Chapter 7
Technical Support for Long-Term Deep Decarbonization

According to the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5 °C released in October 2018, achieving the 1.5 °C target requires net-zero CO_2 emission by the middle of this century. And this necessitates the innovations and applications of a wide array of key revolutionary technologies.

Long-term deep decarbonization development of the world and China entails a variety of medium- and long-term emission reduction technologies. To enable the 1.5 °C target, the analysis on potential and cost of deep decarbonization technologies is essential.

Comprehensive cost–benefit analysis of deep decarbonization technologies underpins technology selection and emissions strategy. This chapter begins by analyzing the comprehensive impact of multiple energy efficiency and low-carbon technologies in terms of technology maturity, economic impact, social impact, environmental impact and ecological impact, followed by a roadmap for the development of major technologies.

In this chapter, over ten deep decarbonization technologies were diagnosed and evaluated, including research and development progress, cost effectiveness, development potential and policy requirements.

7.1 Comprehensive Cost–Benefit Analysis of Long-Term Deep Decarbonization Technologies

7.1.1 Research Background

China's decarbonization technological advances are playing a leading role. The emission reduction potential of traditional technologies is limited, and the contribution of rational demand and structural adjustment and optimization has been on the rise.

Institute of Climate Change and Sustainable Development of Tsinghua University et al., *China's Long-Term Low-Carbon Development Strategies and Pathways*,
https://doi.org/10.1007/978-981-16-2524-4_7

China still has tremendous potential for energy conservation and carbon reduction by using negative and low-cost technologies, which may grow with technological progress and structural upgrade. Deep emissions reduction in end-use sectors calls for the development of low-carbon or zero-emission technologies, processes and products, collaborative innovation of disruptive energy technologies, new materials and information intelligence, and the deep integration of advanced technologies with the shift of green consumption concepts and behavior patterns.

A spate of domestic and international studies has identified carbon capture and storage (CCS), advanced nuclear energy, hydrogen energy, and geoengineering technologies, as well as technologies in the building, transportation, industrial, and energy storage sectors as crucial medium- and long-term emission reduction technologies (see Fig. 7.1). Most of these studies develop roadmaps for the development and deployment of emission reduction technologies based on industry demand and technical economics, without comprehensive cost–benefit analysis (i.e. impacts on environment and ecology). Thus, further research is needed.

As shown in Fig. 7.2, existing research mainly focuses on the research and development of new technologies and cost reduction of existing emission reduction technologies. Domestic research primarily concentrates on technical details and the improvement and dissemination of existing technologies, instead of focusing on the new technologies and other related as the international studies did. The current mainstream perception of medium and long-term emission reduction strategy is more of qualitative understanding, with more interest on improvement of available technologies and systems, cost reduction and proliferation, and less attention to potential new technologies and quantitative assessment of their emission reduction potential. Furthermore, most of the existing research is based on technical and economic costs estimation, lacking goal-driven mid- and long-term technological

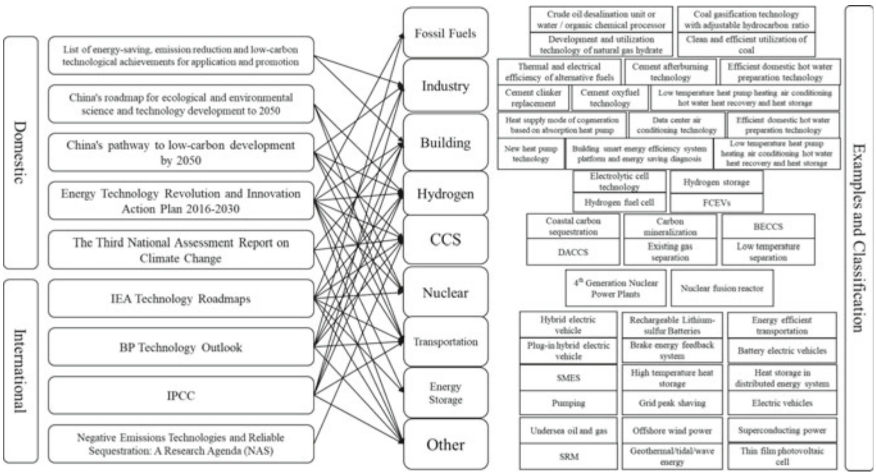

Fig. 7.1 Examples and classification of mid- and long-term emission reduction technologies in domestic and international research

