PERSPECTIVE

Innovating for a Greener Tomorrow

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Abstract: The Dalian Institute of Chemical Physics, Chinese Academy of Sciences (DICP) has been involved in energy related innovation for over seven decades. This article highlights DICP's recent groundbreaking researches in catalysis, chemical engineering, and energy storage, showcasing technologies such as methanol-to-olefins, CO_2 utilization, and advanced vanadium redox flow batteries, addressing some critical challenges in energy security and sustainability. DICP's strong innovation capability has been widely recognized and attributed to the multidisciplinary approach and the deep integration of basic research, applied research and engineering research, which leads to the fast commercialization of the new technologies supporting China's energy transition and carbon neutrality, and contributing to global efforts in clean energy development as well.

Keywords: clean energy, carbon neutrality, methanol-to-olefins, CO_2 utilization, energy storage

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The Dalian Institute of Chemical Physics (DICP), one of more than 100 institutes under the Chinese Academy of Sciences (CAS), is situated in the port city of Dalian. Since its founding in March 1949, research at DICP has closely reflected the scientific and economic demands of China. In the past 75 years, DICP has built up an impressive portfolio of achievements in the basic and applied sciences that have greatly impacted the economic and technological development of China.

The DICP spirit of "Innovation, Collaboration, Academic Rigor and Excellence" has motivated its development. In 1998, DICP participated in the "Knowledge Innovation Program" of CAS in the first batch, marking a pivotal moment in its history.

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By 2020, it has been recognized as "excellent" in performance evaluation of national scientific research institutions.

Traditional areas of excellence at DICP include catalysis, chemical engineering, chemical lasers, molecular reaction dynamics, organic synthesis, modern chromatographic techniques and biotechnology.

Now, DICP is focused on energy-related topics, and its current development strategy is as follows: DICP focuses on sustainable energy research and coordinates the development of environment optimization, biotechnology and advanced material in a multidisciplinary atmosphere by strengthening technological integration and innovation, to play indispensable roles in the national economy and security and to become a leading research institute in the world.

In 2018, CAS launched the Strategy Priority Research Program (Category A) of "Transformational Technologies for Clean Energy and Demonstration," with a total funding of 1.6 billion yuan (227 million USD), focusing on integrating fossil, renewable, and nuclear energy to establish a clean, low-carbon, safe, and efficient energy system, in which DICP is working as a leading institute. This initiative has driven 63 key technological breakthroughs and 55 industrial demonstrations, catalyzing over 180 billion yuan (25.5 billion USD) in industrial investments.

Research Focus: Innovating Across Disciplines

DICP is strongly focused on addressing national scientific demands through cutting-edge, collaborative research in all of its laboratories. With a tradition of excellence in basic and applied research and interdisciplinary innovation, DICP is poised to continue making important advances in a number of research fields.

(1) Catalysis: Form of Molecules

As one of the cradles of catalysis research in China, DICP has made profound contributions to both basic and applied catalysis. In 2008, Prof. LI Can, a CAS Member from DICP was elected chairman of the International Association of Catalysis Societies. In 2016, the 16th International Congress on Catalysis, hosted by DICP, was held in Beijing, attracting more than 2,500 participants from over 50 countries. This was the first time the International Congress on Catalysis was held in China, marking a new level of global recognition.

The State Key Laboratory of Catalysis, established at DICP, has been a critical hub for innovation. Using state-of-the-art experimental and theoretical techniques, the DICP State Key Laboratory of Catalysis is investigating catalytic reactions, creating advanced catalytic materials and developing *in situ* characterization and monitoring techniques that are impacting energy research, as well as environmental and synthetic chemistry. Detailed probing of catalytically active phases, active sites and reaction mechanisms has led to several important insights and discoveries in nanocatalysis, including the synthesis of single-atom catalysts and the discovery of the interface confinement effect.

