III. Chemical, Metallurgy & Materials Engineering

1 Engineering research fronts

1.1 Development trends in the top 12 engineering research fronts

The top 12 engineering research fronts assessed by the Field Group of Chemical, Metallurgy, and Materials Engineering are shown in Table 1.1.1. These fronts include the fields of new energy materials science and engineering, functional materials, composite materials and engineering, materials physics and chemistry, and catalysis. Among these top 12 research fronts, “development of novel fuel cells,” “nanoscale and high-performance metal materials,” “carbon dioxide fixation,” “photocatalysis for solar energy conversion, pollutant degradation, and organic synthesis,” “functionally graded nanomaterials,” “design and preparation of supercapacitors,” and “highly efficient electrocatalytic water splitting” are further developments of traditional existing research fields. However, “functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes functionalization and composites of nanocarbon materials,” “Li–O_2 and metal-air batteries,” “high-efficiency halide perovskite solar cells, luminescent materials, and sensitive detectors,” “new fluorescent molecular probes for bioimaging,” and “controllable synthesis, functionalization, and application of metal-organic framework (MOF) materials” are emerging fronts. The numbers of core papers published each year from 2012 to 2017 for each of the top 12 engineering research fronts are listed in Table 1.1.2.

(1) Functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes

There are numerous types of carbon materials, including charcoal, carbon black, graphite, diamond, linear carbon,

Table 1.1.1 Top 12 engineering research fronts in chemical, metallurgy and materials engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year	Percentage of consistently-cited papers	Patent-cited papers
1	Functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes	34	2 040	60.00	2015.94	50.0%	0.00
2	Development of novel fuel cells	49	1 023	20.88	2016.31	49.0%	0.00
3	Nanoscale and high-performance metal materials	1 834	238 535	130.06	2014.00	–	–
4	Carbon dioxide fixation	19	1 195	62.89	2015.16	26.3%	0.00
5	Lithium–O_2 and metal-air batteries	37	3 019	81.59	2015.19	62.2%	0.00
6	Photocatalysis for solar energy conversion, pollutant degradation, and organic synthesis	18	1 184	65.78	2016.28	50.0%	0.00
7	Functionally graded nanomaterials	40	2 767	69.18	2015.20	67.5%	0.00
8	Design and preparation of supercapacitors	47	2 903	61.77	2015.66	31.9%	0.00
9	Highly efficient electrocatalytic water splitting	21	2 455	116.90	2015.86	61.9%	0.00
10	High-efficiency halide perovskite solar cells, luminescent materials, and sensitive detectors	130	13 521	104.01	2015.91	55.4%	0.00
11	New fluorescent molecular probes for bioimaging	38	1 139	29.97	2015.71	28.9%	0.00
12	Controllable synthesis, function-oriented modification and application of metal-organic framework (MOF) materials	31	2 314	74.65	2015.23	41.9%	0.00

Table 1.1.2 Annual number of core papers published for each of the top 12 engineering research fronts in chemical, metallurgy, and materials engineering

No.	Engineering research front	2012	2013	2014	2015	2016	2017
1	Functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes	2	1	4	1	8	18
2	Development of novel fuel cells	0	1	0	6	18	24
3	Nanoscale and high-performance metal materials	302	367	489	419	216	41
4	Carbon dioxide fixation	1	0	3	9	3	3
5	Lithium–O_2 and metal–air batteries	0	5	5	9	14	4
6	Photocatalysis for solar energy conversion, pollutant degradation, and organic synthesis	0	0	0	1	11	6
7	Functionally graded nanomaterials	0	1	4	21	14	0
8	Design and preparation of supercapacitors	1	4	5	10	7	20
9	Highly efficient electrocatalytic water splitting	0	0	0	11	2	8
10	High-efficiency halide perovskite solar cells, luminescent materials, and sensitive detectors	0	0	7	36	49	38
11	New fluorescent molecular probes for bioimaging	0	0	0	17	15	6
12	Controllable synthesis, function-oriented modification and application of metal-organic framework (MOF) materials	1	3	4	6	14	3

carbon fiber, vitreous carbon, graphite intercalation compounds, fullerenes, carbon nanotubes, and graphene. Carbon nanotubes and graphene have been state-of-the-art materials in research over the past decade. Graphene nanosheet is a new material with a hexagonal scrobiculate-type lattice with a laminated structure composed of carbon atoms with an sp^2 hybridized orbit. Graphene nanosheets can be folded to form carbon nanotubes (a one-dimensional tubular nanostructured carbon material). Both graphene and carbon nanotubes have excellent mechanical, thermal, and electrical properties; however, well-proportioned composite materials cannot be produced using these materials due to their unique small-size effects, surface effects, and strong Van der Waals forces that make them prone to self-agglomeration during preparation of composite materials. On the other hand, their hydrophobic and oleophobic behavior and the chemical inertness of their surfaces result in poor compatibility with other materials, and hence, a low interfacial bonding strength of the composite materials. Thus, functional modification of the carbon materials should be conducted; i.e., introducing heteroatoms or heteroatom functional groups inside or on the surface of the graphite lattice of the nanocarbon material. Functionalization can modify and modulate the electronic structure of carbon atoms in graphite, thereby changing their physicochemical properties, and subsequently improving the processability of nanocarbon materials during the preparation of composite materials.

(2) Development of novel fuel cells

Fuel cells are chemical devices that directly convert chemical energy into electrical energy. Fuel cells are considered the fourth-generation energy technology after thermal power, hydraulic power, and nuclear power generation technology. Fuel cells are considered the most promising green power generation technology from the perspective of saving energy and protecting the ecological environment. Hydrogen is the most commonly used fuel in fuel cells as it has a high energy conversion rate, low emission, high energy density, and high power density. However, 96% of the global hydrogen production is still from nonrenewable sources; some drawbacks of hydrogen energy include transportation and storage, and a lack of supporting infrastructure, which limit large-scale application of fuel cells. Therefore, the development of fuel cells has become a hot research topic, for ① identifying new alternative fuels (e.g., glycol, acetylene glycol, and formic acid) and studying their electro-oxidation mechanism; ② investigating new methods for preparing and modifying newly developed electrocatalytic materials with high performance, long lifetime, and low cost; ③ design and development of a new type of flexible fuel cell with high energy and power densities; and ④ elucidating the mechanism and application of electrocatalysis in the production of high value-added chemicals.

(3) Nanoscale and high-performance metal materials

Development of nanoscale and high-performance metal materials (nanometals) and improvement of their comprehensive performance will greatly promote further rapid development of the industry. The mechanical, electromagnetic, and optical properties of metallic materials are closely related to their grain size. Grain nanocrystallization is an effective way to improve the overall performance of nanometals, as they are composed of nano-sized grains. Research in this area mainly includes material selection, preparation, and characterization of their properties. Currently, nanopreparation is only used for some metal materials, but the size of the prepared nanometal materials is small, have many defects inside the materials, and the preparation process is complicated. Therefore, the development of nanometal preparation processes that can be used for industrial applications will have great potential applicability.

Preparing high-performance nanometals is a hotspot for future research, especially the preparation of bulk nanomaterials. Although this involves many challenges, breakthroughs in the preparation of materials with high strength, superplasticity, and good electromagnetic and chemical properties are expected in the future. Development work is expected to focus on the preparation of surface nanomaterials and bulk nanomaterials and their application in engineering research.

(4) Carbon dioxide fixation

Although 110 million tons of CO_2 are currently used for the production of chemicals each year, and the industrial production of urea, salicylic acid, methanol, cyclic carbonates, and polycarbonates accounts for the majority. Other technologies for converting and using CO_2 are mostly in the research stage. CO_2 is the most stable carbon oxide, which easily reacts with strong nucleophiles to form C–C and C–H; however, it is still challenging to achieve efficient conversion with inactive substrates under mild conditions. The synthesis of cyclic carbonates and their polymers from CO_2 and epoxides is an effective method for CO_2 fixation; ethylene carbonate and bisphenol A polycarbonate have been industrially produced. Catalyst systems developed for this useful conversion process include metal complexes (e.g., Al, Zn, Co, and Mg), organic amines, and metal oxides. Although many homogeneous catalysts are highly efficient for the synthesis of cyclic carbonates, their limited recyclability has impeded large-scale industrial application. In order to address this problem, the development of highly efficient heterogeneous catalysts has become a research hotspot, which will further promote the industrialization of cyclic carbonate production. Ammonia methylation and carbamylation processes are other ways to fix CO_2, which involve the reduction of CO_2 and the formation of C–N. According to previous reports, the market value of methylamines (such as $MeNH_2$, Me_2NH, and Me_3N) exceeds 4000 Euro/ton. Therefore, aminomethylation using CO_2 as a C1 feedstock can create a value-added product. CO_2 can also be used in carboxylation and carbonylation processes. The former involves CO_2 activation by a nucleophilic reagent into a carboxylated product, while the latter includes in situ reduction of CO_2 to CO, followed by carbonylation. Although these two types of CO_2 fixation strategies provide new opportunities for carbonylation and carboxylation, the current catalytic systems suffer from limited activity and the need for harsh processing conditions. Therefore, it is desirable to develop highly efficient catalysts to achieve CO_2 conversion using these processes.

(5) Li–O_2 and metal–air batteries

Metal–air batteries are electrochemical energy storage/conversion devices that use metal as an anode and oxygen as a cathode. Because the oxygen is obtained from the ambient air, the metal–air battery performs at a higher energy density than traditional batteries, making it suitable for a broad range of potential applications in electric vehicles and electrical grid energy storage. Recently, research and development (R&D) advances have been mostly dedicated to Li–air, Zn–air, Al–air, and Mg–air batteries.

Research areas in metal–air batteries (lithium–air for example) include development of bifunctional oxygen reduction/evolution catalysts and explanation of the corresponding reaction mechanism; mechanism of decay of catalytic activity and stability of the catalyst; design of the architecture of the oxygen electrode, lithium/electrolyte interface, and lithium dendrite; corrosion and protection of lithium; synthesis of electrolytes; structural design and manufacture of the batteries; and system integration.

Trends in the development of metal–air batteries include elucidation of the mechanisms of the electrode reaction and ion transfer via in situ characterization techniques; improving models and algorithms to more closely replicate real conditions; creating controllable methods for preparing the material and electrode; and the development of high-efficiency integrated battery systems and low-energy-consumption smart management systems.