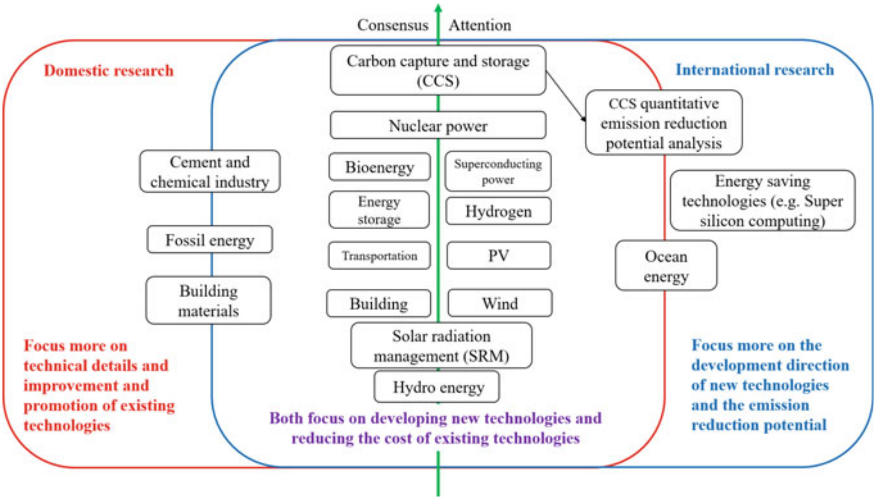

Fig. 7.2 Comparison and analyze of mid- and long-term emission reduction technologies in domestic and international research

strategies or roadmaps that accommodate ecological and social impact after the massive penetration of such technologies.

7.1.2 *Dimensions of Analysis*

As shown in Table 7.1, this study selects renewables (wind and solar), biomass, negative emission technology (CCS), hydrogen, nuclear as well as other technologies, such as demand-side management and energy efficiency improvement technologies, and synthesizes the conclusions on impact assessment in existing studies.

Among these technologies, opinions are divided on the technology maturity of demand side management. Some studies suggest that this kind of technology is fairly mature as it's widely used in daily life. But there is still much room for improvement from a climate perspective, for example, to what extent car-sharing will reduce the demand for cars. There is still big gap in the study of demand influenced by technology breakthroughs, while the impact of economic, social, environmental and ecological on the demand is relatively certain.

As shown in Fig. 7.3, this study rises above traditional technical and economic analysis, and sorts out the diverse categories of technology maturity, employment, environment, ecology, population health, public acceptance and other factors. Comprehensive cost–benefit analysis of wind, solar, biomass, carbon capture and storage, hydrogen, and other technologies is provided in detail, and the conclusions can be reference for holistic evaluation of medium and long-term emission reduction technologies.

Table 7.1 Conclusion of comprehensive impact of mid- and long-term emission reduction technologies made in existing studies

	Technological maturity	Economic impact	Social impact	Environmental impact	Ecological impact
Demand side management	Immature	Relatively certain	Relatively certain	Relatively certain	Relatively certain
Energy efficiency improvement	Mature	Relatively certain	Relatively certain	Relatively certain	Relatively certain
Wind and solar	Mature	Relatively certain	Relatively certain	Relatively certain	Uncertain
Biomass	Relatively mature	Uncertain	Uncertain	Relatively certain	Uncertain
Hydrogen	Immature	Relatively certain	Relatively certain	Relatively certain	Relatively certain
Nuclear	Relatively mature	Relatively certain	Uncertain	Relatively certain	Uncertain
CCS	Immature	Uncertain	Uncertain	Relatively certain	Uncertain

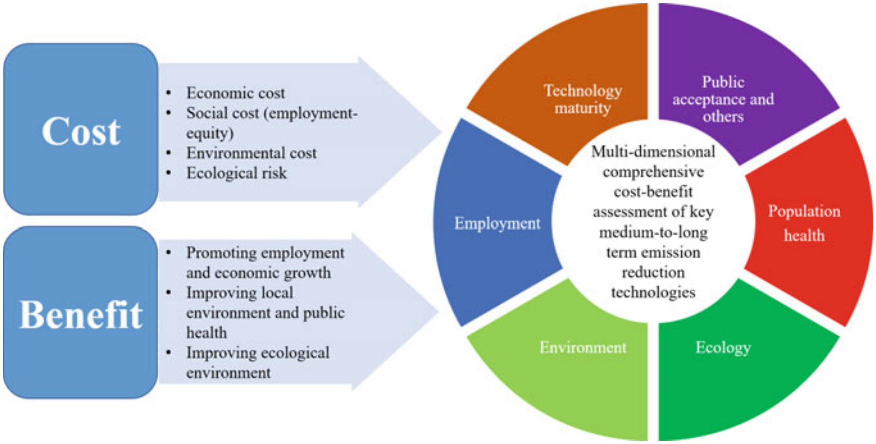

Fig. 7.3 Comprehensive analysis framework of key technologies for deep decarbonization

7.1.3 Horizontal Comparison of Key Technologies and Priorities

Table 7.2 illustrates the horizontal comparison of seven key technologies in terms of their comprehensive cost–benefit from six dimensions. A quasi-quantitative analysis is conducted on the whole despite possible controversies.