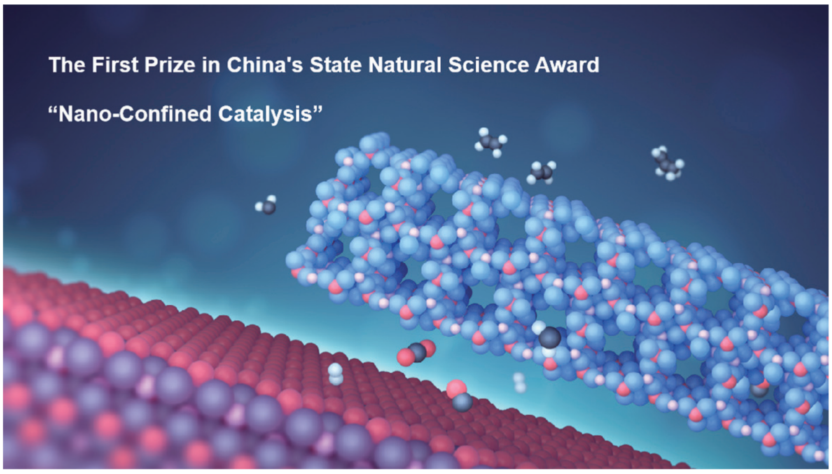
The concept of "nano-confined catalysis" has been proposed by Prof. BAO Xinhe, a CAS Member. "It is like tapping a ping-pang against the table from a certain height. The ball bounces up and down. When you suddenly lower the ping-pong bat, the ping-pang would bounce much more rapidly. Suppose we do something similar to the electrons, somehow like lowering the pat over the ping-pang. In that case, the electrons will vibrate more vigorously, hence changing the property of the materials," explained academician BAO Xinhe. "So, if we can adjust the bouncing electrons to certain heights or energy, it would allow us to control many natural processes."

In 2016, under the nano-confined catalysis concept, BAO's team introduced a breakthrough design called Oxide-Zeolite (OXZEO) coupling catalysts, which leverages the effects of interface and nano-space confinement within an oxide-zeolite composite to selectively convert syngas into light olefins ($C_2^=$–$C_4^=$, hydrocarbons with two to four carbon atoms and at least one double bond). Their work, published in *Science*, demonstrated an OXZEO catalyst capable of converting syngas to light olefins with an impressive 80% selectivity and to C_2–C_4 hydrocarbons with a 94% selectivity—far exceeding the theoretical 58% limit of the conventional Fischer-Tropsch synthesis (FTS) process.Within just three years, this research was successfully transitioned from the laboratory to industry, earning the team the first prize in China's State Natual Science Award in 2020.

Another milestone was achieved by CAS Member ZHANG Tao's team, who coined the concept of "single-atom catalysis" by successfully synthesizing the first "single-atom catalyst (SAC)" with the platinum (Pt) atoms anchored on the iron oxide (FeO_x) support for CO oxidation in 2011. Conventionally, only a small portion of the atoms are involved into reactions due to the embedded atoms into the metal bulk, while

Graphic: DICP

BAO Xinhe is doing experiments.



Graphic: DICP

Schematic diagram of OXZEO catalyst, designed around the concept of nano-confined catalysis.

Graphic: DICP

A 50,000-ton/year industrial unit for converting ethylene into isopropanol.

each atom can be well exposed to catalytic reactions on SACs. Moreover, the single-atom active site offers the capability of mechanism modulation in reactions, which provides the chance to improve the catalytic efficiency and avoid the undesired side reaction. It thus not only maximizes the usage of the precious metals such as platinum, but also makes the catalytic process of CO oxidation far more efficient. Furthermore, it opens up opportunities for catalytic understanding from a single-atom scale, ushering in a new era of heterogeneous catalysis.

In 2022, the world's first 50,000 ton/year industrial process for converting ethylene into isopropanol, using single-atom catalysts, passed appraisal. It marked a major step in scaling single-atom catalysis from the lab scale to real-world industry. Prof. ZHANG Tao was thus awarded the prestigious Future Science Prize in China in 2024.

(2) Chemical Engineering: Turn Black into Green

DICP is developing an impressive number of valuable technologies for industry, with more than 60 large-scale industrial applications being realized since 2017. One of the most significant advancements is clean coal technologies. Because coal is China's dominant energy source, the clean use of coal is critical for the nation's sustainable development. Researchers at DICP are contributing to the country's clean coal effort through the development and refinement of key processes, such as DICP methanol-to-olefins (DMTO), DICP methanol-to-ethanol (DMTE), and coal to alcohol or fuels, which have revolutionized the use of coal as a feedstock for producing light olefins and alcohols—critical raw materials for various industries.

In 2019, the world's first industrial demonstration of producing high-carbon alcohol and liquid fuel from synthetic gas, at a scale of 10,000 ton/year, successfully passed its performance evaluation. By 2022, the industrial demonstration for converting syngas to oil (10,000 ton/year) with cobalt-based catalyst and slurry bed technology also passed its scientific and technological assessment, marking a new direction in clean coal technology. In 2023, the world's largest 600,000 ton/year coal-based ethanol production installation has been commissioned. Now, DICP's DMTE technology has licensed in 15 commercial units (4.95 million ton/year), with 1.8 million ton/year in production.

