optoelectronic, and navigation technology are used to automatically locate mining equipment and personnel in order to achieve safety monitoring and accurate mining. Moreover, the deep integration of materials and artificial intelligence will help improve the performance of engineering equipment in all directions, realize the automatic exploration and detection of the unknown area of mining stopes, and even automatically identify and deal with the complicated production conditions or accidents in underground mines.

Integration technology of intelligent data acquisition, efficient transmission, intelligent analysis, and intelligent control. Intelligent analysis is adopted to determine the real-time production dynamics and use intelligent control in the mine production process based on the acquisition of multivariate data to achieve data collection, transmission, analysis, control, and coordination work in all aspects.

(4) Countries, institutions, and the comparison and cooperation between them

According to Table 1.2.9, the countries with the largest numbers of core papers in this research direction are China, India, Canada, Australia, and the UK. Among them, the core papers from China exceed 50%, and the core papers from other countries account for less than 10%. According to Table 1.2.10, the institutions with the largest number of core patents in this research direction are Xi'an University of Science and Technology, Luohe Medical College, and China University of Mining and Technology, Beijing. Among them, Xi'an University of Science and Technology and Luohe Medical College have a core patent ratio exceeding 5%.

According to Figure 1.2.5, countries such as China, Australia, USA, UK, and Italy have paid more attention to the cooperation among nations or regions in this research direction. Among them, China has built a cooperative relationship with Australia, the USA, and the UK, with the largest number of co-published core paper. Although India and Canada have a high number of core papers, they have no cooperative relationship with other countries.

According to Figure 1.2.6, the institutions with a cooperative relationship with other institutions are Luohe Medical College, Chinese Academy of Sciences, Henan Vocational College of Quality Engineering, Henan Polytechnic Institute, and Commonwealth Scientific and Industrial Research Organisation (CSIRO). Among them, Luohe Medical College has built a cooperative relationship with Henan Vocational College of Quality Engineering and Henan Polytechnic Institute. Furthermore, they have the largest number of co-published core papers. Xi'an University of Science and Technology of Xi'an, China has the largest number of publications. However, it has no co-published papers.

According to Table 1.2.11, China, Australia, the USA, the UK, and India have produced the largest number of cited core papers in this research direction. Among them, more than 50% of the core papers from China have been cited, whereas only 10.2% from Australia have been cited. According to Table 1.2.12, the most productive institutions in terms of the

Table 1.2.9 Countries or regions with the greatest output of core papers on the "key engineering technologies, equipment, and materials for the intelligentization of coal, oil, and gas exploitation"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	43	57.33%	75	51.37%	1.74
2	India	6	8.00%	5	3.42%	0.83
3	Canada	5	6.67%	9	6.16%	1.80
4	Australia	3	4.00%	24	16.44%	8.00
5	UK	3	4.00%	9	6.16%	3.00
6	USA	3	4.00%	8	5.48%	2.67
7	Romania	2	2.67%	11	7.53%	5.50
8	Iran	2	2.67%	2	1.37%	1.00
9	Italy	2	2.67%	2	1.37%	1.00
10	Thailand	2	2.67%	1	0.68%	0.50

Table 1.2.10 Institutions with the greatest output of core papers on the "key engineering technologies, equipment, and materials for the intelligentization of coal, oil, and gas exploitation"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Xi'an Univ Sci & Technol	6	8.00%	0	0.00%	0.00
2	Luohe Med Coll	4	5.33%	0	0.00%	0.00
3	China Univ Min & Technol Beijing	3	4.00%	3	2.05%	1.00
4	Henan Qual Engn Vocat Coll	3	4.00%	0	0.00%	0.00
5	Chinese Acad Sci	2	2.67%	27	18.49%	13.50
6	Shiraz Univ	2	2.67%	2	1.37%	1.00
7	Henan Polytech Inst	2	2.67%	0	0.00%	0.00
8	Univ Alberta	2	2.67%	0	0.00%	0.00
9	Shandong Univ Sci & Technol	1	1.33%	35	23.97%	35.00
10	CSIRO	1	1.33%	24	16.44%	24.00

number of core papers published in this research direction are China University of Mining and Technology, Chinese Academy of Sciences, and Shandong University of Science and Technology. Among them, the core paper outputs of China University of Mining and Technology and Chinese Academy of Sciences are more than 20%.

2 Engineering development fronts

2.1 Development trends in the Top 14 engineering development fronts

The top 14 engineering development fronts assessed by the Field Group of Energy & Mining Engineering are shown in Table 2.1.1. These fronts include the fields of energy and electrical science, technology, and engineering; nuclear science, technology, and engineering; geology resources science, technology, and engineering; mining science, technology, and engineering. Among these top 14 development fronts, "research and application of wireless power transmission and its related equipment," "green mining technology (coal, oil, gas, ores)," and "safe, intelligent, and precise mining technology and equipment" are emerging fronts. "Development and utilization system of fossil energy (coal, and unconventional oil and gas) and core technology and equipment," "spent fuel reprocessing and nuclear facility instrumentation," "renewable resources generation system and its operation and control," "advanced reactor technology and equipment development," "new tools and materials for petroleum engineering," "logging identification of unconventional reservoirs," and "3D geological modeling technology" are further developments of traditional research fields. "Advanced nuclear fuel technology research and development" is the subversive front. "High-voltage and high-power power electronic devices and equipment in power systems," "advanced energy storage technology in energy and power systems," and "using wide spectral remote sensing techniques to explore the mineral deposits and geothermal resources" are the fronts of interdisciplinary integration. The numbers of core papers published each year from 2012 to 2017 for each of the top 14 engineering development fronts are listed in Table 2.1.2.

Figure 1.2.5 Collaboration network among major countries or regions in the engineering research front of "key engineering technologies, equipment, and materials for the intelligentization of coal, oil, and gas exploitation"

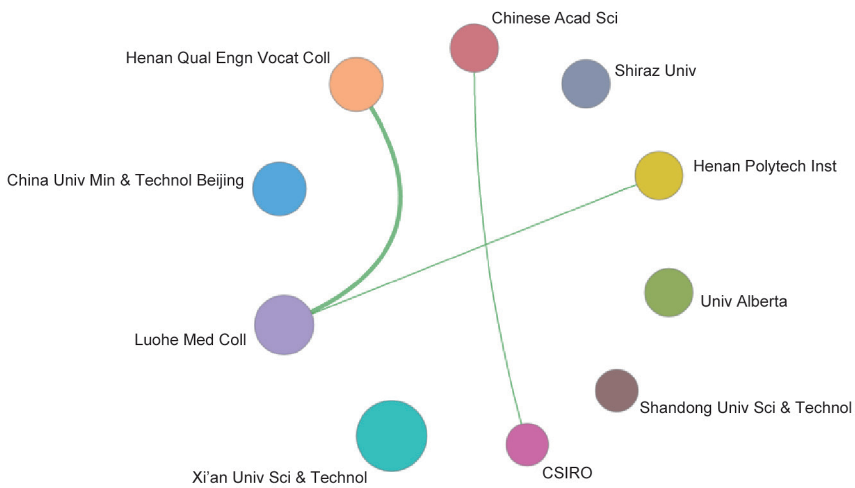

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "key engineering technologies, equipment, and materials for the intelligentization of coal, oil, and gas exploitation"

Table 1.2.11 Countries or regions with the greatest output of citing papers on the "key engineering technologies, equipment, and materials for the intelligentization of coal, oil, and gas exploitation"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	78	53.06%	2017.04
2	Australia	15	10.20%	2016.47
3	USA	11	7.48%	2016.36
4	UK	10	6.80%	2017.30
5	India	10	6.80%	2016.70
6	South Korea	6	4.08%	2017.33
7	Italy	5	3.40%	2014.80
8	Malaysia	4	2.72%	2016.00
9	Japan	4	2.72%	2016.25
10	Taiwan of China	4	2.72%	2017.25

Table 1.2.12 Institutes with the greatest output of citing papers on the "key engineering technologies, equipment, and materials for the intelligentization of coal, oil, and gas exploitation"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	China Univ Min & Technol	24	32.88%	2017.83
2	Chinese Acad Sci	17	23.29%	2015.71
3	Shandong Univ Sci & Technol	10	13.70%	2017.90
4	CSIRO	5	6.85%	2016.80
5	Newcastle Univ	5	6.85%	2017.00
6	China Univ Geosci	3	4.11%	2016.33
7	Univ Sydney	3	4.11%	2016.67
8	New Jersey Inst Technol	2	2.74%	2017.00
9	Univ Malaya	2	2.74%	2015.50
10	Petru Maior Univ Tirgu Mures	2	2.74%	2016.50

(1) Development and utilization system of fossil energy (coal, and unconventional oil and gas) and core technology and equipment

The key technology and equipment of coal exploitation can be divided into two aspects: mining and tunneling. Complete fully mechanized automation, and intelligent and unmanned mining technology and equipment generally refers to the application of automation and intelligent technology in fully mechanized mining equipment to achieve the same work with only a few people, or with unmanned mining on the working face. Developing fully mechanized automation and intelligent technology to achieve unmanned mining on the coal face is the developmental direction of coal mining technology. The main technical orientations include hydraulic-powered support and surrounding rock-coupling adaptive technology; automated top coal caving control systems based on intelligent decision-making, sequential control, memory coal caving, and manual intervention cooperative control; reliable, real-time, and safe working face multi-machine cooperative control systems; automation of the working face end support system and the advanced support system.