(6) Photocatalysts for solar energy conversion, pollutant degradation, and organic synthesis

In photocatalytic processes, highly active electrons and holes, or excited molecules, are generated by the excitation of absorbed photons, which can drive thermodynamically uphill reactions and accelerate downhill reactions. Photocatalysis (including particulate photocatalysis and photoelectrocatalysis) is extensively investigated for solar energy conversion, pollutant degradation, and organic synthesis involving redox reactions.

The total efficiency of photocatalysis is the product of the efficiencies of light absorption, separation of photogenerated carriers, and the catalytic reaction. In order to improve the efficiency of sunlight conversion, novel materials for harvesting light, such as oxides with a wide absorption band, as well as (oxy)nitride, chalcogenide, and (oxy)halide semiconductors are emerging as promising candidates. Several charge separation mechanisms have been proposed and devices are being developed based on heterojunctions, phase junctions, donor-acceptor materials, and facet charge separation. In addition to water splitting and pollutant degradation, several new catalytic reactions, such as photocatalytic CO_2 reduction, ammonia synthesis, and fabrication of high value-added organic products, are becoming research fronts. Such research includes the effects of surface structure, the function of the co-catalyst, and design of new co-catalysts.

(7) Functionally graded nanomaterials

Over the past 30 years, a novel method for developing high-strength materials has been investigated. This technique involves the nanocrystallization of structural materials with much higher strength and hardness than traditional coarse crystalline materials due to the high number of grain boundaries and other interfaces. However, along with these improvements, the plasticity and toughness of the material are greatly reduced, resulting in a degradation of the work hardening ability and stability of the structure. Therefore, further development of nanoscale materials is challenging. To address these problems, the concept of functionally graded nanomaterials has been proposed. This concept refers to continuous changes in the components, structures, and single or compound physical, chemical, and biological properties, with the aim of tailoring the properties and functions of the material to adapt to different environments. For example, a new material with particular functions can be achieved via changing the intensity, diffusion rate, and chemical reaction activity over a large range. The focus of the present research is the development of preparation methods for functionally graded nanomaterials, which can be classified as follows: ① simple and maneuverable powder metallurgy technology; ② self-propagating high-temperature synthesis method for producing high-purity nanomaterials with high efficiency; ③ a wide range of laser cladding methods; ④ gas-phase precipitation method that can produce precise shapes; and ⑤ graded plastic deformation methods that can introduce a large number of defects.

Functionally graded nanoscale materials have created new challenges and opportunities in the development of new materials and processing technologies. On the one hand, it is important to understand the relationship between the structure and performance of the functionally graded nanomaterials, the difference in the deformation mechanism at all levels, and the morphology difference between homogeneous structures. In addition, deeper understanding of the thermal, mechanical, and chemical stability is required. On the other hand, the efficiency, convenience, and cost of the preparation process will be crucial for determining potential applications and allowing further development of functionally graded nanomaterials.

(8) Design and preparation of supercapacitors

Supercapacitors contain passive energy-storage elements that have a high power density. They have many advantages, such as quick charging and discharging, high efficiency, long cycle life, a wide range of operating temperature, and good reliability. Their superior performance and broad range of potential applications have attracted worldwide attention. Electrochemical supercapacitors are energy-storage devices that rely on the principle of an electric double layer or faradaic pseudocapacitance, where their biggest advantages are excellent pulse charge and discharge performance, as well as fast charge and discharge performance. Current studies of supercapacitors are mainly divided into two groups: ① flexible miniaturized supercapacitors for wearable devices; and ② supercapacitors with a high energy density for large-scale energy storage and mobile power. The development of flexible miniaturized supercapacitors is still in its infancy, mainly focusing on the development of flexible electrode materials and electrolytes. Meanwhile, device packaging and encapsulation technology for supercapacitors need to be developed and tailored for the different electrode materials. Conventional sandwich-shaped supercapacitors (with relatively mature packaging technology) are predominantly studied for the development of high-energy-density electrode materials and high-pressure electrolytes.

(9) Highly efficient electrocatalytic water splitting

Electrocatalytic water splitting is a sustainable method for producing hydrogen, which has attracted much research attention. The process involves the two half reactions of water oxidation (evolution of oxygen) and water reduction (evolution of hydrogen). Although the overpotentials for the hydrogen evolution reaction (HER) and oxygen evolution reaction (OER) are relatively high under pH neutral conditions, there is considerable interest in this system due to its mild conditions; the overpotentials can be somewhat reduced by using a pH buffer pair like phosphates and borates. On the other hand, many studies have been carried out using a low loading of noble metal catalysts and non-noble-metal catalysts, including (hydr)oxides, chalcogenides, and nitrides and phosphides of Fe, Co, and Ni. Many non-noble-metal electrocatalysts have similar HER performance to noble-metal electrocatalysts, while some even surpass noble metal electrocatalysts for the OER under alkaline conditions. There are two strategies for improving the activity of HER and OER electrocatalysts. The first is to improve the dispersion and increase the amount active sites by producing small particles with selective facets, core-shell structures, or 3D porous structures. The other strategy is to enhance the intrinsic activity of active sites via the introduction of a new crystal or surface structure, or by taking advantage of the cooperativity of metal elements and modulation of nonmetal elements.

(10) High-efficiency halide perovskite solar cells, luminescent materials, and sensitive detectors

$APbX_3$ is the typical formula of halide perovskites, where A is a cation such as methylammonium, formamidinium, or Cs^+; X refers to I, Br, or Cl; and Pb can be substituted by other metals such as Sn, Bi, Sb, and Ag. In the broad definition, non-ABX_3 type layered perovskites are also included, such as A_2PbX_4 and $A_3Bi_2X_9$. Halide perovskite solar cells have advantages of high efficiency, low cost, and simple fabrication methods, making them one of the state-of-the-art research topics in the field of solar cell. By controlling the crystal growth in the film, defects, and interfaces for electron and hole transport, the photoconversion efficiency of small-area halide perovskite solar cells have exceeded 22%. The development of large-area cells and long-term durability of the cell are key focuses in the current research. Based on the excellent photoelectric properties of halide perovskites, some new halide perovskite materials have shown excellent luminescence performance or potential as sensitive irradiation detectors; these topics are attracting increasing research attention.

(11) New fluorescent molecular probes for bioimaging

Fluorescent probes can identify and mark target molecules using fluorescence signals (e.g., wavelength, intensity, and lifetime). With the development of cell biology, molecular biology, and dye chemistry (especially considering the widespread applications and importance of fluorescent proteins in biology), the field of fluorescence probes is focusing on more precise marking of target molecules, including the use of protein labels, synthetic amino acids, biological intersection reactions (click chemistry), and other techniques. The performance of the fluorescent groups can be greatly improved considering the fluorescence intensity, optical stability, polychromatic wavelength, and Stocks shift. The understanding and use of new fluorescence response mechanisms and accurate analysis of fluorescence signals has been rapidly developing. The focus of fluorescence probe research includes achieving a breakthrough in the diffraction limit of the space resolution, increasing the time resolution for real-time live imaging, and increasing the specificity of the response. Such challenges are being addressed for practical applications, such as fluorescence-guided surgery.

(12) Controllable synthesis, functionalization, and application of MOF materials

MOF materials are composed of metal ions (or clusters) bridged by organic linkers and are a novel subclass of porous organic–inorganic hybrid materials. MOF materials have remarkable advantages over traditional inorganic porous materials considering the wide range of possible chemical compositions and architectures. The past decade has seen explosive growth in the study of MOF materials. Three topics in the MOF field are of particular interest: ① controllable synthesis of MOF materials, including computational design of the composition and architecture, high throughput synthesis and characterization of MOF crystals, and manipulation of the morphology without changing the underlying topology. ② Application-oriented post-synthesis modification of MOF materials, including metal/linker substitution, covalent post-synthesis modification, confinement, pore modulation, hybridization, and hierarchical nanostructure assemblies. ③ Application of MOF materials in fields including CO_2 capture, hydrocarbon storage, adsorption and membrane separation, catalysis, sensors, drug delivery, and photoelectrochemistry. In the future, synthesis of MOFs with reticular structures is expected to focus on the deliberate design and assembly of MOF components, rather than the haphazard trial-and-error method currently used. Efforts in this direction are already being undertaken, which are employing many different feasible strategies, including design and modification of microstructures, tailoring the pore size, and decoration of secondary building units to produce far more sophisticated MOF materials.

MOF materials have a wide range of potential uses, where two in particular are thought to be promising in the near future: ① Adsorbents and separation membranes. It is expected that substantial efforts will be devoted to constructing MOF-based adsorbents and separation membranes in the search for alternative energy-efficient and environmentally friendly separation of H_2, CO_2, CH_4, petroleum-based platform chemicals, biomass-based platform chemicals, and pharmaceutical intermediates, along with the pollutant removal and desalination. ② Functional devices. The ability to integrate MOFs with other functional materials in a miniaturized fashion would allow the development of portable multifunctional devices for applications in medicine, electronics, and optics, as well as microreactors.

1.2 Interpretations for three key engineering research fronts

1.2.1 Functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes

Research into graphene and carbon nanotubes is a hotspot in materials science and related fields. Studies have shown that graphene, carbon nanotubes, and their composite materials have broad potential applications in the fields of electronics, information technology, energy, materials, and biomedicine, and are expected to initiate a new technological revolution in the 21st century. Nanocarbon composites mainly include carbon/polymer composites, carbon/nanoparticle composites, and carbon/carbon composites. Neither graphene nor carbon nanotubes can produce well-proportioned composite materials due to their unique small size effect, surface effect, and strong Van der Waals forces, which make them prone to self-agglomeration during the preparation of composite material. On the other hand, their hydrophobic and oleophobic behavior, as well as the chemical inertness of their surfaces result in poor compatibility with other materials and hence, a low interfacial bonding strength of the composite materials. Thus, functional modification of the carbon materials should be conducted; that is, introducing heteroatoms or heteroatom functional groups inside or on the surface of the graphite lattice of the nanocarbon material. Functional modification can modify and modulate the electronic structure of carbon atoms in graphite, thereby changing their physicochemical properties, and subsequently improving the processability of nanocarbon materials during the preparation of composite materials.Recently, many innovations in the preparation of graphene and carbon nanotube composite materials have been related to the modification of the carbon materials in order to optimize the structures (and hence, performance) of the composite materials. The functionalization of graphene can be broadly divided into mechanisms involving covalent bonding or noncovalent bonding. Covalent-bonding functionalization is mainly used to oxidize carbon materials, producing a large number of oxygen-containing groups (e.g., carboxyl, hydroxy, and epoxy groups), which are highly reactive and facilitate covalent modification. To date, surface functionalization of graphite has been achieved using reagents such as isocyanate, silane coupling agents, and organic amine. Noncovalent bonding functionalization changes the surface properties of a carbon material and improves its dispersibility in water or nonpolar solutions by facilitating physical adsorption or polymer encapsulation on the surface. Since physical adsorption and polymer encapsulation have no detrimental effects on the inherent structure of graphene or carbon nanotubes, their structure and properties can be maintained to a large extent.