(3) Chemical Lasers and Reaction Dynamics

In the domain of chemical lasers and molecular reaction dynamics, DICP has consistently been a trailblazer. ZHANG Cunhao (Tsun-Hao Chang, 1928–2024), one of China's most celebrated scientists and a CAS Member, pioneered high-energy chemical lasers in the country, laying the foundation for a national key laboratory in this field.

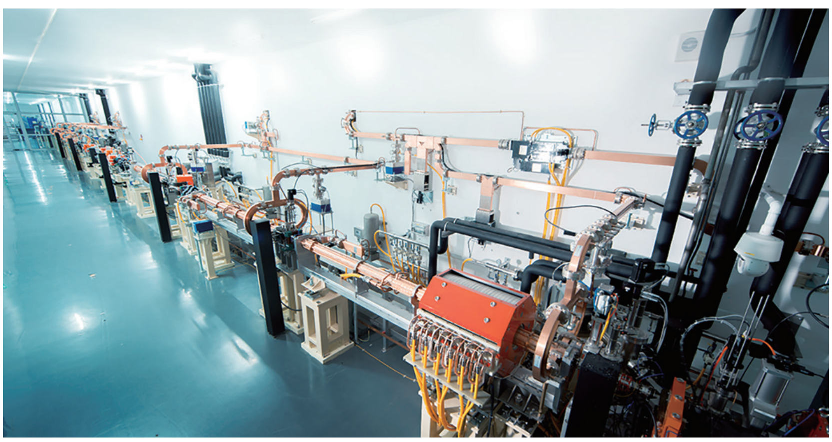
A comprehensive grasp of the most elementary chemical processes is indispensable for attaining significant advancements in diverse fields of research, including energy, environmental, and biological chemistry. The State Key Laboratory of Molecular Reaction Dynamics is one of a small number of facilities worldwide that possess both sophisticated experimental equipment and advanced computational capabilities. By employing crossed molecular beam techniques, researchers integrate experimental findings with precise quantum dynamics calculations, thereby attaining profound insights into pivotal chemical reactions in the gas phase and at the gas–surface interface at the atomic, molecular, and quantum-state levels. Such mechanistic comprehension can facilitate the development of innovative technologies, such as the design of catalysts for hydrogen production. Moreover, the Dalian Coherent Light Source, located in the DICP's Changxing Island Campus, is the first free-electron laser facility operating in the extreme ultraviolet band—a feat that has opened new doors to small molecule reaction dynamics.

(4) Analytical Chemistry and Biotechnology

DICP's expertise is not limited to the field of energy, but rather encompasses a diverse range of research areas that address the global research challenges. The CAS Key Laboratory of Separation Science for Analytical Chemistry under DICP is a leading research institution in the development of innovative techniques for sample preparation, separation, and identification of species in complex samples. The laboratory has a particular strength in the development of chromatography-based techniques and theory. Additionally, the laboratory has made significant contributions to the field of environmental and health mon-

Graphic: DICP

The world's largest 600,000 ton/year coal-based ethanol industrial unit.



Graphic: DICP

The Dalian Coherent Light Source free electron laser device.

itoring. For example, the rapid pesticide residue detection and aflatoxin fluorescence detectors have been used in high-profile international events like the DAVOS forum, showcasing the Institute's impact on public health.

DICP conducts innovative research in plant chemistry and natural medicine. It has developed a multi-dimensional and multi-channel separation and purification system for herbal material science. This comprehensive approach contributes to the development of new drugs and addresses the nation's health and life needs.

Breakthrough: Meeting Nation's Demands

In line with the nation's needs in energy transition and carbon neutrality, DICP has proposed a multi-energy system integration roadmap called "Four Main Threads, Four Platforms" to facilitate multi-energy integration, tailored to China's current energy structure and future development trends. This framework focuses on:

•Clean and Efficient Development and Utilization of Fossil Energy and Coupling Substitution