Intelligent rapid tunneling technology and equipment for coal roadways refers to the driving equipment for coal roadways, such as tunneling machines, anchor machines, crushing transfer machines, and belt conveyors, which have the ability to perceive, memorize, learn, and perform decision-making tasks, controlled by a hubbed automatic control system, with remote visual monitoring, as a means to ensure safe and efficient tunneling technology of "full face rapid excavation and parallel operation of excavation support

Table 2.1.1 Top 14 engineering development fronts in energy & mining engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Development and utilization system of fossil energy (coal, and unconventional oil and gas) and core technology and equipment	7 570	19 467	2.57	2014.51
2	High-voltage and high-power power electronic devices and equipment in power systems	30 142	93 793	3.11	2014.02
3	Spent fuel reprocessing and nuclear facility instrumentation	6 868	6 162	0.90	2014.97
4	Advanced energy storage technology in energy and power systems	34 878	112 316	3.22	2014.26
5	Research and application of wireless power transmission and its related equipment	1 700	32 763	19.27	2014.47
6	Renewable resources generation system and its operation and control	23 387	55 280	2.36	2014.56
7	Advanced reactor technology and equipment development	1 147	6 231	5.43	2013.65
8	Using wide spectral remote sensing techniques to explore the mineral deposits and geothermal resources	5 821	19 950	3.43	2014.40
9	New tools and materials for petroleum engineering	10 890	52 436	4.82	2013.77
10	Green mining technology (coal, oil, gas, ores)	400	1 080	2.70	2014.30
11	Logging identification of unconventional reservoirs	4 766	17 227	3.61	2014.51
12	3D geological modeling technology	3 072	5 108	1.66	2016.51
13	Advanced nuclear fuel technology research and development	46 462	244 048	5.25	2013.69
14	Safe, intelligent, and precise mining technology and equipment	3 932	5 379	1.37	2014.83

Table 2.1.2 Annual number of core patents published for the top 14 engineering development fronts in energy & mining engineering

No.	Engineering development front	2012	2013	2014	2015	2016	2017
1	Development and utilization system of fossil energy (coal, and unconventional oil and gas) and core technology and equipment	599	747	848	1 819	1 796	1 116
2	High-voltage and high-power power electronic devices and equipment in power systems	3 203	4 236	4 377	4 812	4 750	5 115
3	Spent fuel reprocessing and nuclear facility instrumentation	620	841	938	1 145	1 556	1 651
4	Advanced energy storage technology in energy and power systems	4 039	4 882	5 309	5 355	5 627	6 614
5	Research and application of wireless power transmission and its related equipment	140	192	234	255	312	392
6	Renewable resources generation system and its operation and control	2 468	3 501	3 656	4 064	4 251	4 394
7	Advanced reactor technology and equipment development	127	102	144	161	160	232
8	Using wide spectral remote sensing techniques to explore the mineral deposits and geothermal resources	492	811	831	804	1 006	1 308
9	New tools and materials for petroleum engineering	1 077	1 246	1 473	1 608	1 719	1 890
10	Green mining technology (coal, oil, gas, ores)	34	46	48	56	80	86
11	Logging identification of unconventional reservoirs	273	590	608	713	669	880
12	3D geological modeling technology	15	44	157	259	622	1 151
13	Advanced nuclear fuel technology research and development	5 150	5 667	6 509	6 113	6 723	8 068
14	Safe, intelligent, and precise mining technology and equipment	336	528	553	762	907	747

and transportation” in the driving working face. Intelligent rapid tunneling technology has created a new type of rapid tunneling, which is the “trinity” of driving, support, and transportation. It allows for the centralized and coordinated control of the equipment, and provides the foundation for an unmanned driving working face. The main technical directions and key technologies include intelligent cutting technology, intelligent anchor technology, multi-point drive power balance technology for conveyor belts, automatic control technology of tension forces, auxiliary process automation technology, integration technology for the “Internet of Things,” and adaptability research of the system. The development trend of intelligent and rapid tunneling technology for coal roadways has progressed from the “trinity” of driving, support, and transportation, to the “quaternity” of driving, support, transportation, and auxiliary services. In addition, a large database of tunneling machines and a cloud-computing center will be constructed. This platform will effectively solve the problem of the intelligent control and remote service of tunneling machines. “Unattended and intelligent tunneling” will become a reality.

Unconventional oil and gas resources in China are abundant, and they are important strategic alternative resources. However, owing to the characteristics of low porosity, low permeability, large seepage resistance, and the low recovery rate of unconventional oil and gas reservoirs, it is difficult to achieve economical and efficient development of unconventional oil and gas industries through traditional means. There is an urgent need to improve the production and recovery of unconventional oil and gas resources, and to reduce their development cost, through the innovation of engineering systems and core technology equipment for long horizontal well technology, large-scale volume fracturing technology, and high-efficiency “well factory” technology. In turn, it will promote the realization of major breakthroughs in China’s unconventional oil and gas fields, and contribute to the security of China’s energy strategy. Long horizontal well technology is an effective method for expanding unconventional oil and gas reservoir drainage areas, improving the wellbore control volume, and carrying out staged fracturing transformation, which can significantly improve single-well production and recovery. The key technologies for long horizontal drilling and completion include rotary steerable drilling technology, efficient drilling fluid technology, and wellbore integrity control. Volume fracturing transforms the reservoir by fracturing to form one or more main cracks. Furthermore, through segmented multi-cluster perforation, high displacements, large liquid volumes, low-viscosity liquids, and steering materials and technologies interact with natural cracks and artificial cracks to increase the volume of the reforms and increase the initial yields and ultimate recoveries. “Factory-based” drilling uses robotized automatic drills, through the standardization and specialization of all drilling operations, using a streamlined “factory” production model to complete drilling operations in batches, to improve the construction efficiency of equipment, personnel, and organization, and to reduce overall drilling time and development costs. Therefore, long horizontal well technology, volume fracturing, and “well factory” drilling can significantly improve the production and recovery of unconventional oil and gas and reduce operating costs, which have become a hotspot for research and development at home and abroad.

(2) High-voltage and high-power power electronic devices and equipment in power systems

High-voltage high-power power electronic devices are the core for the transmission assignment and transformation of electric energy. For example, in ultra-high-voltage (UHV) power transmission and smart grids, there are large amounts of high-power semiconductor devices, flexible alternative current transmission systems (FACTS) based on power electronic devices, static synchronous compensators (STATCOM), static var compensators (SVC), power electronic transformers (PET), and energy routers. With the development of energy structures and the ever-increasing demand for energy, power devices and equipment achieve higher power and higher switching, and become more intelligent. The investigation of high-power electronic devices such as gate turn-off thyristors (GTO), insulated gate bipolar transistor (IGBT), and integrated gate commutated thyristors (IGCT) is required for long-distance power transmission including nationwide interconnection, sending power from west to east, and mutual supply between south and north. The key issues of high-power devices that must be resolved include their reliability, the current sharing and reduction of thermal resistance in the high-voltage module, and drive protection. SiC and GaN are considered the most promising power semiconductor devices for smart grids and new energy technology. The main related technologies include high-quality epitaxial layer, the reliability of gate oxide, current collapse, and high-voltage terminal. The development of UHV power transmission relies on the performance of power electronic equipment. In the future, intelligent and digitized power electronic equipment will be combined more closely with smart grids.