Carbon nanocomposites using graphene and carbon nanotubes have excellent performance and show unique advantages for various applications. However, industrial application of these materials is still relatively limited as the preparation of the corresponding composite materials needs further development. The limitations of the current preparation methods for composite materials are a major bottleneck in the development of carbon materials science. The research institutions predominantly involved in this research are in China, the United States, and India. The institutes are collaborating and analyzing relevant laws in the preparation of composite materials from different perspectives. This is expected to greatly improve their output and lay the foundation for the industrial production and application of graphene, carbon nanotubes, and other nanocarbon composite materials, allowing these materials to enter the daily life of the consumer.

Countries or regions and institutions with the greatest output of core papers on the "functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes" are listed in Table 1.2.1 and Table 1.2.2, respectively. Countries or regions and institutions with the greatest output of citing papers on the "functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes" are summarized in Table 1.2.3 and Table 1.2.4. The collaboration network among major countries or regions and institutions in the engineering research front of "functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes" are illustrated in Figure 1.2.1 and Figure 1.2.2.

1.2.2 Development of novel fuel cells

Fuel cells are the fourth generation of power produce technology after thermal power, hydropower, and nuclear power technology. Fuel cells are considered as the top ten "high-tech" field of the 21st century in the USA, and have been hailed as a new global power source. A fuel cell converts chemical energy directly into electricity via an electrochemical reaction within the cell. In addition, there is no mechanical transmission of energy within fuel cells; therefore, they produce little noise and have high reliability. In theory, continuous conversion of chemical energy to electric energy can be achieved in fuel cells if the fuel and oxidizer can be constantly supplied.

Hydrogen is an ideal fuel for fuel cells as it has a high energy conversion rate, high energy and power densities, and fast electric oxidation rate. However, 96% of the global hydrogen production is from nonrenewable resources. In addition, the transportation and storage of hydrogen are problematic, and there is a lack of supporting infrastructure, which greatly

Table 1.2.1 Countries or regions with the greatest output of core papers on the "functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	13	38.24%	356	17.45%	27.38
2	China	12	35.29%	367	17.99%	30.58
3	Australia	10	29.41%	1 371	67.21%	137.10
4	India	5	14.71%	272	13.33%	54.40
5	South Korea	4	11.76%	377	18.48%	94.25
6	Italy	3	8.82%	72	3.53%	24.00
7	Germany	2	5.88%	23	1.13%	11.50
8	Spain	2	5.88%	24	1.18%	12.00
9	France	2	5.88%	22	1.08%	11.00
10	Israel	1	2.94%	16	0.78%	16.00

Table 1.2.2 Institutions with the greatest output of core papers on the “functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Univ Tennessee	11	32.35%	334	16.37%	30.36
2	Univ Sydney	10	29.41%	1 371	67.21%	137.10
3	Shandong Univ Sci & Technol	9	26.47%	251	12.30%	27.89
4	Univ Ulsan	4	11.76%	377	18.48%	94.25
5	Shandong Univ	3	8.82%	352	17.25%	117.33
6	Pusan Natl Univ	2	5.88%	227	11.13%	113.50
7	Humboldt Univ	2	5.88%	23	1.13%	11.50
8	Avanzare Innovac Tecnol SL	2	5.88%	24	1.18%	12.00
9	Instit Italiano Tecnol	2	5.88%	24	1.18%	12.00
10	Politecn Torino	2	5.88%	24	1.18%	12.00

Table 1.2.3 Countries or regions with the greatest output of citing papers on the “functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes”

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	409	49.34%	2016.78
2	India	102	12.30%	2016.80
3	USA	99	11.94%	2016.96
4	Iran	53	6.39%	2016.91
5	South Korea	50	6.03%	2016.06
6	Spain	26	3.14%	2016.42
7	Australia	25	3.02%	2016.40
8	Italy	25	3.02%	2016.04
9	UK	20	2.41%	2016.85
10	Turkey	20	2.41%	2016.95

Table 1.2.4 Institutions with the greatest output of citing papers on the “functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Univ Tennessee	41	20.20%	2017.24
2	Chinese Acad Sci	38	18.72%	2016.71
3	Shandong Univ Sci & Technol	28	13.79%	2017.29
4	Sichuan Univ	20	9.85%	2017.24
5	Harbin Inst Technol	16	7.88%	2016.94
6	Univ Sydney	13	6.40%	2015.92
7	Shandong Univ	13	6.40%	2017.24
8	Tsinghua Univ	12	5.91%	2016.75
9	Tianjin Univ	11	5.42%	2017.29
10	Indian Inst Tech	11	5.42%	2016.55

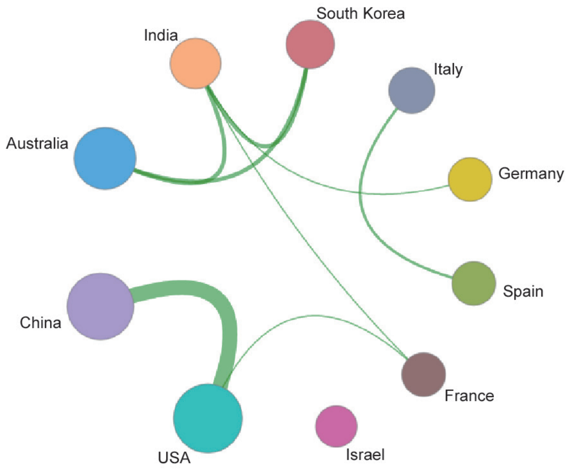

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of "functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes"

limits the promotion and popularization of hydrogen fuel cell applications. Therefore, the development of new types of fuels has become a research hotspot in the field. Toyota has begun developing a fuel-cell system using natural gas as a fuel. The first step in using natural gas as a fuel is to decompose it into hydrogen and carbon monoxide. Then, compressed air is added to the gas mixture, and electricity is generated via a chemical reaction in the fuel cell stack. This process produces some hydrogen and carbon monoxide, which is burnt using a small gas turbine to produce more electricity. Finally, additional electricity is generated using the waste heat via an automotive power generation system. The efficiency of this natural gas fuel cell system was predicted to be 65%. In addition, ethylene glycol, acetylene glycol, formic acid, and other fuels are widely used and studied as alternatives to hydrogen fuel.

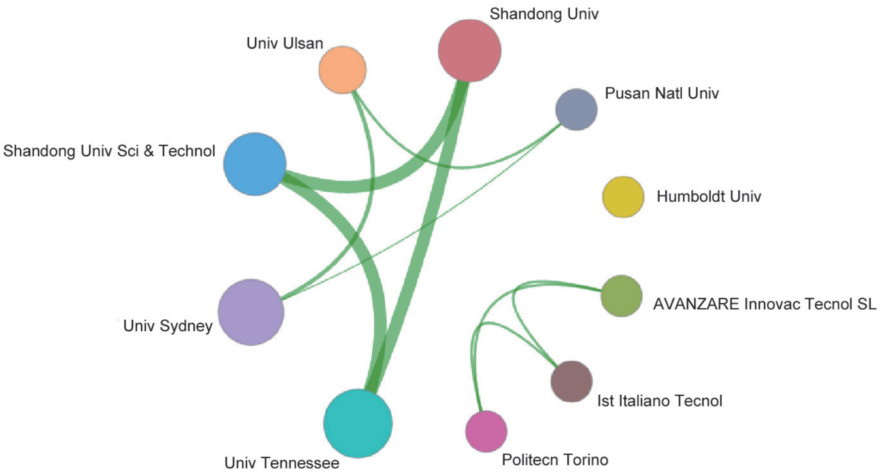

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes"

The catalyst is another key material for fuel cells. The most widely used fuel-cell catalyst is platinum, which has two fatal drawbacks, it is expensive and easy to poison; therefore, there is an urgent need to develop novel alternative catalysts in order to promote the development of fuel cell technology. In 2017, Nisshinbo developed a new catalyst using carbon alloy instead of platinum, which decreased the material cost of the fuel cell by a factor of 1000. For the first time, they successfully realized practical application of a fuel cell without a platinum catalyst. Electrocatalytic oxidation and reduction is a key step to energy conversion in fuel cells, where it is of great significance to exploit the synthesis of highly value-added chemicals using electrocatalysis. For example, the preparation of chemicals and energy materials via electrocatalytic reduction of CO_2 can enable the use of CO_2 as a feedstock and effective storage of clean electric energy.

China has recently issued several policies to support the development of fuel cell technology, including the *Made in China 2025* document published by the Ministry of Industry and Information Technology, China's 13th Five-Year Development Plan, *Action Plan for Energy Technology Revolution and Innovation (2016–2030)*, and *Road Map for Key Innovation Initiatives in the Energy Technology Revolution* documents released by the National Development and

Reform Commission and the National Energy Administration. These policies clearly supported hydrogen energy and fuel cell innovation, and promoted increasing the engineering and industrial capacity of core technologies, such as fuel cells.

Countries or regions and institutions with the greatest output of core papers on the "development of novel fuel cells" are listed in Table 1.2.5 and Table 1.2.6, respectively. Countries or regions and institutions with the greatest output of citing papers on the on the "development of novel fuel cells" are summarized in Table 1.2.7 and Table 1.2.8. The collaboration network among major countries or regions and institutions in the engineering research front of "development of novel fuel cells" are illustrated in Figure 1.2.3 and Figure 1.2.4.