Table 7.2 Horizontal comparison of key technologies in terms of comprehensive cost–benefit

	Technological maturity	Employment impact	Local environmental impact	Ecological impact	Population health	Public acceptance
Demand side management	±	+	++	++	++	++
Energy efficiency improvement	++	+	++	++	++	++
Renewables (such as wind and solar)	++	++	++	−	++	++
Biomass	+	+	±	−	±	++
Hydrogen	−	+	+	±	+	+
Nuclear	+	+	+	−	+	−
CCS	−	+	−	±	−	−
Legend	++: mature +: relatively mature −: not yet fully mature	++: great boost to employment +: boost to employment	++: great boost to local environmental improvement +: boost to local environmental improvement ±: uncertain impact to local environment −: potential damage to local environment	±: uncertain impact on ecology −: potential risk for ecology	++: great boost to population health +: boost to population health ±: uncertain impact on health −: potential adverse impact on population health	++: high public acceptance −: low public acceptance for now

Note + and − signify subjective qualitative judgment of technology impact, of which + denotes positive impact, and − refers to negative impact, and the number of + suggests level of impact

Opinions are divergent on the technology maturity of demand side management, however, there is rising consensus that demand side management produces positive impact on environment, ecology and population health. In general, demand side management and energy efficiency technologies feature universal benefits and represent the key priority areas for future low-carbon development. Yet their potentials and scale are subject to uncertainties in terms of future technological progress and breakthroughs as well as policy implementation.

Renewables such as wind and solar power generation have positive employment and health benefits, with relatively high technology maturity and a high degree of public acceptance. Thus, these renewables could be the priority for developing long-term emission reduction technologies. But their exponential growth should accommodate the eco-friendly spatial layout. For instance, installation of such facilities in high-risk areas could potentially pose local ecological damage, hence precautions are needed.

The amount of biomass is relatively small compared with other renewables, but the maturity of technology is higher. However its impact on the environment and people health cannot be generally described due to its wide variety and various ways of utilization. For example, biogas power generation helps reduce environment pollution, but indoor biomass combustion can be detrimental to human health and air quality. From an ecological viewpoint, the rapid development of biomass means more consumption of land and water resources, and more land was inapproriately explored with abundant artificial irrigation generates mounting risks for the ecological system. The utilization of biomass should be integrated with other sectors such as transport and power generation, and should be intensified to avoid negative impact on health.

Experts pointed out that China's hydrogen technology relies on policy support, and technological breakthroughs. While the key barriers for nuclear power are ecological risks and low public acceptance.

Zero emissions technologies, in particular CCS, are not mature. If future power system still highly dependent on coal-fired generation, the large-scale deployment of CCS and other zero and negative emission technologies would bring negative impacts on environment, not to mention ecological and commercial risks or public acceptance obstacles.

This study assesses the ecological and health impact of the five key technologies on emission reduction cost (see Fig. 7.4). It's observed that improvement in energy efficiency brings all aspects of benefits; the development of wind, solar and other

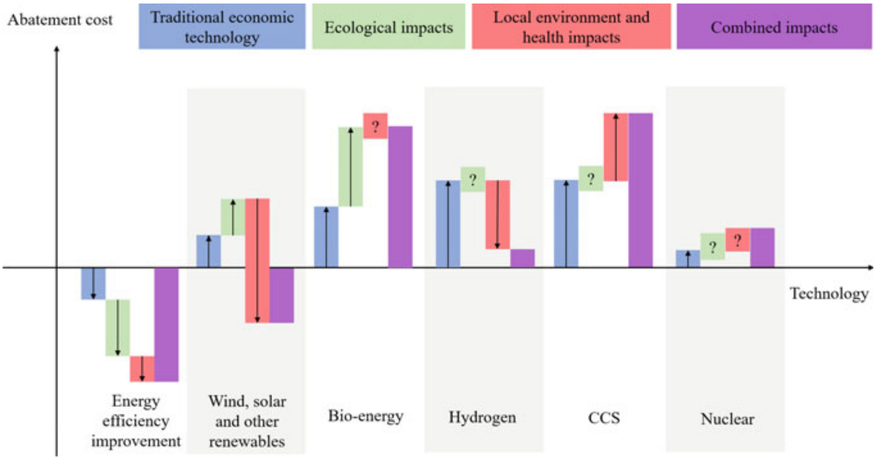

Fig. 7.4 Schematic diagram of abatement cost changes of China's key mid- and long-term emission reduction technologies considering ecological and health impacts

renewables, with the benefits for local environment and population health, features certain overall benefits; biomass, hydrogen and CCS involve high cost of emission reduction because of their potential ecological risks or environmental impact.