(3) Spent fuel reprocessing and nuclear facility instrumentation

Spent fuel reprocessing refers to the treatment and disposal of nuclear fuel (called “spent fuel”) after it is discharged from the reactor. These methods include intermediate storage of spent fuel, post-treatment of spent fuel, treatment of radioactive waste, and final disposal. Spent fuel reprocessing is the core of the latter part of the nuclear fuel cycle. It treats spent fuel components discharged from nuclear power plants, separates and recovers unburned uranium and newly formed plutonium, and treats radioactive waste to satisfy disposal requirements. The post-treatment technique is classified into a wet method (also referred to as “water method”) and a dry method in accordance with the existing state of spent fuel in the main process. The water extraction process is currently the only economical and practical post-treatment process. The commonly used Purexium uranium recovery through extraction involves converting the spent fuel components of the reactor into an aqueous solution of nitric acid via appropriate pretreatment, and thereafter using an organic solvent. The commonly used kerosene solution of tributyl phosphate is used in extraction separation for recovering nuclear fuel and removing fission products. Dry post-processing has certain advantages for dealing with high fuel consumption and spent fuel, especially in a fast reactor, and is an important research direction at present.

To ensure safe and efficient nuclear power operation, automatic operation monitoring of key systems and equipment of nuclear power should be strengthened to improve the reliability of systems and equipment; availability of nuclear power plant operation should be improved, thus to improve economic efficiency; maintenance in unreachable areas should be carried out by robots to reduce the exposure dose of the staff; and eventually, technical conditions are created for serious accident handling and decommissioning including digital technology, artificial intelligence, nuclear instrumentation, and other key instrument technologies related to nuclear safety.

(4) Advanced energy storage technology in energy and power systems

Energy storage technology can be implemented at any stage in the energy production and consumption chains. This is especially important for new energy and modern power systems because energy requirements do not match in space and time. Taking advantage of energy storage technology, energy can be stored and be made available later wherever or whenever it is required. This technology enables otherwise wasted energy streams to be reused, energy efficiency to be improved, and fluctuating renewable energy inputs to be managed. Each of these benefits will be increasingly important and necessary in future smart power systems.

In general, most of the developed and developing energy storage technologies can be applied to electricity networks, depending upon their energy and power ranges. These technologies can be classified based on their physical-chemical properties. They are electrochemical energy storage, such as various conventional and emerging secondary chemical batteries and flow batteries; chemical energy storage, such as hydrogen storage technology; thermochemical energy storage, such as ammonia dissociation-recombination and methane dissociation-recombination; thermal energy storage, such as sensible heat and latent heat utilization technology; kinetic energy storage, such as flywheel energy storage; potential energy storage, such as pumped hydro and compressed air energy storage; electrical and magnetic storage, such as superconducting magnetic energy storage and super capacitors.

The most suitable storage technology must be chosen considering the intended application and economic parameters such as cost of investment, energy or power densities, life cycle, and impact on the environment.

(5) Research and application of wireless power transmission and its related equipment

Wireless power transfer techniques apply near-field resonant coupling, electromagnetic wave, or acoustic wave to wirelessly transmit power from the transmitter side to the receiver side. The near-field inductive resonant coupling technique is widely adopted in many applications such as uniform wireless charging platform for various portable electronics, stationary electric vehicle wireless charging device, dynamic wireless charging system for electric vehicles, wireless charging facility for industrial robots, wireless charging device for implantable electronics, wireless charging facility for monitoring devices or aerial surveillance drones of power grid, and underwater wireless charging system for unmanned submarines. Space solar power station, which is based on microwave or laser wireless power transfer technique, is a promising solution for future renewable power generation. High-power far-field wireless power transfer, high-power high-frequency power conversion, high-power high-frequency power devices, maximum efficiency point tracking, dynamic control techniques, coupled-field analysis, and metamaterials have become the research focus. Future wireless power transfer techniques, with longer power transfer distance, higher power, higher efficiency, higher safety, and miniature size, will play important roles in transportation electrification, aeronautics and astronautics, implantable medical devices, underwater detection, and smart homes.

(6) Renewable resources generation system and its operation and control

The operation and control of renewable generation system is a comprehensive technology based on advanced power electronics, control theory, and information and communication technology that aims at the secure, efficient, and flexible operation of renewable generation systems (such as wind farms and PV plants) under variable capacity and integration modes.

Centralized and distributed modes could be adopted in renewable generation. Centralized generation could achieve large-scale utility of renewable energy and centralized integration as well as a long-distance delivery with the construction of clustered renewable generation stations. The centralized mode of renewable generation could solve the conflict between renewable energy and load center distribution in China and it conforms to the future development trends of power systems in China. However, the centralized renewable generation system is faced with several technical challenges, such as fault ride-through, grid-connection stability, flexible operation control, efficient delivery, and prediction-based grid dispatching. In distributed mode, renewable energy is converted, integrated, and utilized locally with the assistance of distributed generation units and power converters. It has the technical advantages of economy, efficiency, flexibility, and reliability. The main challenges for distributed renewable generation are the coordination with the distribution network, fault location and protective relay in the DC system, and the stability issue with system control.

The main goal and trend of operation and control of renewable energy generation are to upgrade the primary energy structure and build a clean, low-carbon, secure, and efficient power system. Different scales and operation modes for different local conditions may be adopted so that all kinds of renewable energy can be utilized and consumed efficiently. The negative effects on power system security and stability operation caused by random, intermittent, and volatile characteristics should be avoided.

Present studies mainly focus on the following topics: stability control technology of DC delivery systems of renewable energy generation bases; integration of distributed generation with microgrids and active distribution networks; DC grid-connection and consumption of high-proportion distributed generation; optimal dispatching and intelligent control of multiple renewable energy generation; coordinated operation technology of clustered power electronics devices in renewable energy generation for secure and stable grid connection.

(7) Advanced reactor technology and equipment development

In response to the research and development of advanced reactor technology and equipment, the International “Fourth-generation Nuclear Energy International Forum” proposed six types of reactors (including their respective fuel cycles) for research and development for the fourth-generation nuclear power and research and development “road map” in 2002; The International “Global Nuclear Energy Partnership” is committed to promoting joint research and development of advanced nuclear energy technologies for safety, sustainable development, economy, and nuclear non-proliferation; the IAEA launched an international project dedicated to the development of sustainable and innovative nuclear energy systems. The goal of the development of the fourth-generation nuclear power plant is to have inherent safety, fully utilize nuclear resources, improve thermal efficiency, develop nuclear energy for hydrogen, metallurgy, chemical, and other purposes, dispose of nuclear waste, prevent nuclear proliferation, and counter terrorism. Currently, six of the most promising reactor systems have been selected internationally, namely sodium-cooled fast reactor, ultra-high-temperature reactor, gas-cooled fast reactor, lead-cooled or lead-bismuth eutectic cooled reactor, lead-cooled fast reactor, molten salt reactor, and supercritical water reactor. The fourth-generation reactor chooses fast-spectrum reactors because of its ability to proliferate nuclear fuels. Sodium-cooled fast reactors, lead-cooled fast reactors, gas-cooled fast reactors, and molten salt reactors all have this capability, significantly improving the utilization of uranium resources, which can be transformed to minimize waste. The role of ultra-high-temperature gas-cooled reactor is to achieve high-temperature hydrogen production and improve the power generation efficiency of nuclear power plants. Furthermore, its high-temperature heat can expand the application of nuclear energy in the industrial field. The United States launched a traveling wave reactor for its nuclear energy characteristics, and China and the United States jointly developed this project. The traveling wave reactor is a special design of a fast neutron reactor. Using high-performance fuel and material technology, the long life and deep fuel consumption make the majority of the natural uranium ^{238}U undergo in situ proliferation and incineration in the heap, reducing the demand for spent fuel after treatment.

(8) Using wide spectral remote sensing techniques to explore the mineral deposits and geothermal resources

Using wide spectral remote sensing techniques to explore the mineral deposits and geothermal resources is very efficient, for aiding national industrial development. With the increasing degree of resource exploration, prospecting for new deposits becomes more difficult, and advanced techniques are required. The remote sensing techniques have gradually become effective for the exploration and assessment of resources. Many nations are eager to launch various exploration satellites which can carry equipment receiving a wide spectrum, such as visible to near infrared, shortwave infrared, thermal infrared, and microwaves. Remote sensing techniques can effectively explore resources in the arid-semiarid and shallow coverage areas. The earth surface is half covered by vegetation, which causes difficulty in exploration. However, remote sensing can discover deposits underneath the areas covered by vegetation, using techniques of suppression of vegetation information and spectral chromatography. Clean geothermal resources, highly appreciated by international society, are covered by the vegetation. However, the identified temperature field by using thermal infrared spectrum and the structure interpretation by microwave mapping reveal the information of covering areas. Information enhancement and extraction avoid messy information, which effectively guide exploration and yield accurate prediction. In brief, for the exploration of mineral deposits and geothermal resources, remote sensing is effective, by using various wide spectral data. Enhancing and extracting key information are also critical techniques. The all goals are for providing the guidance of exploration, locating the targets of deposits, and achieving breakthrough of resource quantities.