1.2.3 Nanoscale and high-performance metal materials

The preparation of metal materials with improved performance is responding to the needs of the ever-expanding industrial sector. Since the 1980s, nanometals have gradually attracted global attention due to their unique performance and broad range of potential applications, and are expected to be a core part of the industrial revolution of the next century. Currently, the development focus in the nanometal materials field is related to metal surface nanocrystallization and preparation of bulk nanomaterials, resulting in the development of a series of high-performance metal materials. The core technology of nanometal research is the nanopreparation of metal materials, including electrolytic deposition, powder metallurgy, and mechanical processing (e.g., large plastic deformation and shot peening) methods. However, these preparation processes can be complicated and easily produce defects in the material. Currently, many groups are investigating surface modification of nanometals (i.e., graded nanometal materials), which improve the mechanical, friction, wear, and corrosion properties of the materials to some extent. However, there are still limitations in the processing of bulk nanometal

Table 1.2.5 Countries or regions with the greatest output of core papers on the "development of novel fuel cells"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	44	89.80%	914	89.35%	20.77
2	Japan	7	14.29%	63	6.16%	9.00
3	USA	5	10.20%	217	21.21%	43.40
4	India	2	4.08%	53	5.18%	26.50
5	Canada	2	4.08%	16	1.56%	8.00
6	Denmark	1	2.04%	13	1.27%	13.00
7	Spain	1	2.04%	15	1.47%	15.00

Table 1.2.6 Institutions with the greatest output of core papers on the "development of novel fuel cells"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Soochow Univ	22	44.90%	431	42.13%	19.59
2	Chinese Acad Sci	10	20.41%	227	22.19%	22.70
3	Univ Chinese Acad Sci	6	12.24%	146	14.27%	24.33
4	Taiyuan Univ Technol	5	10.20%	180	17.60%	36.00
5	Tokyo Univ Sci Yamaguchi	5	10.20%	41	4.01%	8.20
6	Zhejiang Normal Univ	4	8.16%	47	4.59%	11.75
7	Shandong Univ	4	8.16%	156	15.25%	39.00
8	Peking Univ	4	8.16%	156	15.25%	39.00
9	Xiamen Univ	2	4.08%	57	5.57%	28.50
10	SUNY Stony Brook	2	4.08%	98	9.58%	49.00

Table 1.2.7 Countries or regions with the greatest output of citing papers on the “development of novel fuel cells”

No.	Country/Region	Citing core papers	Percentage of citing papers	Mean year
1	China	354	64.48%	2016.80
2	USA	66	12.02%	2016.76
3	Japan	25	4.55%	2016.56
4	India	20	3.64%	2016.90
5	South Korea	20	3.64%	2016.85
6	Iran	18	3.28%	2016.50
7	Canada	17	3.10%	2017.24
8	Australia	10	1.82%	2016.70
9	Germany	10	1.82%	2016.30
10	France	9	1.64%	2016.56

Table 1.2.8 Institutions with the greatest output of citing papers on the “development of novel fuel cells”

No.	Institution	Citing core papers	Percentage of citing papers	Mean year
1	Soochow Univ	52	22.81%	2016.96
2	Chinese Acad Sci	51	22.37%	2016.76
3	Univ Chinese Acad Sci	24	10.53%	2016.54
4	Zhejiang Normal Univ	19	8.33%	2017.11
5	Shandong Univ	19	8.33%	2016.50
6	Univ Sci & Technol China	15	6.58%	2017.00
7	Peking Univ	14	6.14%	2017.00
8	Xiamen Univ	12	5.26%	2016.83
9	Beijing Univ Chem Technol	11	4.82%	2017.18
10	Univ Toronto	11	4.82%	2017.27

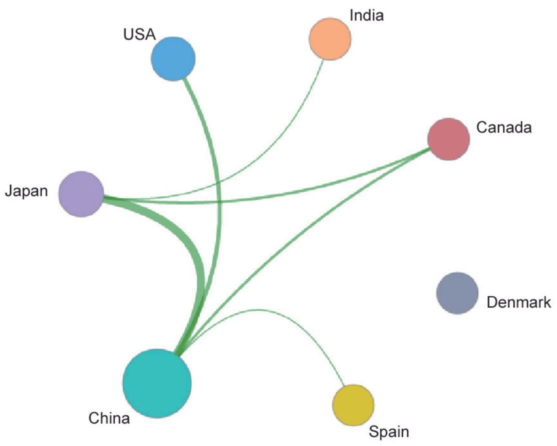

Figure 1.2.3 Collaboration network among major countries in the engineering research front of “development of novel fuel cells”

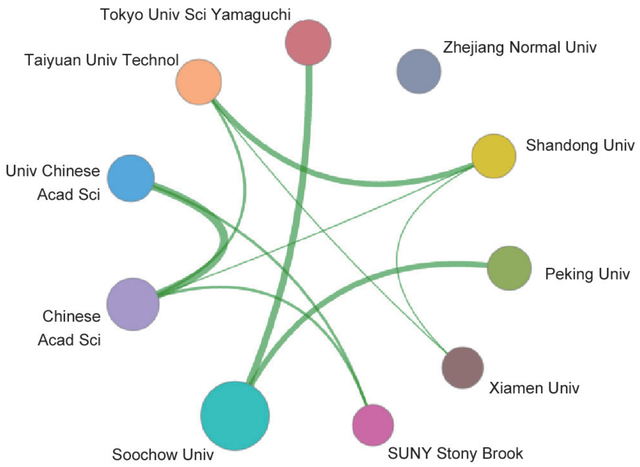

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of “development of novel fuel cells”

materials and development of preparation processes that can be up-scaled to provide opportunities for industrial applications.

The top ten countries and institutions producing core papers in the “nanoscale and high-performance metal materials” field since 2012 are listed in Table 1.2.9 and Table 1.2.10, respectively. The cooperation between these countries and institutions are shown in Figure 1.2.5 and Figure 1.2.6, respectively. The top countries or institutions that have cited the chosen core papers are shown in Table 1.2.11 and Table 1.2.12, respectively. Nanometal research mainly focuses on nanofabrication and characterization of metal materials, while a few groups have studied nanofabrication of bulk materials. The majority of the core papers were published by the top three countries (China, the USA, and Singapore). China’s output of core papers accounted for 48.80% of the total, while the number of core papers from the USA accounted for 28.90%. China and the USA have the highest level of collaboration, followed by Singapore, Australia, and China, then South Korea, Japan, and the USA. The Chinese Academy of Sciences has the most core papers of any institute, followed by Nanyang Technological University in Singapore. There is also a lot of collaboration between the Chinese Academy of Sciences with University of Science and Technology of China, Tsinghua University; between National University of Singapore with Zhejiang University, and Nanyang Technological University. The top country with the greatest output of citing papers is the same as the country that

Table 1.2.9 Countries or regions with the greatest output of core papers on the “nanoscale and high-performance metal materials”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	895	48.80%	109 180	45.77%	121.99
2	USA	530	28.90%	76 486	32.06%	144.31
3	Singapore	139	7.58%	23 576	9.88%	169.61
4	South Korea	137	7.47%	18 388	7.71%	134.22
5	Australia	110	6.00%	14 207	5.96%	129.15
6	Germany	104	5.67%	17 550	7.36%	168.75
7	Japan	99	5.40%	13 131	5.50%	132.64
8	UK	70	3.82%	9 074	3.80%	129.63
9	India	58	3.16%	5 315	2.23%	91.64
10	Saudi Arabia	41	2.24%	4 963	2.08%	121.05

Table 1.2.10 Institutions with the greatest output of core papers on the “nanoscale and high-performance metal materials”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Chinese Acad Sci	164	8.94%	22 160	9.29%	135.12
2	Nanyang Technol Univ	97	5.29%	19 330	8.10%	199.28
3	Univ Sci & Technol China	53	2.89%	6 653	2.79%	125.53
4	Tsinghua Univ	46	2.51%	6 014	2.52%	130.74
5	Zhejiang Univ	38	2.07%	5 182	2.17%	136.37
6	Natl Univ Singapore	37	2.02%	4 158	1.74%	112.38
7	Fudan Univ	37	2.02%	3 720	1.56%	100.54
8	Stanford Univ	35	1.91%	7 042	2.95%	201.20
9	Argonne Natl Lab	33	1.80%	5 248	2.20%	159.03
10	Univ Calif Berkeley	33	1.80%	4 061	1.70%	123.06

Table 1.2.11 Countries or regions with the greatest output of citing papers on the "nanoscale and high-performance metal materials"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	24 269	45.61%	2015.66
2	USA	10 946	20.57%	2015.53
3	South Korea	4 440	8.34%	2015.48
4	Germany	2 459	4.62%	2015.57
5	Japan	2 279	4.28%	2015.51
6	UK	1 949	3.66%	2015.71
7	Australia	1 931	3.63%	2015.71
8	Singapore	1 927	3.62%	2015.43
9	India	1 910	3.59%	2015.65
10	France	1 102	2.07%	2015.55

Table 1.2.12 Institutes with the greatest output of citing papers on the "nanoscale and high-performance metal materials"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Acad Sci	4 449	36.19%	2015.57
2	Univ Chinese Acad Sci	1 174	9.55%	2015.89
3	Nanyang Technol Univ	1 142	9.29%	2015.38
4	Tsinghua Univ	1 028	8.36%	2015.69
5	Univ Sci & Technol China	820	6.67%	2015.68
6	Peking Univ	783	6.37%	2015.70
7	Zhejiang Univ	780	6.34%	2015.58
8	Soochow Univ	745	6.06%	2015.78
9	Huazhong Univ Sci & Technol	717	5.83%	2015.68
10	Natl Univ Singapore	657	5.34%	2015.46

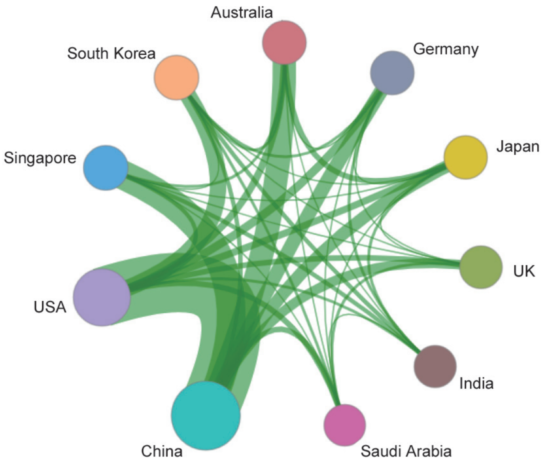

Figure 1.2.5 Collaboration network among major countries in the engineering research front of "nanoscale and high-performance metal materials"

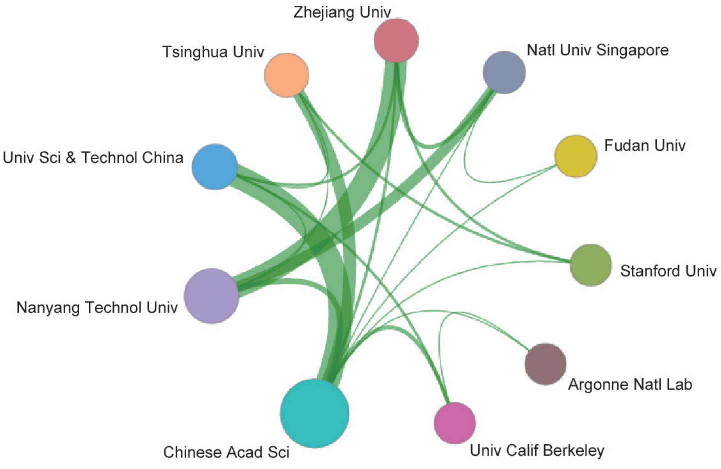

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "nanoscale and high-performance metal materials"

published the highest number of core papers, China. Similarly, the top institute with the greatest out of citing the core papers is the same one that published the highest number core papers, Chinese Academy of Science.