It should be noted that, with a comprehensive evaluation, the cost of emission reduction from of energy efficiency improvement, renewables such as wind and solar, biomass, hydrogen, and CCS are increasing in turn. It is expected that with the decarbonization of the power industry, the cost–benefit analysis and comparison of these technologies will be subject to more changes.

7.1.4 The Strategic Importance of Advanced Low-Carbon Technologies to Deep Decarbonization

As shown in Fig. 7.5, power supply system, energy system and strategic technologies in the technology innovation system are mutually reinforcing. Deep decarbonization entails the development of advanced low-carbon technologies as a strategic support. With close interplay between the technology innovation system and the energy system, the selection, management, and breakthrough of technologies all coincide with the development of energy system.

In general, the development of low-carbon technologies in the energy system will be complemented by technological innovation and revolution in the whole society. Specifically, the low-carbon technologies of the power supply system are interrelated with the energy Internet, energy big data, energy and artificial intelligence

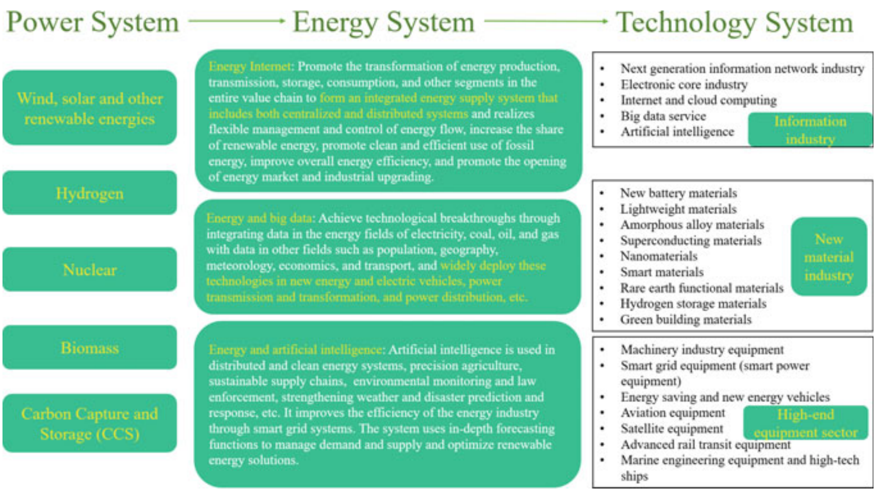

Fig. 7.5 Mutual support of strategic technologies in power system, energy system, and technological innovation system

technologies of the energy system, and are further correlated with the development of industries such as information technology, new materials and high-end equipment.

7.1.5 Conclusions and Suggestions

A holistic assessment of such dimensions of low-carbon technologies as employment, environment, ecology, health impacts and public acceptance, would improve the assessment on technology potential, cost effectiveness and spatial layout, which would also help to promote the synergies between carbon emission reduction and sustainable development.

Technologies of demand side management and energy efficiency have positive effects on sustainable development, and represent the key priority areas for the future of low-carbon development. Yet their potentials and scale are subject to uncertainties in terms of future technological progress and breakthroughs.

Renewables such as wind and solar power could be the priority of mid-to long-term emission reduction technologies. But their exponential growth should accommodate eco-friendly spatial distribution and forestall potential ecological risks.

Resting only on marginal land and rainwater irrigation, energy crop farming cannot meet the demand of deep emission reduction in China. Near-term development of energy crops primarily serves the transport sector. Yet given its potential risks of taking up land resources and straining water resources, it should be deemed as a transitional technology for the low or even zero carbon transportation before electrification takes hold in the sector. The long-term development of energy crops should concentrate on the supply of power and heating of the electricity sector, with the installation of CCS at the end of the pipe.

Hydrogen is projected to serve a high percentage of end-use energy need by 2050 with considerable potential for emission reduction. Hydrogen market in China has huge potential. Its development in the future hinges on the level of cost reduction as demand soars.