(9) New tools and materials for petroleum engineering

As the exploration and development of oil and gas reservoirs have become more complex, there is an urgent need to develop new tools and materials for petroleum engineering for dealing with the complex conditions in a wellbore, which include high temperature and high pressure. This can help accelerate the exploration and exploitation of hydrocarbon reservoirs and ensure successful drilling. New tools for petroleum engineering mainly involve the fields of drilling, completion, production, etc., and new materials are applied to improve the performance of petroleum tools, drilling fluids, fracturing fluids, proppants, etc.

Currently, the exploration and development of oil and gas in the world are progressing from shallow ground to deep ground, from shallow sea to deep sea, and from conventional to unconventional fields. There is an urgent need to conduct research on tools and materials in petroleum engineering, which aims at improving the scale and efficiency of exploration and development under the strategies of being innovation-driven and made in China 2025. At present, the research hotspots of new tools for petroleum engineering include intelligent steerable tools, rotary steerable tools, single-well injection-production tools, and separate-layer water injection tools. Advanced materials, which include nanometer materials, functional gradient materials, and carbon fiber composite materials, can be used to improve the performance of tools. Furthermore, nano drag reducing agent, nano oil displacement agent, and self-healing polymer materials can play an important role in increasing the performance of drilling fluids, fracturing fluids, proppants, and other fluids.

(10) Green mining technology (coal, oil, gas, ores)

Green mining controls the mining disturbance to the mining environment within a regional environmental capacity, and optimizes the utilization of resources, while minimizing the impact on the ecological environment. In the process of mining, scientific and orderly mining must be strictly implemented, and the disturbance to the mining area and the surrounding environment should be controlled within the controllable range of environment. Green mining of coal, oil, and gas, as well as ore, indicates that all the available energy resources, such as coal, oil, gas, ore, mash gas, water, land, and gangue should be understood and treated from a perspective of the mining activity, preventing or mitigating adverse effects to the environment or other resources during the mining of energy resources, and realizing the economic benefits that accompany the optimum environmental and social benefits.

Green mining of coal resources, a direction borne out of the environment problems caused by coal mining in large quantities, is still the focus of research on energy resources. The techniques of exploitation and innovation should be employed from the beginning of the coal mining method; moreover, research on corporate mining and the utilization of associated resources, as well as technology and equipment, should be improved. The research topics are as follows: water preserved from mining, land and building protection, ecological reconstruction, simultaneous extraction of coal and gas, surface subsidence that retards mining, reduction of gangue emissions, concentration and utilization of marsh gas, utilization of solid waste, clean exploitation and processing of ore resources, ecological restoration of mine lot wastelands, the benefit-and-effect evaluation of mineral exploitation, the safety as well as monitoring and early warning of mine lot environments, etc. The key points of metal and nonmetal green mining include the integration of mining and processing, non-waste mining, breakthroughs in mechanization for continuous tunneling and mining, and innovations in tunneling and mining techniques with high-pressure water jets, lasers, or plasma.

Green oil exploitation is an integrated and systematic concept, aiming at environmental, social, and economic benefits, through a sustainable method. Clean oil exploitation or non-pollution product systems by means of ecological research with modern techniques should be realized; furthermore, they can be transformed into ecological products in the market. Therefore, a switch from a high-consumption development mode with high energy consumption and high pollution to a sustainable development mode with ecological and economic integration is required. The key innovations involve water conditioning to improve the quality of injection water, fine filters for injection water, improvement of resource utilization through the creation of key equipment, and increased production with the innovation of production and process control.

(11) Logging identification of unconventional reservoirs

Unconventional reservoirs refer to the reservoirs that cannot be economically explored using traditional techniques to obtain natural productivity, and require new technologies to improve reservoir permeability or fluid viscosity. Conventional logging methods have poor applicability in unconventional reservoirs, which require new logging technology to develop logging identification techniques for unconventional reservoirs. At present, the main technologies include elemental capture spectroscopy (ECS) logging, imaging logging, nuclear magnetic resonance logging, and other special logging techniques, as well as rapid identification of overlapping logging images, natural gamma and tri-porosity logging identification, electromagnetic resistivity and resistivity-fluid properties method, and effective fracture interval detection technology of shale oil and gas. These technologies have high recognition accuracy and speed, which can improve the accuracy of prediction of effective reservoirs of unconventional reservoirs by determining the continuous identification depth of effective reservoir and non-reservoirs, and satisfy the production requirements of effective fracturing intervals in the exploration and development of effective reservoirs in unconventional reservoirs. Future logging identification of unconventional reservoirs is still a difficult and hot topic, which will be optimized through collection technology, petrophysical research, processing and interpretation methods, and reservoir evaluation. It is expected that the digital petrophysical technology will play a more important role in logging evaluation and analysis in the future. In addition, the logging interpretation evaluation software is being developed toward multidisciplinary integration, and more attention is being paid to the comprehensive evaluation of oil and gas reservoirs; further, the research on the logging basic theory is intensified and the analysis techniques are more abundant.

(12) 3D geological modeling technology

3D geological modeling technology is a method to combine the spatial information management, geological interpretation, spatial analysis and prediction, geostatistics, physical content analysis, and graphical visualization in a virtual 3D environment by using computer technology and is applied to geological analysis. Data sources include borehole data, profile data, 3D seismic data, and other geological data. Modeling methods include phased geological modeling, petrographic modeling of sedimentary microfacies constraints, and parameter modeling of porosity, permeability, and saturation. Kriging method, stochastic modeling method, sequential Gaussian simulation method, dual-mode iteration technique, sedimentary-facies-coupled petrophysics modeling, well-to-seismic modeling, 3D reservoir parameter modeling, and 4D seismic technology have become the research hotspots. 3D seismic modeling software will become more mature and will be widely used in the future, from focus on shape modeling only to equal attention on form and physical property, and will be more closely combined with the geophysical data in the seismic, logging, electrical, gravity, and magnetic aspects, as well as drilling and geological data. It will be more closely integrated with various professional models (mineral description, accumulation simulation, 3D inversion of gravity and magnetic field, sedimentary environment analysis, etc.), which indicates that the mainstream IT technologies such as big-data analysis, cloud computing, and Internet of things will become the main techniques used in this regard.

(13) Advanced nuclear fuel technology research and development

After the Fukushima nuclear accident in Japan in 2011, countries began to accelerate the research and development of advanced nuclear fuels represented by accident tolerance fuels (ATF). Compared with conventional fuels, ATF fuels enhance the safety of reactors and spent fuel pools in the event of an accident by enhancing the ability of fuel-bearing fission products and cladding materials to resist oxidation, providing longer incident response times, and therefore potentially proactively or passively mitigating the consequences of the accident, achieving deeper fuel consumption, and improving fuel economy. ATFs can be used in new and in-service nuclear power plants, and hence, the development of ATF fuels is of great significance for the safe development of nuclear power. The research and development direction focuses on innovative cladding and new fuels. It can be classified into three directions: improving the high-temperature oxidation resistance and strength of the zirconium alloy cladding; developing a non-zirconium alloy with high strength and oxidation resistance; and developing a new fuel with better performance and retention of fission products than UO_2. The extended ATF should also include changes in geometry, such as ring fuel. The related research includes materials, processes, and inspection and verification techniques.

(14) Safe, intelligent, and precise mining technology and equipment

By means of different technologies including “intellisense,” intelligent control, the Internet of Things, and cloud computing and big data, intelligent precise mining technology and equipment for mining safety are proposed as a new mining mode that integrates the intelligent mining technique requiring few workers (unmanned), and it has 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 intellisense, 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 few workers (unmanned), 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 few workers (unmanned), based on the Internet and scientific mining. China has concentrated on safety mining that requires few workers (unmanned), and it will further accelerate the intensity of innovation for mining technology, with plans to break through the basic and full implementation of a safe-intelligent-precise mining mode in the years 2020, 2035, and 2050, respectively, indicating a full realization of high-tech industrial upgrades that will boost the Chinese dream of powerful energy technology.