Countries or regions and institutions with the greatest output of core papers on the "nanoscale and high-performance metal materials" are listed in Table 1.2.9 and Table 1.2.10, respectively. Countries or regions and institutions with the greatest output of citing papers on the on the "nanoscale and high-performance metal materials" are summarized in Table 1.2.11 and Table 1.2.12. The collaboration network among major countries or regions and institutions in the engineering research front of "nanoscale and high-performance metal materials" are illustrated in Figure 1.2.5 and Figure 1.2.6.

2 Engineering development fronts

2.1 Development trends in the top 12 engineering development fronts

The top 12 engineering development fronts assessed by the Field Group of Chemical, Metallurgy, and Materials Engineering are shown in Table 2.1.1. These topics include new energy materials science and engineering, functional materials, composite materials and engineering, metal materials engineering, catalysis engineering, metallurgical engineering, and cell biology engineering. Among these development fronts, "green and intelligent metallurgical manufacturing processes," "preparation and application of light metal alloys," "advanced processing of rare and precious metals," "catalytic conversion of fossil resources and biomass," "key materials and technology for large-scale energy storage," "key technologies and materials for supercapacitor," "new-generation high-energy Li–S batteries and solid-state Li batteries," and "preparation, structural connections, and applications of advanced composites" are further developments of traditional fields. However, "crystal engineering and large-scale applications of metal-organic framework (MOF) materials," "key methods for preparing graphene-based functional materials and their application in energy storage," "development and application of additive manufacturing (3D printing)," and "cell therapy" are emerging fronts. The annual numbers of patents published within these fields from 2012 to 2017 are shown in Table 2.1.2.

Table 2.1.1 Top 12 engineering development fronts in chemical, metallurgy, and materials engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Key materials and technology for large-scale energy storage	503	991	1.97	2014.68
2	Catalytic conversion of fossil resources and biomass	154	310	2.01	2014.73
3	Green and intelligent metallurgical manufacturing processes	981	1 103	1.12	2014.57
4	Development and application of additive manufacturing (3D printing)	338	8 417	24.90	2014.12
5	Preparation, structural connections, and applications of advanced composites	196	6 487	33.10	2013.91
6	Key technologies and materials for supercapacitors	609	1 573	2.58	2015.12
7	New-generation high-energy Li–S batteries and solid-state Li batteries	579	991	1.71	2015.67
8	Key methods for preparing graphene-based functional materials and their application in energy storage	853	1 825	2.14	2015.33
9	Preparation and application of light metal alloys	165	2 967	17.98	2013.52
10	Crystal engineering and large-scale applications of metal-organic framework (MOF) materials	590	1 084	1.84	2015.67
11	Advanced processing of rare and precious metals	170	333	1.96	2014.67
12	Cell therapy	237	398	1.68	2014.73

Table 2.1.2 Annual number of core patents published for the top 12 engineering development fronts in chemical, metallurgy, and materials engineering

No.	Engineering development front	2012	2013	2014	2015	2016	2017
1	Key materials and technology for large-scale energy storage	66	77	91	84	87	98
2	Catalytic conversion of fossil resources and biomass	17	30	25	26	28	18
3	Green and intelligent metallurgical manufacturing processes	118	185	193	159	155	171
4	Development and application of additive manufacturing (3D printing)	54	60	87	86	29	22
5	Preparation, structural connections, and applications of advanced composites	43	42	32	49	28	2
6	Key technologies and materials for supercapacitors	63	61	93	121	98	138
7	New-generation high-energy Li–S batteries and solid-state Li batteries	28	43	57	107	125	166
8	Key methods for preparing graphene-based functional materials and their application in energy storage	58	85	97	143	216	254
9	Preparation and application of light metal alloys	43	53	32	18	16	3
10	Crystal engineering and large-scale applications of metal-organic framework (MOF) materials	20	44	64	119	131	160
11	Advanced processing of rare and precious metals	24	31	26	23	28	38
12	Cell therapy	32	39	28	40	58	40

(1) Key materials and technology for large-scale energy storage

Currently, large-scale energy storage technologies mainly include pumped hydro storage, compressed air, flow batteries, lithium-based batteries, phase-change energy storage, lead-acid batteries, thermal storage, superconductors, flywheels, supercapacitors, and Na–S batteries. Among these technologies, pumped hydro is currently the only technology that has achieved large-scale use. However, it is limited by geographical conditions; there is a mismatch between the geographical position of wind and solar resources and locations suitable for pumped hydro in China. In addition, it cannot meet the required energy storage for future large-scale development of wind and solar energy. Hence, it is imperative to develop alternative energy storage technologies. There are three essential requirements for large-scale energy storage systems: ① high reliability; ② cost-effective life cycle; and ③ low environmental impact over its life cycle. Many of the proposed energy storage technologies have limitations with respect to scale, cost, and lifetime. Among the solutions, compressed air and flow batteries are relatively mature technologies and have become development priorities for current large-scale energy storage systems. Li polymer batteries and phase-change energy storage have advantages of high energy density, easy management, combined heat and power, and are suitable for regional energy supplies. With the rapid growth of the global energy demand, many countries have introduced a number of scientific and technological plans to meet this need, where the developed countries have taken the lead in energy storage technology. For example, the scale of compressed air energy storage systems is currently over 100 MW; the lifetime of flow battery is about ten years; the lifetime of flywheels and supercapacitors has exceeded twenty years; the cost of superconductor, thermal, and compressed air energy storage systems is less than 1000 USD/kW; and various energy storage technologies have entered the stage of large-scale demonstration and commercial applications.

(2) Catalytic conversion of fossil resources and biomass

Energy is a common global concern and diversification of the global energy structure is a present trend. It is predicted that by 2040, oil, gas, and coal will still account for three-quarters of the total energy supply, although a rapid increase in renewable energy production is underway. Therefore, the clean and efficient transformation and use of petroleum, coal, natural gas, and biomass is an important direction in the current energy field. A breakthrough in modern coal chemical technology is the key for future coal use. In the future, the fuel market will be affected by new energy policies, and the direct conversion of oil to chemicals will be developed to adapt to changes in the market. Biomass is an important part of the renewable energy supply, and its large-scale, low-cost, and efficient transformation and use is expected to be a future development trend. In recent years, the rapid development of catalysis science has played an important role in the growth of new technologies and the improvement of existing ones.

(3) Green and intelligent metallurgical manufacturing processes

The large scale of the metallurgy industry results in high total energy consumption and emission of pollutants. This industry is subject to increasing environment constraints and pressure to reduce energy use. Hence, it is imperative to promote green development and intelligent manufacturing in the metallurgy industry and achieve harmonious development with society. In the case of manufacturing in the metallurgy industry, green manufacturing refers to the principle of “reduce, reuse, and recycle,” with the goal of zero emissions, and total reuse of waste heat, residual pressure, residual gas, waste water, and solid waste produced during the process, finally achieving a clean and environmentally friendly process. The state-of-the-art green manufacturing technologies developed to date include: waste heat recovery and use of slag, new composite ferrous coke technology, combined optimization of material, energy, and information flow (big data) in iron and steel works, and CO_2 capture, storage, and use. The metallurgy industry, in particular the steel industry, has highly automated processes. The development of intelligent manufacturing has a good foundation and widespread potential. With the help of intelligent manufacturing technologies, such as Internet + and the Internet of Things, the customization, flexibility, greening, networking, and intelligence of steel production can be improved, which will promote transformation and upgrade of the steel industry. The key technologies for intelligent manufacturing in the steel industry include: intelligent expert systems based on industrial big data, the use of robotic systems, multi-objective real-time optimization of on-line technologies in production, use of big data for intelligent fault diagnosis and maintenance of key technology and equipment, optimization of supply chains, and integration of information technology for cooperative manufacturing.

(4) Development and application of additive manufacturing (3D printing)

Additive manufacturing, also known as 3D printing, is an advanced manufacturing technology which has nearly 30 years of development. It is used for rapid manufacturing due to its advantage of 3D freedom of movement, and is widely used in the development of new products and small batch manufacturing. The system uses alloy powder or wire as a raw material and the product is deposited layer-by-layer using in situ high-power laser melting and rapid solidification. Additive manufacturing technology can be classified into two categories according to the different states of the metal during the deposition process: ① a molten pool of the metal is produced during processing; for example, laser engineered net shaping (LENS) and direct metal deposition (DMD); ② the metal powder is distributed before deposition of the following layer, including direct metal laser sintering (DMLS), selective laser melting (SLM), fused deposition modeling (FDM), and selective laser sintering (SLS) methods. In general, this technology has several advantages, including fast manufacturing and efficient material use, where no molds are required; this reduces the manufacturing cost by 15%–30% and reduces the production cycle by 45%–70%. Functional metal parts with complex shapes can be produced that are difficult or even impossible to fabricate using traditional methods. In addition, graded functional structures with different components and textures can be formed in the same part without repeat molding and intermediate heat treatments. Furthermore, rapid solidification results in metal parts that are completely compact with a fine structure, and tensile performance exceeding that of cast materials. The near-net-shape parts can be used directly or only require a small amount of subsequent machining. Additive manufacturing is a green transformative technology based on digital manufacturing that is characterized by its low cost, short cycle time, and ability to control the shape and performance of a product. This technology has huge development potential and broad prospects in future aviation and aerospace, nuclear power, petrochemical, marine, and manufacturing industries. In the past 20 years, this technology has become a research hotspot in the interdisciplinary field between materials process engineering and advanced manufacturing, attracting worldwide attention from government, industry, and academia.