• Multi-Energy Complementation and Large-Scale Application of Renewable Energy

• Low-Carbon and Zero-Carbon Industrial Process Reengineering

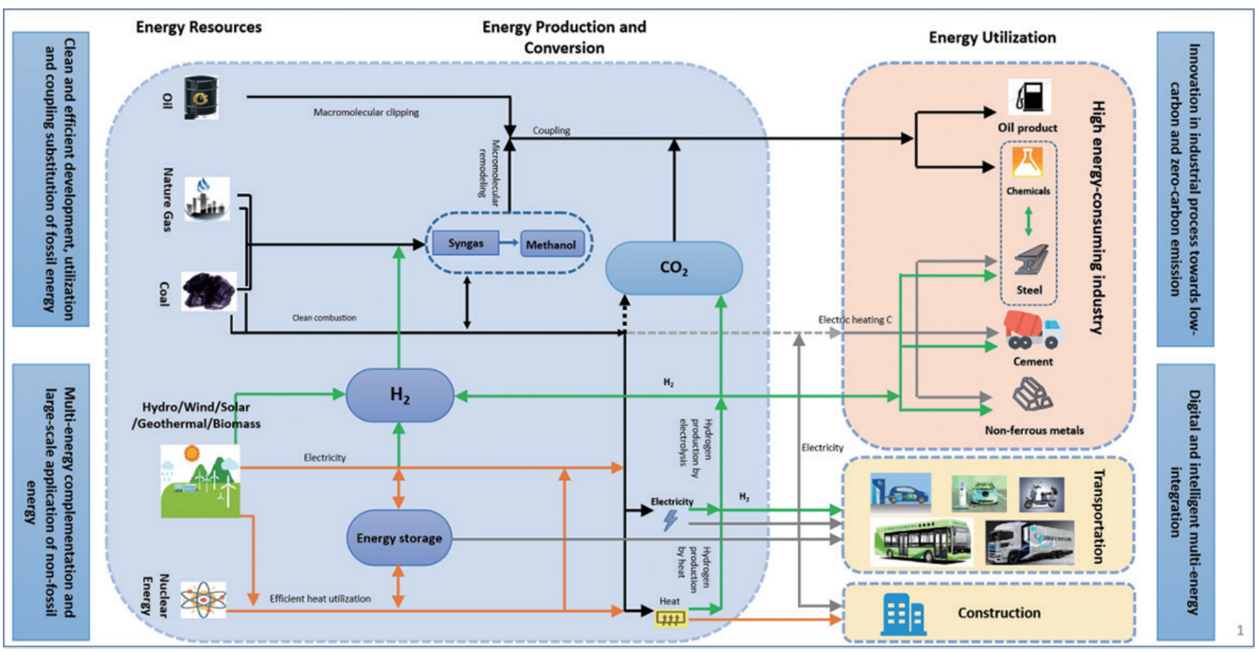
• Digital and Intelligent Energy Systems

Supporting these strategic threads are key platforms, including synthetic gas/methanol, carbon dioxide, hydrogen, and energy storage. This holistic approach aims to enhance energy production, consumption, and carbon fixation, thereby promoting the transformation of the

The world's first industrial methanol-to-olefins unit.

Graphic: DICP

Diagram of the Multi-energy system integration roadmap.



Graphic: DICP

energy structure and the reengineering of industrial processes.

For instance, DICP's development of the Dimethyl ether or Methanol-to-Olefins (DMTO) technology has been a game-changer for the coal chemical industry. Light olefins, crucial raw materials for the chemical industry, have long been derived from petroleum.

Given China's energy profile, utilizing coal as a substitute has been a strategic priority. Developed by the team led by Prof. LIU Zhongmin, a Member of the Chinese Academy of Engineering (CAE) at DICP, this groundbreaking technology saw its first application in 2010 when the world's first coal-to-olefins plant using DMTO technology was successfully commissioned at Shenhua Baotou.This remarkable achievement attracted wide attention, earning the first prize of the National Technical Invention Award in 2014.

Since its initial implementation, DMTO technology has undergone significant evolution, now in its third generation (DMTO-III). The current capabilities of this technology are impressive, with a single DMTO-III industrial facility boasting an annual production capacity of 1.05 million tons of ethylene and propylene. The total production capacity of light olefins for all licensed DMTO units has reached 23.4 million tons per year, with 10.4 million tons per year coming on stream. The economic impact of this technology is equally noteworthy, having driven investments of approximately 400 billion yuan (about 56.7 billion USD).

DMTO technology has propelled China to a position of global leadership in the coal-to-olefin industry. This achievement was highlighted by Chinese President XI Jinping at the 2021 Science and Technology Conference, where he emphasized that DMTO as a key technological innovation drives the rapid development of China's coal-to-olefin industry.