Negative emissions technologies, such as BECCS, are not mature for now. Large scale deployment of negative emission technologies would most likely trigger adverse local environmental impact, not to mention their ecological and commercial risks as well as public acceptance challenge. Therefore, it should be viewed as the backup technology for mid-and long-term emission reduction, and more research is needed.

Nuclear energy is instrumental in securing clean, safe and reliable power supply. Meanwhile, it can boost jobs along the industry chain, and take the role of a major contributor to deep decarbonization of the power system in line with the targets of temperature limit. Despite its great potential, nuclear power in China is hampered by such challenges as supply chain development, cost, safety, and political factors. Thus, stronger policy support is essential for its future development.

For future development, this chapter puts forward the following suggestions.

- Strengthen multi-dimensional and systematic research on the cost–benefit of emission reduction technologies, and identify the spatial variation pattern of diverse technologies under varied future scenarios and varied constraints.
- Speed up efforts in building a market-oriented system of green technology innovation, and harness the role of various market in promoting the development of emission reduction technologies.
- Make systematic and continuous efforts to establish an innovation system for demand side management and energy efficiency technologies; employ a mixture of levers such as policy design, R&D of science and technology, education and publicity to raise public awareness, boost penetration of new products and technologies, foster innovation of the consumption pattern and improve the demand structure.
- Ensure the strategic security of green technology industrial supply chain, and speed up the breakthrough of bottleneck technologies.
- Explore the pathway of strengthening intellectual property protection and enhancing the balance of interests of intellectual property to prompt technological development and diffusion.
- Create a diverse investment and financing guarantee mechanism for the R&D of strategic technologies and a risk sharing mechanism for backup technologies.
- Deeply engage in global cooperation and trade in green technologies via the Belt and Road Initiative and the South-South Cooperation Framework, and facilitate global cooperation on emission reduction technologies and build a shared future for the technological innovation community.

7.2 Evaluation of Deep Decarbonization Technologies

This section analyzes and evaluates 12 deep decarbonization technologies under four categories in terms of their R&D progress, cost effectiveness, development potential, and policy requirements, etc.

7.2.1 Deep Decarbonization Technologies for Energy and Power Storage Systems

With a high proportion of intermittent renewable power fed to the grid in the future, large-scale energy storage, smart grid and distributed renewable energy network technologies are essential for the safe and stable operation of the power system.

1. Electrochemical Energy Storage Technology

As of the end of 2018, the cumulative installed capacity of energy storage projects worldwide had reached 181.0 GW, of which, pumped storage was the largest, standing at 170.7 GW, or 94.3% of the total. Electrochemical energy storage takes second spot with 6,625.4 MW, of which lithium ion battery held the largest capacity at 5,714.5 MW.

Table 7.3 compares key operating and economic parameters of energy storage technologies. Recent years have seen extensive research on energy storage technologies, especially electrochemical energy storage, with commercial demonstration and applications in massive grid connection with renewables, demand-side storage, frequency regulation, etc. [1]. But large-scale deployment is yet to be commercialized. Despite continuous cost reduction of lithium battery in recent years, there is still a big gap compared to the cost of pumped storage [2, 3], and challenges in technology, cost, and business model need to be overcome in order to gain penetration. Superconducting magnetic energy storage, supercapacitor, flywheel, and other energy storage technologies feature low cost per unit output power, but their unit energy costs are high, hence mostly applied for high-load and short-time occasions [4, 5] without massive adoption. Continuous revenue is the driver for the development of energy storage technologies, most of which, due to the cost barrier, have not been extensively used. The good news is the cost of electrochemical energy storage is rapidly falling, as studies found, and is on track to reach a level comparable to pumped storage.

With the improvement of safety, lifespan, and energy conversion efficiency, the market of lithium ion battery for electric energy storage has seen steady growth. Nowadays, domestic lithium battery technologies primarily consist of three mainstream routes: lithium iron phosphate ($LiFePO_4$) system, NCM system, and lithium titanate system. Considering the return of investment, lithium iron phosphate battery is being commercialized at a faster pace. The safety and stability of NCM lithium battery are mediocre. Lithium titanate battery has relative low energy performance compared with the other two, but it has excellent low temperature performance and can be used over ten thousand times under the condition of high charging and discharging rate. Battery energy storage technologies has flourished in the world

Table 7.3 Comparison of energy storage technologies by key metrics and economics

	Pumped storage	Electrochemical energy storage	Superconducting magnetic energy storage	Flywheel	Supercapacitor
Efficiency (%)	75	85	90	90	90
Energy (W·h/kg)	–	10 ~ 200	–	5 ~ 100	5 ~ 30
Power (W/kg)	Low	Low	High	High	High
Cost ($/kg)	60 ~ 2,000	300 ~ 2,500	300	350	300
Lifespan	Very long	Mid	Long	Long	Long
Length of discharging	Several hours	Several hours	Several seconds	Several seconds	Several seconds

in recent years, and represent a major route for the development of energy storage technologies.