2.2 Interpretations for three key engineering development fronts

2.2.1 Development and utilization system of fossil energy (coal, and unconventional oil and gas) and core technology and equipment

(1) Complete fully mechanized automation, and intelligent and unmanned mining technology and equipment for coal mines

Fully mechanized longwall mining is the main mining method for coal mines. The technological advancement of fully mechanized mining equipment is the engine for promoting the development of safe, efficient, and green mining technology for coal. The deep integration of modern automation, informatization, intelligent technology, advanced manufacturing technology, and coal mining technology makes it possible to produce fully mechanized automation, and intelligent and unmanned mining technology and equipment. Research on intelligent mining technology and equipment is required, as outdated mining methods and equipment must be eliminated, in order to achieve safe, efficient, and green mining of coal resources. Improving the automation and intelligence level of equipment, and requiring few people or using unmanned mining is the only possible way for the development of fully mechanized mining and the modernization of mines.

To better describe the technical connotations and the level of automation technology required for a fully mechanized mining face that operates according to the level of perception, decision, and execution of the fully mechanized mining equipment control system, the terms defined are automatic fully mechanized mining face, intelligent fully mechanized mining face, and unmanned fully mechanized mining face. An automatic fully mechanized mining face indicates that the equipment is electromechanically integrated; this includes the adoption of hydraulic supports, coal mining machines, and scraper conveyors with automatic functions, which requires few people as operators, and allows safe and efficient mining. An intelligent, fully mechanized mining face is an electromechanically integrated equipment system with the adoption of comprehensive perception, self-learning, decision-making, and automatic execution functions, which allows for a highly automated mining face that requires few people for remote monitoring, and allows for safe and efficient mining. An unmanned, fully mechanized mining face indicates that the mining face adopts remote intelligent integrated control systems, and is a complete automated, intelligent, and highly reliable system with electromechanical integration, which achieves completely unmanned (within both face ends), safe, and efficient mining.

Fully mechanized, automatic, and intelligent mining is the basis for the mining of unmanned working faces, which is the ultimate target of mine technology development. The technology orientations and the key technologies to be developed are as follows.

1) The study of hydraulic-powered supports and surrounding rock coupling adaptive technology, and automated top coal caving control systems, based on intelligent decision-making, sequential control, memory coal caving, and a manual intervention cooperative control, for a reliable, real-time, and safe working face multi-machine cooperative control system.

2) The study of the sensitivity of coal rock characters to the cutting head load; the establishment of on-line monitoring of the cutting head load, with abrupt changes and detection of the criteria of the cutting state; the development of intelligent control technology of the precise location of the autonomous shearer, including self-learning, and intelligent adjustment from memory. Research on the multi-source information fusion method of the integrated system of shearer cutting–hydraulic powered support–transportation, aiming at the elimination of conflict for collaborative work, and the establishment of prevention of the collision algorithm and its technology; finally, the development of a reliable, real-time, and safe collaborative working system in the working faces.

3) The study of the failure mode and the fault mechanism of key components of the fully mechanized mining equipment; the establishment of an evaluation system for fully mechanized equipment key components and system reliability, aiming at automatic, intelligent, and unmanned working faces.

4) Strengthening of the automation study on the working face end and advanced support to solve the constraints caused by the above places.

With the development and popularization of fully mechanized, automatic technology, high-efficiency technology is the fundamental solution to achieving safe, high-yield, and high-efficiency mines. The reliability and adaptability of complete equipment in a fully mechanized working face are improved with integration with automatic, intelligent technology. At present, unmanned mining operation has been achieved in some advanced coal mines, or under limited conditions. Continual technical research on fully mechanized, automatic, and intelligent technology is the developing orientation for mine technology science.

(2) Intelligent rapid tunneling technology and equipment for coal roadways

Mining and tunneling coordination has always been an important issue in the coal production process. With the increase in the automation and intelligence level of the equipment in the fully mechanized coal mining face, the unbalance of mining and tunneling owing to excavation efficiency has become a difficult problem in the modern large mine. In the last few decades, the level of driving technology for coal roadways has been greatly improved in China. Especially in recent years, the Taiyuan Research Institute, China Coal Technology & Engineering Group Corp (CCTEG), and Shendong have co-developed an efficient and rapid driving system. This system was applied to the fully mechanized coal mining faces in Coal Seam 5-2 in the Daliuta Coal Mine in Shendong mining areas from July 2014 to November 2015, and it allowed for full-section rapid excavation, a parallel operation of tunneling, supporting, and transportation, remote monitoring operation, and an auxiliary operation. Currently, it is the fastest driving system with the highest degree of mechanization, automation, and informatization in China. However, there are still shortcomings in this highly efficient and rapid driving system, including the following issues: ① The system is only adaptable to mines with better geological conditions, such as Shendong, and the adaptability of the system is not high; ② The mechanization, automation, and intellectualization of the supporting equipment are generally not high, and should be further improved; ③ The reliability of single machines must be improved; ④ The system did not achieve parallel operation. Therefore, it is necessary to further study the problems related to the rapid tunneling of coal roadways, and to explore intelligent rapid tunneling technology, in order to further improve the technical indexes of the tunneling operation, and to satisfy the needs of safe and efficient coal mining.

The intelligent rapid tunneling technology and equipment for coal roadways refer to the driving equipment of coal roadways, such as the tunneling machine, anchor machine, crushing transfer machine, and belt conveyor, which have the ability to perceive, memorize, learn, and perform decision-making tasks. They use a hubbed automatic control system, and also use remote visual monitoring as a means to realize safe and efficient tunneling technology of “full face rapid excavation, parallel operation of excavation support, and transportation” in driving the working face. Intelligent rapid tunneling technology has created a new type of rapid tunneling, which is the “trinity” of driving, support, and transportation. This has achieved centralized and coordinated control of equipment, and it provides the foundation for an unmanned driving working face.

Foreign excavator and full-section boring machines have automatic cutting technology, transmission equipment monitoring, and automatic control technology, which enable full-function remote control and monitoring of the cutting section. Germany, the United States, and Austria have mastered multi-point drive technology for the line friction of the flexural belt conveyor, and for the turning technology of the conveyer belt. However, at present, the automated single machine equipment is mostly used in non-coal mines such as metal ore, salt mines, and other non-coal mines. The technology and equipment of the coal mining face in foreign countries are still at the semi-automation level, and there is no complete set of technology and equipment for intelligent rapid tunneling at present.

The main technical directions and key technologies include intelligent cutting technology, intelligent anchor technology, multi-point drive power balance technology of the conveyor belt, automatic control technology of the tension force, auxiliary process automation technology, integration technology for the Internet of Things, and the adaptability research of the system.

The development trend of intelligent and rapid tunneling technology for coal roadways is based on the “trinity” of driving, support, and transportation, progressing to the “quaternity” of driving, support, transportation, and auxiliary services. In addition, a large database of tunneling machines and the cloud-computing center will be constructed. This platform will effectively solve the problem of the intelligent control and remote service of tunneling machines. "Unattended and intelligent tunneling" will become a reality.

(3) Unconventional oil and gas development and utilization systems, and core technology and equipment

Unconventional oil and gas are characterized by a difference in reservoir characteristics and accumulation mechanisms from conventional oil and gas reservoirs. Such oil and gas accumulation can only be developed economically by using advanced technology, large-scale stimulation measures, and/or special recycling processing, owing to its special reservoir rock properties (low matrix permeability and natural cracks), special infill injection (absorbed gas and methane hydrate from self-generated and self-reserved rock), and/or special fluid properties (high viscosity). The key parameters are that the porosity of the reservoir is generally less than 10%, and that the permeability is less than $1\times10^{-3}\ \mu m^2$. The key indicators are the "continuous distribution of large areas of oil and gas, no apparent trapping limits" and "no natural industrial stable outputs, no apparent Darcy seepage flow." With the increasing difficulty in the exploration and development of conventional oil and gas, unconventional oil and gas resources have increasingly attracted attention worldwide. It can be said that unconventional oil and gas is an inevitable trend and choice for the development of the world oil and gas industry. Therefore, accelerating the development and utilization of unconventional oil and gas resources is of great strategic significance to compensate the energy gap, and to ensure national energy security.