(5) Preparation, structural connections, and applications of advanced composites

Advanced composite materials with high-performance fibers as reinforcing materials (e.g., carbon, boron, aramid, and silicon carbide fibers) have advantages of low density, high specific strength and specific stiffness, and good fatigue resistance, vibration damping, and mechanical properties. Such materials are the first choice for designing lightweight structural materials and are widely used in aerospace, automotive, wind power generation, machinery manufacturing, and medical fields. The research focus for advanced composite materials includes optimizing the design of the composite structure, along with developing large-scale integral molding technology, regenerative functions, composite connection methods, self-healing properties, and the combination of intelligence, stealth, and other functionality. The bonding methods for advanced composite materials include adhesive, mechanical, and hybrid connections. In the future, the connection modes for composite materials are expected to include a variety of new connection techniques in addition to mechanical and adhesive bonding. The overall trend is to optimize the design of the bonds to achieve integration of composite structural parts to achieve enhanced stability and reliability of the joints.

(6) Key technologies and materials for supercapacitors

Supercapacitors (also known as electrochemical capacitors, gold capacitors, and farad capacitors) include electric double layer capacitors and pseudocapacitors, which store energy by polarizing electrolytes. Although supercapacitors are electrochemical systems, they do not undergo a chemical reaction during energy storage, and the process is reversible; hence, supercapacitors can be repeatedly charged and discharged billions of times. Supercapacitors are expected to replace traditional chemical batteries as they have large capacity, high power, long lifespan, and low cost, in addition to being environmentally friendly. Hence, they have a broader range of applications than traditional batteries. This technology is constantly evolving, driving applications from the initial field of electronic equipment into power and energy storage. The core challenge in supercapacitor technology is preparing low-cost supercapacitors with high energy density while maintaining the high power density, long cycle life, and environmentally friendly properties of traditional capacitors. These requirements can be realized through the development of key electrode materials, highly compatible capacitor separators, and high-pressure electrolytes, while optimizing the system design and integration of supercapacitors.

(7) New-generation high-energy Li–S batteries and solid-state Li batteries

Lithium–sulfur (Li–S) batteries are a new generation of high-energy density secondary battery, employing Li as the anode and S as the cathode. To date, the reported specific energy of Li–S batteries is more than 600 Wh/kg, which is three times that of Li-ion batteries. However, development challenges include poor cycle stability of the battery due to polysulfide shuttle effect, where polysulfides generated during the discharge of Li–S batteries diffuse to the anode. In addition, the lithium metal becomes powered and generates dendrites during the cycling. Recent directions in technical research include optimization of the cathode composition and structure, such as the addition of anchoring agents for polysulfides to inhibit the shuttle effect; addition of a catalyst to enhance conversion of polysulfide to lithium sulfide; deposition of artificial solid electrolyte interphase films on the surface of the Li anode and construction of a 3D network structure to uniformly deposit Li ions, thereby improving the cycle stability of the Li-S batteries.

In solid-state Li batteries, the liquid electrolyte is replaced by a solid-state electrolyte and Li metal acts as the anode. Since the solid-state electrolyte has a high melting point and excellent mechanical properties, which can inhibit the formation of lithium dendrites, solid-state Li batteries are expected to become the next generation battery system with high specific energy and good safety. Recent directions in technical research include: preparation of solid-state electrolytes with high ionic conductivity at room temperature and good compatibility with metallic Li; and modification and optimization of the interface between the solid-state electrolyte and electrodes, thereby improving the electrochemical performance of solid-state Li batteries.

(8) Key methods for preparing graphene-based functional materials and their application in energy storage

Graphene is a hexagonal scrobiculate-lattice two-dimensional carbon nanomaterial composed of carbon atoms in an sp^2 hybridized orbit. The scientific community has been studying graphene for more than a decade. Although graphene was proved to exist alone in 2004, patents using this material only increased sharply after 2010. A large number of inventions and technologies are emerging every year, predicting that the industrial application of graphene technology will enter a period of rapid development in the next few years. The crucial research directions of graphene are expected to focus on the preparation of graphene suspensions or powders, macroscopic graphene (such as fibers, films, aerogels, and foams), and graphene composite materials. Graphene is expected to be widely used in supercapacitors and various new types of batteries, and will gradually be used as an active energy storage medium instead of only as a conductive agent (as used in the early applications). This requires functionalization of the graphene and preparation of suitable functional or composite materials, such as 3D graphene, and graphene-coated silicon for Li battery anodes, which can also be used as a capacitor or the positive electrode of Li–S batteries.

(9) Preparation and application of light metal alloys

With the rapid development of high-tech fields, such as aerospace, high-speed rail, nuclear power, automotive, and biomedical, the demand for high-performance metal alloys is significantly increasing. Most development work involves Al-, Mg-, Ti-, and Zr-based alloys, including: high-performance Al alloy for structural and wire applications; Mg alloys with high strength and toughness, and wear and corrosion resistance; biodegradable and biomedical Mg alloys; medical titanium alloys; high-strength, high-toughness Zr-based amorphous alloys and ceramic materials.

The high performance of Al alloys is due to the micro-alloying effect. The current research focus in this area is selecting and controlling the types and quantities of elements that play different roles in the alloy. To date, the hotspot for Mg alloy research is achieving high strength and toughness. In order to achieve this goal, design of the alloy composition and preparation process is used to optimize the material performance. Currently, the tensile strength at room temperature of advanced high-strength cast magnesium alloys and cast wrought magnesium alloys is ⩾400 MPa and ⩾550 MPa, respectively. Improvement of the plasticity and toughness of high-strength lightweight alloys is a current hotspot. Improving the plastic toughness of high-strength lightweight alloys through grain refinement, new phases, new structures (e.g., the long-period stacking order structure), and optimization of the interface and texture is the focus of development in several countries. In addition to being a structural material, Mg alloys are used for medical applications. In particular, biodegradable biomedical Mg alloys are a future development trend, where improving their corrosion resistance is a research focus. Systematic research on Ti alloys is underway, where lowering the production cost and developing new Ti-based materials are expected to further expand their application. Zr-based amorphous alloys have excellent mechanical properties, good corrosion resistance, and high catalytic performance; these properties have resulted in their widespread use in electronics and military applications.

(10) Crystal engineering and large-scale application of MOF materials

MOF materials, composed of metal ions (or clusters) bridged by organic linkers, are a novel subclass of porous organic–inorganic hybrid materials. The flexibility with which the metal nodes and organic linkers can be varied has led to thousands of compounds with permanent and regular porous networks. MOFs have a wide range of potential uses, including gas storage, separation, catalysis, and energy technology. Crystal engineering using both modeling and experimental methods is an efficient strategy to design and synthesize MOF materials. Substantial efforts in this direction have already been undertaken, including: ① high throughput synthesis, screening, and characterization of MOF crystals; ② systematic investigation of the nucleation and growth of MOF crystals; and ③ scaled-up synthesis of MOF materials. Considering the cost and environmental impact, an impending challenge is improving the space-time-yield of MOF synthesis while greatly reducing the consumption of organic solvents. Thus, the development of aqueous synthesis methods or solvent-free processes with high space-time-yield has been demonstrated as a feasible solution to overcome these issues. In addition, precise control of the nucleation and growth of MOF crystals is expected to yield MOF materials with uniform particle size distributions on a large scale. In the future, the field will focus on two aspects of large-scale application of MOF materials; namely, adsorbents/separation membranes and functional devices. An alternative energy-efficient and environmentally friendly separation pathway will be established using MOF-based adsorbents and membranes. Meanwhile, on-going development combining different areas of expertise (including chemistry, engineering, medicine, biology, electronics, and optics) will promote commercialization of MOF-based devices. The poor stability of MOF materials is of particular concern; the use of MOF materials in demanding conditions remains a challenge (although MOF crystals are constructed from metal-containing inorganic units and organic linkers connected by relatively strong bonds). Substantial efforts have already been undertaken to resolve this problem using a series of feasible strategies, such as the integration of MOFs with functional protective materials, or using functional decorations to improve their stability.

(11) Advanced preparation of rare and precious metals

Rare and precious metals generally include rare and refractory metals, such as titanium, zirconium, hafnium, vanadium, niobium, tantalum, molybdenum and tungsten; rare light metals such as lithium, rubidium, and cesium; scattered metals such as gallium, indium, thallium, germanium, rhenium, selenium, and tellurium; rare earth metals such as scandium, yttrium, and lanthanide; rare radioactive metals such as scandium, yttrium, polonium, actinide, thorium, and uranium; and precious metals such as gold, silver, and platinum group metals (ruthenium, rhodium, palladium, osmium, iridium, and platinum). Rare and precious metals are important basic materials for the national economy, social development, and national defense, and are widely used in the energy, metallurgy, petrochemical, machinery, aerospace, information, marine, biomedical, and transportation sectors and for building materials and textiles. Due to their low abundance in the Earth's crust and their distinct physical and chemical properties, rare and precious metals are difficult to extract and process. Developed countries attach great importance to the R&D of rare and precious metals and almost monopolize the international market of high-end and high value-added products. For a long time, China lacked the core technology of independent intellectual property rights for the preparation and processing of some high-purity rare and precious metal products. Because of the high manufacturing cost, large-scale production has not been realized, which has restricted the development of emerging industries, such as optoelectronics. With increasing demand for rare metals in high-end equipment manufacturing, strategic emerging industries, and major projects, advanced processing methods for rare and precious metals has become a global R&D focus. The key technologies include: preparation methods for ultra-high-purity rare metals; large-scale manufacturing technology for rare and precious metals for target high-end functional components; large-scale and deep processing technology for high-purity rare metal products for high-end equipment manufacturing; methods for producing high-quality rare and precious metal powder; welding technology for rare and precious metals to achieve various specifications; and methods for combining the rare and precious metals with conductive materials.

(12) Cell therapy

Cell therapy encompasses many technologies where certain cells are injected or transplanted into the human body to trigger cell-mediated immunity, anti-cancer or tissue/organ regeneration, improved immune function, wound repair and regeneration, disease treatment, and anti-aging effects. Although cell therapy has a history of more than 500 years, the development of modern technologies, such as inducible stem cell cultures, tissue engineering, and genetic engineering, are now resulting in commercialization of the method. Based on the host of cells used, cell therapy can be classified as autogeneic or allogeneic cell therapy. Depending on the sources or targets of the cells (e.g., embryonic, neural, mesenchymal, or hematopoietic stem cells), the method can target diseases of the immune system or blood, diabetes, and neurological conditions. Cell therapy has already shown huge potential in such fields.

In addition to the application of cell therapy, investigation of the underlying mechanisms is also a focus, including control of cell differentiation, dedifferentiation, and inducible differentiation, and study of the signal factors and epigenetic mechanisms involved.