The barriers for lithium battery energy storage technology lie in recycling and safety. The internal temperature of NCM battery rises to 200 ~ 300 degrees when it is subjected to collision, acupuncture, overcharging, or short circuit, which triggers reactions of anode materials and the subsequent swelling and explosion, among other safety hazards. Plus, control measures are not readily available when accidents occur.

2. Hydrogen Energy Storage

Hydrogen production through renewable energy electrolysis attracts great interests as hydrogen can be used as a cross-seasonal and cross-regional means of energy storage.

Different from traditional battery energy storage, the technology of hydrogen energy storage utilizes water electrolysis to produce hydrogen and store energy in the form of gaseous fuel, which can be used in chemical industry, hydrogen fuel cell vehicles, and gas stations, etc. Such technology is not only good for local application, but also long-distance transport with the aid of natural gas pipelines. Hydrogen energy storage technology is a major branch of power-to-gas (PtG) technology—the process of converting electrical energy into gas, usually hydrogen, which is injected into a natural gas pipeline or converted to methane by methanation.

The core concept of power-to-gas emerged as early as the nineteenth century. But it's not until 2009 that the first power-to-gas equipment was launched. So far, the practical application of both technologies has been rather limited. Relatively speaking, Power-to-gas is used more often and is mainly concentrated in Germany and other European countries. In the aforementioned projects, the transformed gas is either fed into the natural gas pipeline or directly used for transportation and power generation.

The German government is pinning its hope on power-to-gas, which is deemed in some studies as the silver bullet for the energy transformation of the country. The northern part of Germany has the largest concentration of wind farms, whereas electricity is primarily consumed in the south. Thus, Germany chose to convert electricity into hydrogen for storage and replace direct power transmission.[1]

Relevant studies show that, since hydrogen storage technology is still at the stage of R&D and demonstration, which is hard to evaluate future cost precisely. Plus, it entails more energy conversion than electrochemical energy storage, which makes for greater energy loss and equipment investment, hence greater difficulty in cost reduction.

At present, the overall efficiency of operational power-to-gas demonstration projects is roughly 60%. The conversion efficiency of each project depends on the specific power-to-gas technology. As shown in Table 7.4, the investment cost and life span of varied power-to-gas technologies are different—the larger the power-to-gas capacity, the smaller the investment per unit of capacity. The AWE (Alkaline water electrolysers) represents a better choice for large-scale application than PEME (Proton Exchange Membrane electrolysers); whereas the technical constraint

[1] http://www.juda.cn/news/19716.html.

Table 7.4 Technical and economic parameters of varied power-to-gas technologies

	Type of technology	Conversion efficiency (%)	Life span (Year)	Fixed investment cost (USD/kW)	Energy consumption (kWh/Nm^3)[a]
1	AWE (Alkaline water electrolysers)	70–80	20–30	800–1,500	5–7.5
2	PEME (Proton Exchange Membrane electrolysers)	75–90	3–5	1,500–3,000	5.8–6.3
3	CM (Chemical Methanol)	70–85	3–8	500–1,500	
4	BM (Bio-Methanol)	95–100		500–800	

Note 1 $Nm^3/h = 0.0899$ kg/h。
[a]This set of data is related to the rated power. Varied power makes for data variance

of BM (Bio-Methanol) makes it suitable for small power-to-gas projects despite its higher efficiency and lower cost, and CM (Chemical Methanol) should be the preferred option for methanation for large power-to-gas projects. Annual operating/maintenance costs of power-to-gas stations are generally considered to be around 5% of fixed investment costs. Studies estimate that the average daily operating cost of AWE and CM is approximately $3500–5300, and that of PEME and BM combination is roughly $1400–2300.

China also attaches great importance to the research of power-to-gas technology. The R&D and demonstration project of 70 MPa hydrogen stations based on renewable energy/hydrogen storage was launched during the 12th Five-Year Plan period, with a focus on the application of power-to-gas in hydrogen stations for fuel cell vehicles. The research and demonstration project for direct hydrogen production through wind power and fuel cell power generation system was also deployed, targeting key technologies for wind power hydrogen and fuel cell integrated system. However, compared with the strategic planning and rapid development of hydrogen storage technology in advanced countries, there is still a big gap in key technologies and applications for China.