The branch engineering technologies for unconventional oil and gas exploration mainly include drilling technology (horizontal well drilling technology is the leading mainstream technology), fracturing technology, and platform-type "factory" mining technology.

Horizontal well drilling technology. Compared with vertical wells, horizontal wells have the advantages of large oil and gas drainage areas, high single-well production, high penetration, high employing reserves, saving land occupation, and avoidance of obstacles and harsh environments. This plays an important role in improving single-well oil and gas production, and recovery of oil and gas, and it has become a key technology for the efficient exploration and development of unconventional oil and gas resources. With the development of horizontal wells and process technologies, new horizontal well technologies have been developed, such as extended-reach horizontal wells, sidetracking horizontal wells, multi-branch horizontal wells, pinnate horizontal multilateral wells, cluster horizontal wells (PAD), under-balanced horizontal wells, and coiled tubing drilling.

Fracturing technology. In recent years, the scale of fracturing has developed from miniaturization to maximization. The number of fracturing layers has progressed from a single layer to multiple layers. Fracturing wells have progressed from vertical wells to horizontal wells, with the development of various fracturing technologies and supporting processes, such as vertical well segmental fracturing, horizontal well segmental fracturing, repeated fracturing, and simultaneous fracturing, which have become the core technologies for the economic and effective development of unconventional oil and gas resources, and have played a key role in the rapid development of unconventional oil and gas. At present, fracturing technology is being developed in the following three aspects: ① The existing fracturing technology is being continuously developed and integrated, such as continuous tubing fracturing, slim hole fracturing, downhole mixing fracturing, and other technologies; ② fracturing equipment develops to be high-power, modular, miniaturized, and portable; ③ efficient, low-cost, environment-friendly fracturing technology will be an important development direction in the future, such as volumetric fracturing transformation, high-speed channel fracturing, and other technologies being tested.

Platform-style "factory" mining technology. This is mainly based on a cross-well superseding strategy, using cluster horizontal well drilling, simultaneous fracturing, or cross-fracturing operation, where dozens of wells are synchronized in a well site, saving land and reducing costs. This breaks through the problem of poor efficiency of single-well mining in a well site, and provides an efficient operation mode for the economic development of unconventional oil and gas resources, such as shale gas.

At present, unconventional oil and gas development technology is complicated and expensive. In the future, we should investigate how to reduce costs, in order to achieve the expected mining targets on the basis of ensuring the smooth exploration and exploitation of unconventional oil and gas resources. The main research trends includes adhering to long-term basic theoretical innovation, to provide a solid theoretical basis and technical guidance for the exploration and development of unconventional oil and gas; adhering to core technology advancement and large-scale application, which is the key to breakthroughs in the field of unconventional oil and gas; focusing on horizontal well-scale fracturing and platform-type “factory” mining; strengthening process technologies and developing low-cost supporting technologies as soon as possible; strengthening the regulation and control of development of unconventional oil and gas resources; formulating scientific development plans; developing, utilizing, establishing, and planning the required talent team training system; forming a talent organization composed of researchers and technical experts to ensure the rational development of unconventional oil and gas resources.

(4) Comparisons and cooperation between countries and institutions

According to Table 2.2.1, the countries with the largest number of core patent outputs in this research direction are China, the USA, Japan, Russia, and Germany. Among them, the proportion of China’s patents exceeds 80%, and the proportion of patents of the other countries is less than 5%. According to Table 2.2.2, the institutions with the largest number of core patent outputs in this research direction are UYMT, UYMB, SHGR, UYHP, and SNPC. Among them, only UYMT, UYMB, and SHGR have a core patent ratio exceeding 2%.

According to Figure 2.2.1, countries such as USA, China, Australia, Canada, and Germany have paid more attention to cooperation among nations or regions in this research direction. Among them, China and USA have formed a cooperative relationship, and have a much larger number of co-authored core patents. Although Japan and Russia have a high number of core patents, they have cooperative relationship with no more than two countries or regions, and they have no cooperative relationship with China.

According to Figure 2.2.2, the institutions with a cooperative relationship with other institutions are UYMT, UYMB, SHGR, SNPC, and Xi'an University of Science and Technology. Among them, UYMT, UYMB, and SHGR have a cooperative relationship with each other, and have the largest number of co-published core patents. Xi'an University of Science and Technology has a cooperative relationship with UYMB and SHGR; however, they have a lower number of co-published core patents.

2.2.2 High-voltage and high-power power electronic devices and equipment in power systems

(1) Concept description and key techniques

High-power power electronic technology uses high-power semiconductor devices to realize effective power conversion and transmission through the accurate energy flow control with information flow, and to improve the conversion efficiency and accuracy of high-power power electronic equipment. Nowadays, China is at a critical stage owing to the development of energy structures and the ever-increasing demand for energy. Thus, UHVAC transmission and smart grids are attracting widespread attention. Hence, power converters and semiconductor devices face new challenges and opportunities. However, there are still some important issues that must be solved in achieving high power, high frequency, and intelligentization.

(2) State-of-the-art and future development trends

Power devices with high voltage and high power. To achieve long-distance power transmission including nationwide interconnection, sending power from west to east, and mutual supply between south and north, IGBT and IGCT with higher energy capability are urgently required. ABB and Mitsubishi have reported 8500V/4240A thyristor and 4500V/2100A IGBT, respectively. At present, 6-inch 8000V/4000A thyristor, 4500V/4000A IGCT, 3300V/2400A IGBT are in mass production in China. In 2018, the first 4500V/3000A crimping IGBT has been proposed by CRRC. The key issues of high-power devices that must be resolved include the fast switching and reliability of GTO, current sharing and reduction of thermal resistance in the IGBT module, and drive protection.

Novel high-voltage devices with high frequency. To satisfy the requirements of the development of smart grid and new energy technology, novel high-voltage devices with high frequency are required to realize converters with high efficiency and power density. Currently, SiC and GaN are considered the most promising power semiconductor devices. The 900 V–1700 V SiC and 30 V–650 V GaN devices are already industrialized in Europe, USA, and Japan. Furthermore, 10 kV SiC MOSFET, 27 kV SiC IGBT, and 22 kV SiC GTO samples have been reported. So far, 10 kV SiC MOSFET and 10 kV SiC IGBT samples have already been reported in China. The key issues that must be resolved include high-quality epitaxial layer, the realization of gate oxide, and high-voltage terminal.

Table 2.2.1 Countries or regions with the greatest output of core patents on the "development and utilization system of fossil energy (coal, and unconventional oil and gas) and core technology and equipment"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	6 330	83.62%	10 363	53.23%	1.64
2	USA	364	4.81%	5 646	29.00%	15.51
3	Japan	227	3.00%	679	3.49%	2.99
4	Russia	132	1.74%	111	0.57%	0.84
5	Germany	82	1.08%	612	3.14%	7.46
6	South Korea	78	1.03%	45	0.23%	0.58
7	Australia	64	0.85%	287	1.47%	4.48
8	France	50	0.66%	359	1.84%	7.18
9	India	48	0.63%	139	0.71%	2.90
10	Canada	41	0.54%	786	4.04%	19.17

Table 2.2.2 Institutions with the greatest output of core patents on the "development and utilization system of fossil energy (coal, and unconventional oil and gas) and core technology and equipment"

No.	Institutions	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	UYMT	China	247	3.26%	1 221	6.27%	4.94
2	UYMB	China	189	2.50%	356	1.83%	1.88
3	SHGR	China	153	2.02%	440	2.26%	2.88
4	UYHP	China	141	1.86%	332	1.71%	2.35
5	SNPC	China	91	1.20%	374	1.92%	4.11
6	UYTL	China	85	1.12%	150	0.77%	1.76
7	Univ Xi'an Sci & Technology	China	79	1.04%	128	0.66%	1.62
8	KOBM	Japan	74	0.98%	225	1.16%	3.04
9	BJSW	China	73	0.96%	67	0.34%	0.92
10	SDST	China	69	0.91%	108	0.55%	1.57

UYMT: Univ China Mining & Technology; UYMB: Univ China Mining & Technology Beijing; SHGR: Shenhua Group Corp. Ltd.; UYHP: Univ Henan Polytechnic; SNPC: China Petroleum & Chem Corp.; UYTL: Univ Taiyuan Technology; KOBM: Kobe Steel Ltd.; BJSW: Beijing Shenwu Environment & Energy Tech; SDST: Univ Shandong Sci & Technology.