2.2 Interpretations for three key engineering development fronts

2.2.1 Key materials and technology for large-scale energy storage

Energy is fundamental for the sustainable development of human society and the economy. With the development of society, the demand for energy is increasing, causing a shortage of fossil energy and deterioration of the environment. Promoting changes to the energy structure, efficient use of fossil fuels, and large-scale use of renewable energy are important strategies for global energy security and sustainable economic development. However, the production of renewable energies, such as wind and solar, is intrinsically discontinuous and unstable. Therefore, large-scale energy storage technology is required in order to realize large-scale access to renewable energy, which is a key supporting technology for modifying the energy system. Existing large-scale energy storage technologies, such as vanadium flow batteries, compressed air storage, and gel polymer battery/phase-change thermal storage, are characterized by their high safety, low cost, large capacity, and long lifetime. Such technologies are expected to effectively meet current needs and have made important progress in fundamental research, trial production of devices, and small-scale demonstration. There is an urgent need for further multidisciplinary academic research in order to achieve the leap from research to engineering applications.

The development of energy storage technologies has attracted attention from governments and become a research focus. As of the end of 2016, the cumulative installed capacity of commissioned global energy storage projects was 168.7 GW, a year over year growth of 2.4%. Among the different technologies, the cumulative installed capacity of electrochemical energy storage ranked third, with a scale of 1769.9 MW, a year over year growth of 56%. According to the third edition of the *Rethinking Energy 2017* report released by the International Renewable Energy Agency, the future use of batteries for energy storage will increase significantly. It is expected that the global battery energy storage market will increase to 14 billion USD by 2020. The USA has long supported and focused on the development of energy storage, and convened the Summit on Renewable Energy and Energy Storage in the Smart Grid in 2016. The Obama administration announced the *Federal and Private Sector Action Plan for Expanding Renewable Energy and Energy Storage*, which defines the energy storage needs and allocation targets for more than eight states in the following five years, where investors will provide 130 million USD for energy storage. With the aim of making renewable energy the core of Germany's future power supply, the German government is implementing an ambitious energy transformation strategy that will increase the renewable energy power supply to 35% by 2020 and more than 50% and 80% by 2030 and 2050, respectively; the rapid development of energy storage technology plays a critical support role in this strategy. Japan has been continuously funding R&D of energy storage technology since the 1970s. Over the past ten years, Japan has invested more than 40 billion JPY (more than 3 billion CNY) in the R&D of energy storage technology. Japan’s current installed capacity of energy storage is ranked first in the world and occupies about 11% of the total installed capacity of electricity. In 2012, South Korea launched the *Strategy for Energy Storage Technology R&D and Industrialization*, and will invest 6.4 trillion KRW (about 32 billion CNY) for energy storage technology research, development, and application by 2020.

The Chinese government is paying increasing attention to energy storage. Various national science and technology, and energy strategic plans, such as the *Development Outline of National Medium and Long-term Science and Technology (2006–2020)*, *Development Plan of the 13th Five-Year National Strategic Emerging Industry*, and *13th Five-Year National Science and Technology Innovation Plan* have highlighted energy storage technology as one of the key development directions. In addition, with support from Technology Plans, such as those from the National Natural Science Foundation (Program 973 and Program 863), and national key R&D plans, many energy storage technologies in China have made progress in basic research, key technology R&D, trial production of devices, and small-scale demonstration. Energy storage technology research in China started relatively late; thus, there is still a considerable gap between the level of research produced in China and that of the rest of the world, especially in terms of system integration, demonstration of devices, and comprehensive management of energy systems.

Countries or regions and institutions with the greatest output of core patents on the “key materials and technology for large-scale energy storage” are listed in Table 2.2.1 and Table 2.2.2, respectively. The collaboration network among major countries or regions and institutions in the engineering development front of “key materials and technology for large-scale energy storage” are illustrated in Figure 2.2.1 and Figure 2.2.2.

2.2.2 Catalytic conversion of fossil resources and biomass

Energy is one of the most important issues attracting global concern and is crucial for domestic economic and social development. According to the 2018 edition of BP Energy Outlook, the global energy structure is diversified. Demand for oil will continue to increase in the near future, where most of the growth in demand is driven by petrochemical products, while natural gas will become the second largest resource of

Table 2.2.1 Countries or regions with the greatest output of core patents on the "key materials and technology for large-scale energy storage"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	149	29.62%	180	18.16%	1.21
2	Japan	110	21.87%	140	14.13%	1.27
3	USA	105	20.87%	409	41.27%	3.90
4	Germany	54	10.74%	100	10.09%	1.85
5	South Korea	52	10.34%	58	5.85%	1.12
6	Taiwan of China	8	1.59%	13	1.31%	1.63
7	France	6	1.19%	5	0.50%	0.83
8	India	5	0.99%	0	0.00%	0.00
9	Russia	3	0.60%	0	0.00%	0.00
10	Canada	2	0.40%	35	3.53%	17.50

Table 2.2.2 Institutions with the greatest output of core patents on the "key materials and technology for large-scale energy storage"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	YUAS	Japan	64	12.72%	53	5.35%	0.83
2	MATU	Japan	24	4.77%	21	2.12%	0.88
3	BOSC	Germany	17	3.38%	46	4.64%	2.71
4	SGCC	China	17	3.38%	22	2.22%	1.29
5	BATT	USA	12	2.39%	111	11.20%	9.25
6	CHWE	China	12	2.39%	21	2.12%	1.75
7	HITB	Japan	11	2.19%	42	4.24%	3.82
8	LITE	Germany	11	2.19%	16	1.61%	1.45
9	OCIO	Korea	10	1.99%	3	0.30%	0.30
10	MINN	US	9	1.79%	4	0.40%	0.44

YUAS: GS Yuasa Corp; MATU: Panasonic Corp; BOSC: Bosch GmbH Robert; SGCC: State Grid Corp China; BATT: Battelle Memorial Inst; CHWE: Chilwee Power Co Ltd; HITB: Hitachi Chem Co Ltd; LITE: Li-Tec Battery GmbH; OCIO: OCI Co Ltd; MINN: 3M Innovative Properties Co.

energy. The share of coal in primary energy consumption will decline, but China is still the largest coal market, expected to account for 40% of global demand in 2040. In addition, China's renewable energy consumption will grow rapidly.

A vital mission of the current energy R&D is to create new technologies for clean and efficient use of oil, coal, natural gas, and biomass, in order to solve the increasingly prominent problems related to energy and environment. In particular, the clean and efficient use of coal is of great significance to China. The modern coal chemical industry has shown to be quite promising in clean and efficient use of coal. The successful implementation of large coal chemical demonstration projects, i.e. coal to olefins, coal to liquid, and coal to ethylene glycol, has shown that the China is leading the innovations of clean coal technology in the world. Recent breakthroughs in the coal-to-ethanol and syngas to-olefins technologies further demonstrated China's capability for sustainable innovations regarding to

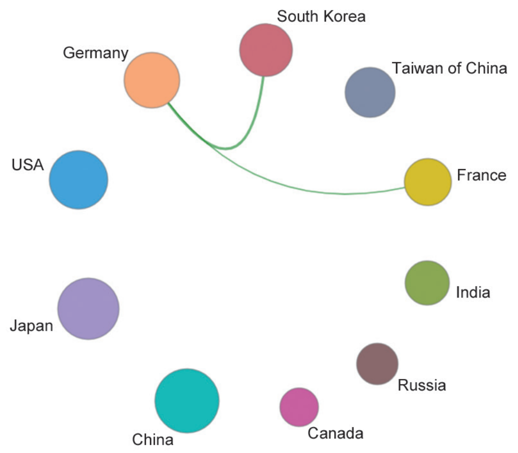

Figure 2.2.1 Collaboration network among major countries in the engineering development front of “key materials and technology for large-scale energy storage”

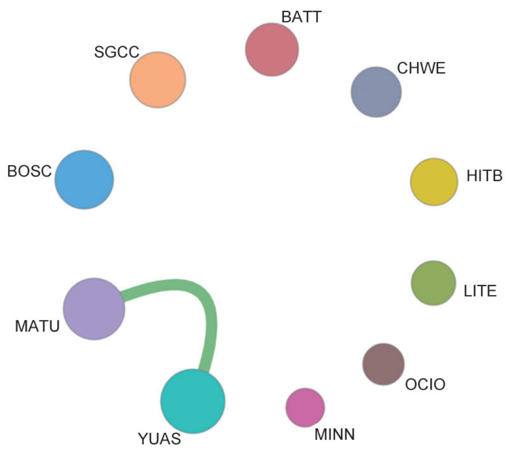

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of “key materials and technology for large-scale energy storage”

R&D and industrialization of coal to chemical technologies. The integration of large-scale refineries and chemical industries has become a notable trend in the chemical industries. Developing new processes for more efficiently converting crude oil to high-value chemicals is also important for changing future oil consumption. The breakthrough of methane conversion technology provides important support for the use of unconventional gas resources, such as shale gas. For biomass transformation, biodiesel, biomass pyrolysis oil, ethanol/butanol by fermentation, gasification-syngas Fischer-Tropsch synthesis, and cellulose to ethylene glycol have shown significant progress. Large-scale, low-cost, efficient conversion of biomass to chemicals is expected to be the most likely breakthrough in the near future.

In most of these energy transformation processes, catalysis plays a very important role. Most breakthroughs in new technology depend on the application of new catalytic materials and the development of high performance catalyst. Precise control of the active sites and reaction paths is of great significance for enhancing the excellent properties of traditional catalytic materials (e.g., molecular sieves) and improving the efficiency of catalytic processes. Innovations in the synthesis of catalysts, developing green processes, and catalyst recovery remain important directions of catalyst engineering.

Countries or regions and institutions with the greatest output of core patents on the “catalytic conversion of fossil resources and biomass” are listed in Table 2.2.3 and Table 2.2.4, respectively. The collaboration network among major countries or regions and institutions in the engineering development front of “catalytic conversion of fossil resources and biomass” are illustrated in Figure 2.2.3 and Figure 2.2.4.

2.2.3 Green and intelligent metallurgical manufacturing processes

The metallurgy industry is a fundamental basic industry for the China’s national economy, providing important raw materials that guarantee social development, and strongly supporting the development of related industries. As the situation regarding global climate change and carbon emissions becomes increasingly serious, the development of the metallurgy industry is facing increasing environmental pressure. In particular, as the steel industry is a major consumer of resources and energy, environmental problems related to steel production are increasingly concerning for the society at large. Developing the steel industry using green and intelligent technologies is thought to be critical for transforming and upgrading the industry.