Currently, the cost of hydrogen storage in power-to-gas technology remains persistently high for two main reasons. Firstly, the electrolytic hydrogen production device is expensive. Economical operation can only be ensured with high utilization and a long running time throughout the year. Secondly, the energy conversion process incurs heavy loss of energy. Therefore, the key to the development of hydrogen energy storage technology is cost reduction and efficiency improvement. Only focusing on technical issues would not be enough to enhance the integrated energy application of hydrogen. Newer and more applications should also be developed to make new business models possible.

3. Nuclear Hydrogen Production Technology

Nuclear hydrogen production uses the heat generated by nuclear reactors as the main energy source, to make the large amount of hydrogen produced from hydrogen-containing substances (e.g. water or fossil fuels) in an efficient and carbon-free manner.

The pathway of developing nuclear hydrogen production technology should take into account the following factors: technical features (including capacity, purity of hydrogen, end-user, and waste management), cost (i.e. price of hydrogen, technical economics evaluation, and R&D cost, etc.) and risk (technology development, maturity, and R&D), etc. The process heat provided by the reactor must be utilized to achieve the efficient conversion of nuclear energy to hydrogen. The mainstream technologies include thermochemical cycle (sulfur-iodine cycle and mixed sulfur cycle) and high-temperature steam electrolysis. The former mainly involves chemical technology with a more complex process yet easier scale-up, so is suitable for large-scale hydrogen production. The latter is mainly determined by material technology, and its process is simple, which applies to small-scale hydrogen production.

Currently, the pressurized water reactor (PWR), which is widely used for power generation, is mostly utilized for power generation due to its relatively low outlet temperature. High temperature gas-cooled reactor is considered as one of the most suitable types for hydrogen production on account of its high outlet temperature, inherent safety and proper power.

The past decades have witnessed continued worldwide research efforts on hydrogen production via nuclear energy.

1. Japan: from the 1980s to now, Japan Atomic Power Agency (JAEA) has been conducting research on high temperature gas-cooled reactor and hydrogen production through iodide-sulfur recycling. The outlet temperature of its proprietory 30 MW high temperature gas-cooled test reactor (HTTR) was further raised to 950 °C in 2004. Combined with its commercial reactor (GTHTR300C), the co-generation of heat and power based on sulfur-iodine circulating hydrogen is being developed, and basic designs including cost estimates have been completed.
2. United States: the main research has been focusing on sulfur iodine cycle, mixed sulfur cycle and high temperature solid oxide electrolysis hydrogen production. In 2003, a preliminary evaluation and cost estimate of HTGR combined with sulfur-iodine circulating hydrogen production was conducted, which showed that the most important factors affecting the cost were nuclear thermal cost and electricity price of hydrogen production unit.
3. Canada: The supercritical water cooling reactor (SCWR) was developed, but the maximum output did not meet the demand for iodide-sulfur cycle. Then, a new cycle—copper-chlorine cycle—was proposed and developed with around 400–500 °C reaction temperature only, and supports with a net output of hydrogen and oxygen from water. The feasibility of the cycle has been verified by experiments, and a modification scheme for the model has been proposed to solve potential problems.

4. Argentina: At the end of last century, a recycling hydrogen production scheme from iron chlorine, cobalt chlorine, vanadium chlorine and vanadium chlorine was proposed. As estimated that the energy efficiency of the four methods are roughly 26%, 25%, 27% and 71%, respectively.
5. China: Institute of Nuclear and New Energy Technology of Tsinghua University developed and designed a sulfur-iodine cycle and high-temperature steam electrolysis system, and built an integrated laboratory-scale bench with hydrogen production capacity of 100 NL/h. At the end of 2013, the facility verification of the I-S closed cycle was achieved, and the production rate of hydrogen reached to 60 NL/h. The schedule is to complete the research on key equipment and technologies of high-temperature gas-cooled hydrogen reactor by 2020, validate the pilot project of high-temperature gas-cooled hydrogen reactor by 2025, and carry out the project demonstration of ultra-high-temperature reactor—nuclear energy hydrogen–hydrogen production and hydrometallurgy by 2030.