Graphic: DICP

A 100MW/400MWh vanadium flow battery energy storage power station for peak shaving that reduces strain on the grid.

In the realm of large-scale renewable energy utilization, energy storage technology plays a crucial role. It effectively addresses critical challenges in power systems, including operational safety, electricity balance, and the integration of renewable energy sources. These solutions are essential for supporting the extensive development and utilization of renewable energy.

A notable advancement in energy storage solutions has been achieved by the research team led by Prof. LI Xianfeng at DICP. They have successfully developed an advanced vanadium redox flow battery technology, marking a significant breakthrough in this field. The key achievements of this research are the design and production of critical components, including ion conductive membranes, electrolytes, and bipolar plates, which enhances the technology's accessibility and scalability.

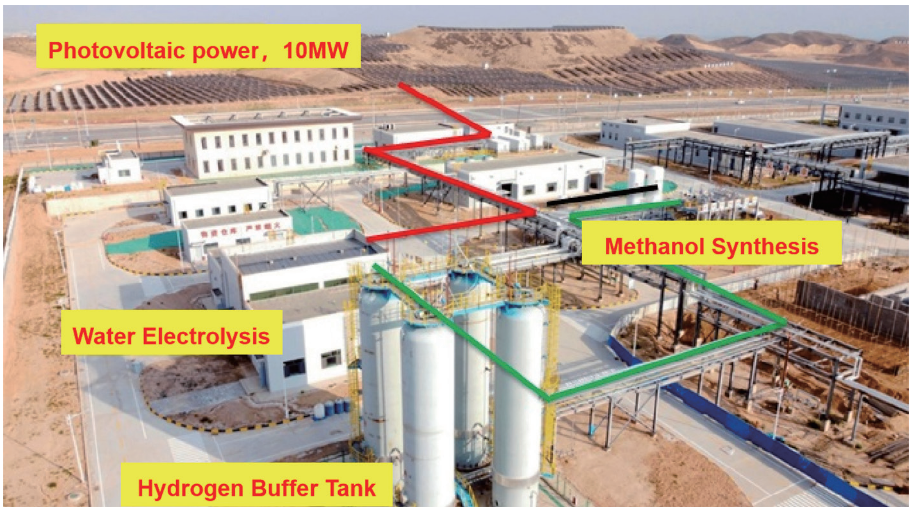
In October 2022, the world's first 100-megawatt-level vanadium redox flow battery power station for energy storage and peak regulation, designated as a National Demonstration Project, was successfully connected to the power grid. This inaugural phase boasts an impressive capacity of 100MW/400MWh, which means that the system can deliver 100 MW of power continuously for 4 hours before the energy is exhausted, showcasing the technology's potential for large-scale energy management.

For further advancement in the field, the team has developed a new generation of this technology. They have completed the construction of a 300MW cell stack production line in its initial phase. A 250kW/1MWh energy storage system with a non-fluorinated composite porous ion conductive membrane has been integrated. The innovative system represents a significant leap in efficiency and environmental sustainability.

The global impact of this technology is evidenced by its recent export to other countries, including Europe countries such as Belgium. This international adoption marks a significant milestone, demonstrating the

Graphic: DICP

The megawatt-level proton exchange membrane (PEM) water electrolysis hydrogen production system (left) and the megawatt-level hydrogen proton exchange membrane fuel cell power generation system (right).



Graphic: DICP

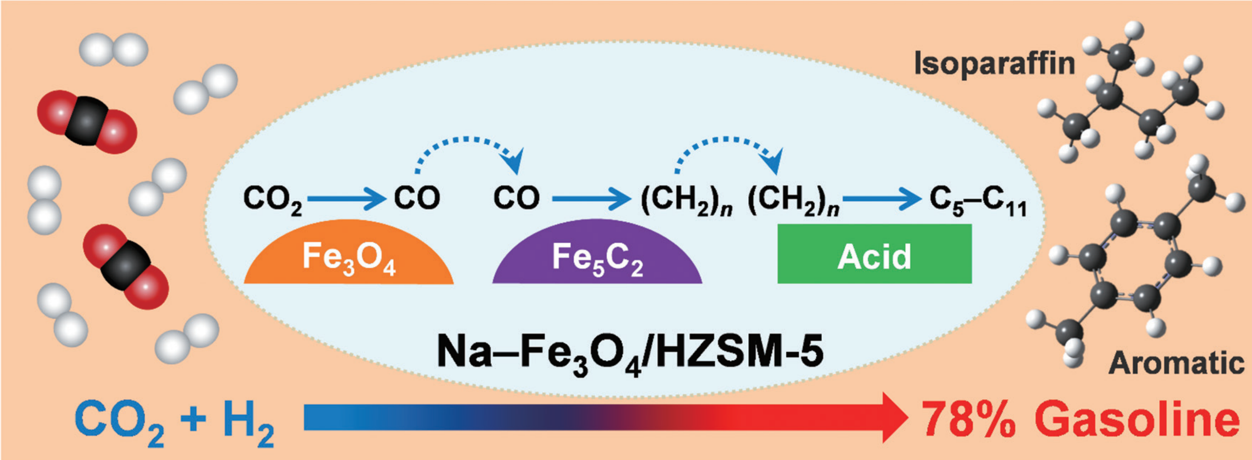
A 1,200 ton/year "Liquid Sunshine" demonstration unit that uses sunlight power to convert CO_2 into methanol in Lanzhou, China.