Promoting the “greening” of the manufacturing process is a major priority in the steel industry. Clean production and greening of the entire manufacturing process will be realized via the following three functions in the steel manufacturing process: steel product manufacturing, energy conversion, and treating the produced waste. These processes will follow the

Table 2.2.3 Countries or regions with the greatest output of core patents on the "catalytic conversion of fossil resources and biomass"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	78	50.65%	258	83.23%	3.31
2	China	48	31.17%	63	20.32%	1.31
3	Netherlands	10	6.49%	2	0.65%	0.20
4	South Korea	6	3.90%	7	2.26%	1.17
5	India	5	3.25%	2	0.65%	0.40
6	Saudi Arabia	5	3.25%	4	1.29%	0.80
7	Germany	4	2.60%	0	0.00%	0.00
8	France	3	1.95%	7	2.26%	2.33
9	Japan	3	1.95%	0	0.00%	0.00
10	Australia	1	0.65%	2	0.65%	2.00

Table 2.2.4 Institutions with the greatest output of core patents on the "catalytic conversion of fossil resources and biomass"

No.	Institutions	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	ESSO	USA	22	14.29%	111	35.81%	5.05
2	UNVO	USA	16	10.39%	8	2.58%	0.50
3	SNPC	China	12	7.79%	16	5.16%	1.33
4	SABI	USA	10	6.49%	4	1.29%	0.40
5	SHEL	Netherlands/USA	6	3.90%	24	7.74%	4.00
6	CACP	China	5	3.25%	1	0.32%	0.20
7	LUMM	USA	5	3.25%	11	3.55%	2.20
8	CALI	USA	4	2.60%	4	1.29%	1.00
9	CELA	USA/China	3	1.95%	28	9.03%	9.33
10	UNCZ	China	3	1.95%	2	0.65%	0.67

ESSO: Exxonmobil Chem Patents Inc; UNVO: Universal Oil Prod Co; SNPC: SINOPEC Corp; SABI: SABIC Global Technologies BV; SHEL: Shell Oil Co; CACP: CAS Dalian Chem & Physical Inst; LUMM: Lummus Technology Inc; CALI: Chevron USA Inc; CELA: Celanese Int Corp; UNCZ: Univ Changzhou.

principle of "reduce, reuse, and recycle", where waste heat, residual pressure, residual gas, waste water, and solid waste will be fully recycled with the goal of zero emissions. In recent years, various technologies have been developed and applied to advance green development of steel manufacturing, including: the "three dry" technology (dry coke quenching, dry gas cleaning in the blast furnace, and dry gas cleaning in the converter); comprehensive use of waste water; use of by-product gas (in the coke oven, blast furnace, and converter) as a secondary energy source; and comprehensive use of solid waste (e.g., blast furnace slag and converter slag). These technologies have effectively achieved energy savings and emission reductions in the steel industry. Currently green manufacturing frontier technologies include: waste heat recovery and use of slag; novel use of carbon-iron composites; combined optimization material, energy, and information flow (big data) in iron and steel works; and carbon dioxide capture, storage, and use.

Intelligent manufacturing is an important trend in the future development of manufacturing industries, and is also an important way to transform and upgrade the steel industry.

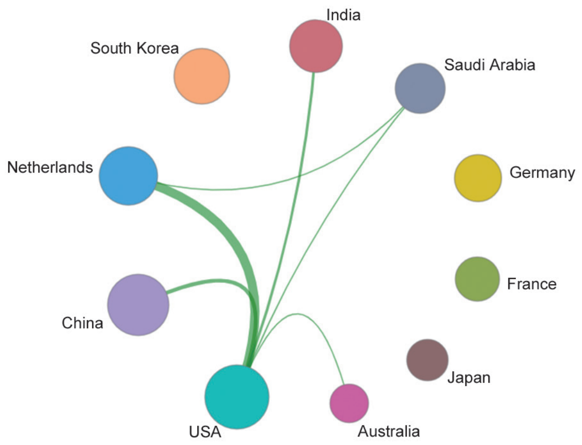

Figure 2.2.3 Collaboration network among major countries in the engineering development front of "catalytic conversion of fossil resources and biomass"

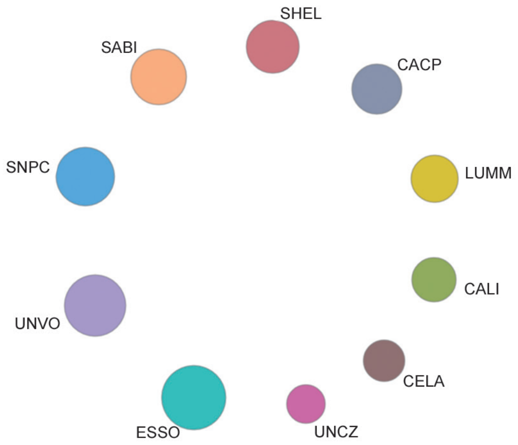

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of "catalytic conversion of fossil resources and biomass"

The steel industry is highly automated and the development of intelligent manufacturing has good foundation and broad prospects in this field. With the help of intelligent manufacturing technologies, such as Internet + and the Internet of Things, we will promote the customization, flexibility, greening, networking, and intelligence of steel production methods, and promote the transformation and upgrading of the steel industry. In recent years, intelligent manufacturing methods have been increasingly applied to steel manufacturing, business management, logistics and distribution, and product sales. Demonstration of intelligent factories and digital workshops has been built around intelligent manufacturing processes and mass customization. The application of technology and equipment, such as human-machine interfaces, industrial robots, and intelligent logistics management in the production process has been achieved. The application of simulation optimization, digital control, real-time monitoring, and adaptive control of iron and steel manufacturing processes is promoted. However, intelligent manufacturing in the steel industry is still in its infancy and key technologies need to be developed in the future, including intelligent expert systems based on

Table 2.2.5 Countries or regions with the greatest output of core patents on the "green and intelligent metallurgical manufacturing processes"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	914	93.17%	1039	94.20%	1.14
2	Japan	20	2.04%	38	3.45%	1.90
3	Russia	10	1.02%	1	0.09%	0.10
4	USA	10	1.02%	21	1.90%	2.10
5	South Korea	8	0.82%	2	0.18%	0.25
6	India	3	0.31%	0	0.00%	0.00
7	Taiwan of China	3	0.31%	0	0.00%	0.00
8	Australia	2	0.20%	1	0.09%	0.50
9	UK	2	0.20%	0	0.00%	0.00
10	Poland	2	0.20%	0	0.00%	0.00

industrial big data, application of intelligent robots, multi-objective real-time optimization of on-line operations, use of big data for intelligent fault diagnosis and maintenance of key systems, intelligent optimization of the supply chain, and integration of information technology for cooperative manufacturing.

The countries and institutions publishing the most core patents in the field of “green and intelligent manufacturing in the metallurgy industry” since 2012 are given in Table 2.2.5 and Table 2.2.6, respectively. The cooperation between these countries and institutions are shown in Figure 2.2.5 and Figure 2.2.6, respectively. China is the main publisher of the core patents, accounting for 93.17% of the total number of patents. The number of citations for the core patents and the main research institutes are mainly concentrated in China, indicating that China’s R&D in this field is leading the world. According to the average cited frequency of core patents, the USA and Japan are higher than China, indicating that these countries have well-developed basic technology and strong R&D programs, as recognized by other researchers around the world. There is little cooperation between the major countries and institutions, indicating that most of the research is performed independently.

Table 2.2.6 Institutions with the greatest output of core patents on the “green and intelligent metallurgical manufacturing processes”

No.	Institutions	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	CMEG	China	59	6.01%	78	7.07%	1.32
2	BAOS	China	21	2.14%	14	1.27%	0.67
3	SHGG	China	19	1.94%	34	3.08%	1.79
4	ANSH	China	13	1.33%	9	0.82%	0.69
5	JGJT	China	12	1.22%	38	3.45%	3.17
6	HBIS	China	10	1.02%	9	0.82%	0.90
7	BJSW	China	9	0.92%	3	0.27%	0.33
8	UYDB	China	9	0.92%	42	3.81%	4.67
9	JGHX	China	8	0.82%	8	0.73%	1.00
10	WSGC	China	8	0.82%	26	2.36%	3.25

CMEG: Metallurgical Corp China; BAOS: Baoshan Iron & Steel Co Ltd; SHGG: Beijing Shougang Int Eng Technology Co; ANSH: Angang Steel Co Ltd; JGJT: Shandong Iron & Steel Co Ltd; HBIS: Hebei Iron & Steel Co Ltd; BJSW: Jiangsu Province Metallurgical Design; UYDB: Univ Northeastern; JGHX: Gansu Jiu Steel Group Hongxing Iron & Steel Co Ltd; WSGC: Wuhan Iron Steel (Group) Corp.

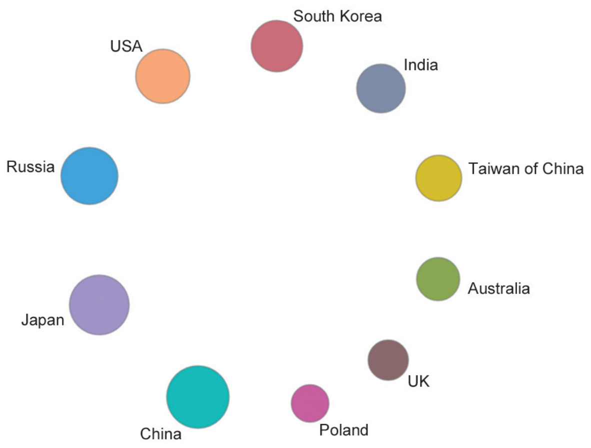

Figure 2.2.5 Collaboration network among major countries in the engineering development front of “green and intelligent metallurgical manufacturing processes”

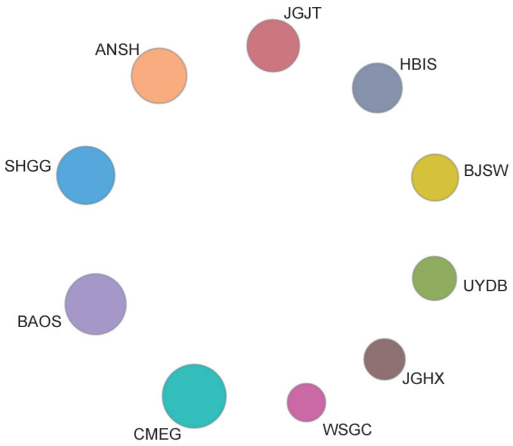

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of “green and intelligent metallurgical manufacturing processes”

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