Intelligent high-power electronic equipment. The capacity improvement of power transmission relies on the performance of power electronic equipment such as FACTS, STATCOM, SVC, PET, and energy router. The key issues that must be resolved include power electronic equipment with high capacity and high reliability, and high-efficiency equipment technology.

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

The core technology of high-voltage power devices and equipment for power systems in China is advancing satisfactorily overall but the quality and quantity in certain institutions still need to be improved. As shown in Table 2.2.3 & 2.2.4, the number of enterprises operating in the field of high-power electronic devices and equipment in China is considerably large. However, the average number of citations and cited proportion of the related patents from China are much less than those from the USA, Europe, and Japan. As shown in Figure 2.2.3, there is a strong cooperative relationship among these developed countries and regions

Figure 2.2.1 Collaboration network among major countries or regions in the engineering development front of "development and utilization system of fossil energy (coal, and unconventional oil and gas) and core technology and equipment"

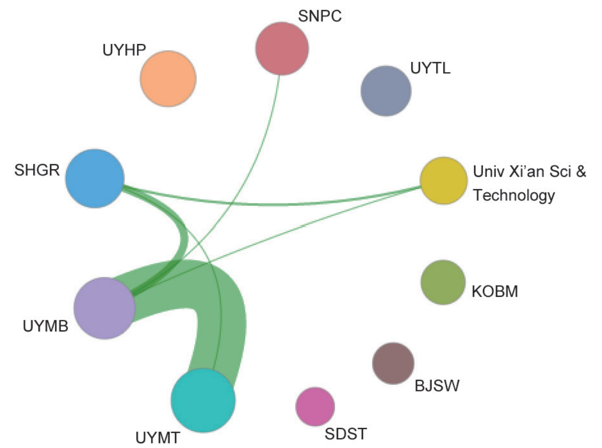

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of "development and utilization system of fossil energy (coal, and unconventional oil and gas) and core technology and equipment"

in the field of high-power electronic devices and equipment. Moreover, many enterprises take part in the research through division of labor and collaboration. Among them, the semiconductor enterprise and foundry are also included as shown in Figure 2.2.4.

2.2.3 Spent fuel reprocessing and nuclear facilities instrumentation

(1) Conceptual explanation and key technologies

1) Spent fuel reprocessing refers to the treatment and disposal of nuclear fuel (called "spent fuel") after being discharged from the reactor. These methods include intermediate storage of spent fuel, post-treatment of spent fuel, treatment of radioactive waste, and final disposal. Spent fuel reprocessing is the core of the latter part of the nuclear fuel cycle. It treats spent fuel components discharged from nuclear power plants, separates and recovers unburned uranium and newly formed plutonium, and treats radioactive waste to satisfy disposal requirements. The post-treatment technique is classified into a wet method (also referred to as "water method") and a dry method in accordance with the existing state of spent fuel in the main process. The water extraction process is currently the only economical and practical post-treatment process. The commonly used Purexium uranium recovery through extraction involves converting the spent fuel components of the reactor into an aqueous solution of nitric acid via appropriate pretreatment, and thereafter using an organic solvent. The commonly used kerosene solution of tributyl phosphate is used in extraction separation for recovering nuclear fuel and removing fission products. Dry post-processing has certain advantages for dealing with high fuel consumption and spent fuel, especially in a fast reactor, and is an important research direction at present.

2) To ensure the safe and efficient operation of nuclear power operation during the whole life, the automatic operation monitoring of key systems and equipment of nuclear power should be strengthened, thus to improve the reliability of systems and equipment; the availability of nuclear power plant operation should be improved, thus to improve economical efficiency; robot maintenance is carried out in unreachable areas, to reduce the exposure dose of workers; and ultimately technical conditions for serious accident handling and decommissioning is created. Digital technology, artificial intelligence and nuclear instrumentation, and other key instrument technologies related to nuclear safety are included.

(2) Development status and future development trend

1) The medium treated by the spent fuel reprocessing plant of the power reactor is highly radioactive, toxic, and corrosive, and has outstanding problems such as nuclear criticality safety and radiation safety. The requirements for engineering technology, special equipment, online control and monitoring, and far-distance operation and maintenance are high, and

Table 2.2.3 Countries or regions with the greatest output of core patents on the "high-voltage and high-power power electronic devices and equipment in power systems"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	19 056	63.22%	21 726	23.16%	1.14
2	Japan	4 897	16.25%	30 528	32.55%	6.23
3	USA	1 643	5.45%	22 001	23.46%	13.39
4	South Korea	1 200	3.98%	2 995	3.19%	2.50
5	Germany	1 139	3.78%	5 953	6.35%	5.23
6	Switzerland	469	1.56%	3 607	3.85%	7.69
7	Russia	403	1.34%	125	0.13%	0.31
8	Austria	256	0.85%	2 126	2.27%	8.30
9	Taiwan of China	221	0.73%	822	0.88%	3.72
10	France	196	0.65%	1 087	1.16%	5.55

Table 2.2.4 Institutions with the greatest output of core patents on the "high-voltage and high-power power electronic devices and equipment in power systems"

No.	Institutions	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	SGCC	China	2 186	7.25%	3 583	3.82%	1.64
2	FJIE	Japan	771	2.56%	5 982	6.38%	7.76
3	INFN	Austria	673	2.23%	4 827	5.15%	7.17
4	MITQ	Japan	590	1.96%	3 980	4.24%	6.75
5	CRRC	China	497	1.65%	802	0.86%	1.61
6	ALLM	Switzerland	438	1.45%	3 161	3.37%	7.22
7	TOKE	Japan	437	1.45%	2 232	2.38%	5.11
8	NPDE	Japan	419	1.39%	3 037	3.24%	7.25
9	TOYT	Japan	419	1.39%	2 187	2.33%	5.22
10	CSPG	China	274	0.91%	311	0.33%	1.14

SGCC: State Grid Corp China; FJIE: Fuji Electric Co., Ltd.; INFN: Infineon Technologies AG; MITQ: Mitsubishi Electric Corp.; CRRC: Zhuzhou CRRC Times Electric Co., Ltd.; ALLM: ABB Technology Co., Ltd.; TOKE: Toshiba Corp.; NPDE: Nippondenso Co., Ltd.; TOYT: Toyota Jidosha KK; CSPG: China Southern Power Grid Co., Ltd.

nuclear fuel reprocessing technology is difficult to study. It is necessary to develop a series of special engineering techniques, special equipment, and instruments. The development of post-processing processes generally includes laboratory process conditions and cascade experiments, laboratory-scale bench warming tests, and pilot-scale thermal verification processes; the development of key equipment requires experience prototype development, equipment amplification research and development of prototypes, and engineering prototype development; the typical unit process, equipment, layout, and maintenance program also requires 1:1 scale engineering verification under non-release (or cold uranium) conditions. Thus, the engineering design of the nuclear fuel reprocessing plant can be carried out to improve the reliability, operability, and maintainability of the reprocessing plant, thus ensuring the operating rate, economy, and safety.

Sustainable development of nuclear energy must address the two major problems of uranium resources: optimization of utilization and minimization of radioactive waste. Returning of the uranium and thorium extracted via post-treatment to a

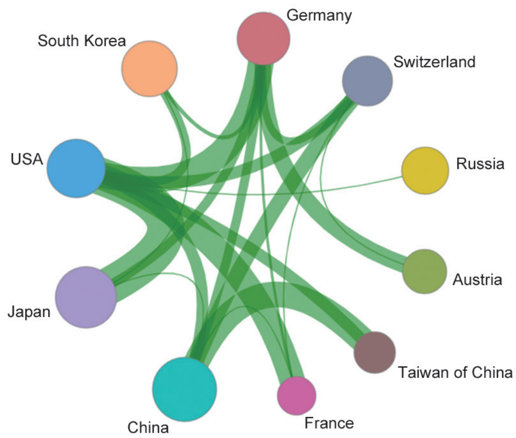

Figure 2.2.3 Collaboration network among major countries or regions in the engineering development front of "high-voltage and high-power power electronic devices and equipment in power systems"

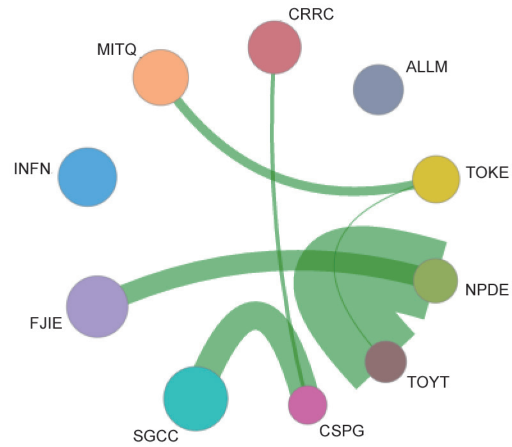

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of "high-voltage and high-power power electronic devices and equipment in power systems"

thermal reactor for reuse can only increase the utilization rate of uranium resources by 30%; returning to a fast reactor for reuse can increase the utilization rate of uranium resources by 60 times. Furthermore, long-lived, highly radiotoxic secondary lanthanides and fission products separated via post-treatment are consumed in the fast reactor through incineration and metamorphism, which can effectively reduce not only the impact of spent fuel on the environment, but also the supervision time, thus significantly reducing economic and social costs. Therefore, the closed cycle of nuclear fuel, especially in fast reactors, is the only possible way for the sustainable development of nuclear energy.