competitiveness and reliability of Chinese energy storage solutions in the global market.

Hydrogen, serving as both fuel and industrial raw material, can stabilize power systems through an "electricity-hydrogen" coupling system while enabling the expansion of renewable energy into hard-to-decarbonize sectors such as chemical manufacturing and metal smelting. This positions hydrogen as a vital component of the multi-energy integration system. Prof. SHAO Zhigang's team has prioritized research on hydrogen energy production and its applications. They have successfully developed a proton exchange membrane (PEM) water electrolysis system for hydrogen production, along with a hydrogen fuel cell. In July 2022, both the megawatt-scale PEM hydrogen production system and the megawatt-scale hydrogen fuel cell power generation system—developed by the team with independent intellectual property rights—successfully passed their project evaluation.

In the pursuit of carbon neutrality, the production of high-value chemicals and fuels using CO_2 as a raw material has emerged as a critical strategy. Researchers at DICP have conducted research in related fields, with two research teams achieving notable breakthroughs. Prof. LI Can, a Member of CAS, has pioneered low-energy-consuming, large-scale renewable energy electrolysis for hydrogen production with his team. They have also developed innovative solid solution catalyst for producing methanol from carbon dioxide hydrogenation with high selectivity, high conversion rate, stability of sintering resistance and sulfur resistance. In 2020, this research culminated in the construction of the world's first 1,200 ton/year CO_2 hydrogenation to methanol pilot in Lanzhou, China.

This achievement realized the entire "Liquid Sunshine" process, a concept that transforms renewable energy into liquid fuels. The significance of this tech-



Graphic: DICP

Schematic diagram of CO_2 hydrogenation catalytic reaction.

Graphic: DICP

A 1,000 ton/year CO_2 hydrogenation to gasoline pilot plant.

nology was recognized globally, and it was selected as one of the "Top Ten Emerging Technologies in the Field of Chemistry" by the International Union of Pure and Applied Chemistry (IUPAC) in 2022. Building on this success, the world's first 100,000 ton/year "Liquid Sunshine" fuel synthesis project is currently under construction in Ordos, Inner Mongolia, marking a significant scale-up of this technology.

Besides these efforts, Prof. SUN Jian's team has made groundbreaking advances in the direct synthesis of high-quality gasoline from CO_2 hydrogenation by developing a multifunctional catalytic system using iron/molecular sieves, which enable a precise control of the spatial structure and interaction between complex active iron species and adjacent acid sites, effectively promoting the synergistic matching of C–O bond activation and C–C bond coupling. The team also developed supporting reactors which promoted the reaction from laboratory to industrialization.

The practical application of this technology has been demonstrated through the world's first 1,000 ton/year CO_2 hydrogenation to gasoline pilot plant. This facility produces high-quality gasoline under mild conditions, with high octane value isomers and aromatics as the main components, meeting China's national VI emission standards. The process achieves impressive efficiency, with CO_2 conversion rates of up to 95% and gasoline selectivity reaching 85%.

These advancements in CO_2 utilization technologies provide innovative directions for addressing energy security challenges while contributing to carbon neutrality goals.

Outlook

Embracing the future, the Dalian Institute of Chemical Physics will continue to uphold its spirit of "Innovation, Collaboration, Academic Rigor, and Excellence". As a "national team" in institutionalized scientific research, DICP remains committed to advancing clean energy technologies and contributing to the transformation of China's energy landscape. By leveraging its role as a leading national research institution, DICP aims to continue its tradition of excellence and innovation, helping shape a sustainable, low-carbon future for generations to come.