2) Instrumentation in nuclear facilities includes digital technology, artificial intelligence and nuclear instrumentation, and other key instrument technologies related to nuclear safety. Among them, nuclear measuring instruments use certain characteristics of radiation to measure radiation types and related physical parameters. Instrumentation in nuclear facilities mainly includes three parts: reactor control, safety protection, and environmental monitoring. According to the type of instrument, it includes nuclear instrumentation and key instruments related to nuclear safety. China has established a nuclear instrumentation equipment manufacturing system that is relatively complete in product variety and can satisfy general needs. However, with the development of advanced nuclear power technology, the safety and reliability of nuclear power plants are being continuously improved, and the subsequent nuclear instrumentation requirements and measurement accuracy, operating environment, and product reliability requirements of key instruments related to nuclear safety are also constantly improving; thus, product replacement is imperative. Owing to the gaps in testing and inspection capabilities among key materials and the design and manufacturing levels and conditions, the existing products of domestic manufacturers have been unable to satisfy the technical requirements of the third-generation nuclear power plants.

The USA, France, UK, Russia, India, Japan, and other countries have all the aspects of the nuclear fuel cycle. Except for the United States, they all adhere to the post-development and nuclear fuel closed cycle. At present, the total post-processing capacity of the world is approximately 4 850 tons per year, and more than 90 000 tons of spent fuel has been reprocessed. France's UP3, UP2-800, and UK THORP reprocessing plants are state-of-the-art commercial reprocessing plants. Internationally, research and development on the post-processing of spent fuel in fast reactors is actively carried out, and finally, an integrated fuel reactor (fuel manufacturing-reactor-post-treatment at the same site) closed fuel cycle (U, Pu, MA recycling) is realized.

To gain intelligence and wisdom, and to upgrade the high-tech strategic industry level of the nuclear industry, it is necessary to deeply and widely apply a new type of artificial intelligence technology represented by industrial robots, image recognition, deep self-learning systems, adaptive control, autonomous manipulation, human–machine hybrid intelligence, and virtual reality intelligence. The measures also include the use of intelligent instrument intelligent controllers for the establishment of nuclear power plant digital control system; the use of Internet+ to establish a big-data system to develop digital nuclear power plants; (three-dimensional dynamic) development of virtual reality technology; operational guidance and accident handling guidance; intelligent maintenance of equipment system in a nuclear power plant; using robots or robotic systems to repair unreachable areas in highly radioactive areas.

(3) Focus on the analysis of countries and institutions and the comparison and cooperation between them

According to Table 2.2.5, the countries with the largest number of core patent outputs in this research direction are Japan, the USA, China, the Netherlands, Germany, South Korea, France, and Russia. Among them, the proportion of core patents from Japan exceeds 30%, the proportion of core patents from the USA and China exceeds 20%, the proportion of core patents from the Netherlands is approximately 6%, and the proportion of core patents from the other countries is less than 6%.

As evident from Table 2.2.6, the institutions with the largest number of core patent outputs in this research direction are GENE, PHIG, CGNP, and MITQ, and their proportion of core patent output exceeds 5%.

According to Figure 2.2.5, the USA, the Netherlands, Germany, France, Japan, and Russia are more concerned about the cooperation between countries or regions in this field.

According to Figure 2.2.6, the institutions with a cooperative relationship with other institutions include CGNP and CNNU, and the number of core patents published by means of the cooperation is also the largest; HITA has a cooperative relationship with two research institutes, TOKE and GENE.

Table 2.2.5 Countries or regions with the greatest output of core patents on the “spent fuel reprocessing and nuclear facilities instrumentation”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Japan	193	30.54%	700	18.37%	3.63
2	USA	170	26.90%	1 921	50.42%	11.30
3	China	153	24.21%	182	4.78%	1.19
4	Netherlands	38	6.01%	767	20.13%	20.18
5	Germany	28	4.43%	289	7.59%	10.32
6	South Korea	21	3.32%	42	1.10%	2.00
7	France	16	2.53%	115	3.02%	7.19
8	Russia	14	2.22%	3	0.08%	0.21
9	Canada	9	1.42%	54	1.42%	6.00
10	Poland	6	0.95%	2	0.05%	0.33

Table 2.2.6 Institutions with the greatest output of core patents on the "spent fuel reprocessing and nuclear facilities instrumentation"

No.	Institutions	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	GENE	USA	38	6.01%	404	10.60%	10.63
2	PHIG	Netherlands	34	5.38%	571	14.99%	16.79
3	CGNP	China	32	5.06%	68	1.78%	2.13
4	MITQ	Japan	32	5.06%	71	1.86%	2.22
5	HITA	USA	29	4.59%	120	3.15%	4.14
6	SHMA	Japan	29	4.59%	146	3.83%	5.03
7	TOKE	Japan	25	3.96%	38	1.00%	1.52
8	CNNU	China	17	2.69%	17	0.45%	1.00
9	USGO	USA	12	1.90%	47	1.23%	3.92
10	WESE	USA	10	1.58%	76	1.99%	7.60

GENE: General Electric Co.; PHIG: Konink Philips NV; CGNP: China Guangdong Nuclear Power Group Co., L; MITQ: Mitsubishi Electric Corp.; HITA: Hitachi Ltd.; SHMA: Shimadzu Corp.; TOKE: Toshiba Corp.; CNNU: China National Nuclear Corporation; USGO: National Nuclear Security Administration, which is an agency within the U.S. Department of Energy and is closely related to U.S. Department of Homeland Security; WESE: Westinghouse Electric Co., LLC.

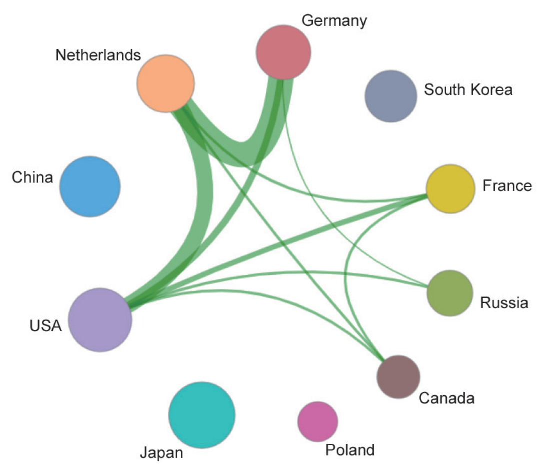

Figure 2.2.5 Collaboration network among major countries or regions in the engineering development front of "spent fuel reprocessing and nuclear facilities instrumentation"

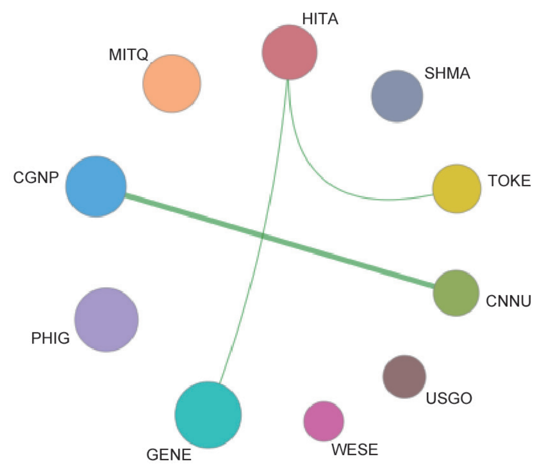

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of "spent fuel reprocessing and nuclear facilities instrumentation"

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