The International Atomic Energy Agency (IAEA) established the Coordinated Research Program (CPR) in 2012, in order to evaluate the technical economics of nuclear hydrogen production. The CPR intended to assess the technical and economic potential of nuclear hydrogen production by comparing alternative technologies, and through information sharing among member countries. Except for China, Members from 11 countries are currently involved in the project, such as US, Germany and Japan. Nuclear power routes identified for hydrogen production could be: supercritical water-cooled reactor (SCWR), pebble bed modular reactor (PBMR), high temperature gas-cooled reactor (HTGR) and prismatic gas-cooled reactor (PRISM). Possible technologies for hydrogen production could be: sulfur-iodine cycle, copper-chlorine cycle, mixed sulfur cycle, steam methane reforming and high temperature electrolysis.

Based on the data produced by 2014, IAEA estimated the cost of four available technologies using HEEP software: Canada CANDU pressurized-water reactor, China INET HTR-PM, Germany HTR-Modul and Japan GTHTR300C ultra-high temperature reactor, corresponding to CASE I, II, III and IV. CRP estimated the average cost of hydrogen under four scenarios (excluding costs of storage and transportation) at $2–3/kg, with about 40% coming from hydrogen production and 60% from nuclear heat production. Considering the unique economic feature in different regions, the fluctuation would be around 20%.

As shown in relevant studies, the cost of nuclear hydrogen production would decrease in the future, depending on the large-scale industrialization of technologies. Around 2030, the cost may drop to a level of competitive with conventional processes.

4. Deep Decarbonization Technologies for Power Sector

Low-carbon power generation, smart grid, energy storage, demand-side response, and energy Internet techonologies will be the key to support net zero emission of the power system.

Smart grid and energy Internet are crucial deep decarbonization technologies to the power sector with five key technologies. As combined with renewable power generation technologies, a zero emission power system with 100% clean energy could be achieved.

Key technology 1: Virtual synchronization technology. Virtual synchronous technology mainly simulates the characteristics of the synchronous generator, such as the ontology model, active frequency modulation and reactive voltage regulation, so that the grid-connected inverter could be comparable with the traditional synchronous generator considering operation mechanism and external characteristics. Distributed power sources, such as energy storage, wind power, photovoltaic, electric vehicles, etc., are mostly connected to the distribution network in the form of an inverter interface, which provides a well application scenario for virtual synchronous generators. Virtual synchronization technology can increase the stability of new energy access and improve the potential of power grid to absorb clean energy.

According to studies, the cost of virtual synchronous machine renovation for wind farm is around 100 RMB/kW. There is no additional cost of standard virtual synchronous machine for new wind farms. The renovation of virtual synchronous machine of photovoltaic power plant adds the cost to about 600 RMB/kW. The standard virtual synchronizer for new photovoltaic power plant adds the cost to 200 RMB/kW. The cost of centralized virtual synchronizer is 220 RMB/kW, when a continuous decrease of energy storage prices followed, the construction cost would fall to around 100 RMB/kW by 2050.

Key technology 2: Solar thermal power generation technology. Solar thermal power generation collects solar energy by reflecting sunlight to solar collector, and provides high-pressure superheated steam to drive steam turbine for power generation through heat exchanger. The heat storage medium heated by solar energy can be stored in huge containers that can still turn a turbine to generate electricity hours after sunset. As the working mode of wind power and PV is greatly affected by the weather, the green power from wind and PV is random and intermittent. Therefore, the grid has an upper limit to accept the green power from wind and PV. Solar thermal power generation technology can provide controllable and low-randomness clean and green power, and also improve the potential of power grid to absorb clean energy.

According to professional forecasts, the investment of solar thermal power generation in the future will decrease by 10% year-on-year. At present, the unit kilowatt cost of solar thermal power generation in China is about 12,000 ~ 14,000 RMB/kW, which will drop to 9,000 ~ 11,000 RMB/kW by 2050. The normalized power generation cost of solar thermal power plant will fall to 0.67 ~ 0.76 RMB/kWh by 2020, and 0.50 ~ 0.56 RMB/kWh by 2050.

Key technology 3: Grid-side energy storage technology. It is difficult to harness the systematic and overall benefits of energy storage from power generation side and demand-side, as it has small energy storage capacity, scattered installation, and unlikely to follow unified grid regulation. On the contrary, as grid-side energy storage is usually large in scale and connected to the dispatching center at all levels. It contributes to the operation of the power system including load regulation, frequency regulation, blocking relief, voltage support, reactive power control, emergency standby in case of failure, etc. Grid-side energy storage also can ensure the spatial–temporal transfer of renewable energy, adjust frequency with thermal power units, and participate in various auxiliary power services, which could greatly improve the potential of the grid to integrate clean energy.

As shown in the research, the cost of existing energy storage technology is about 0.62 ~ 0.82 RMB/kWh. In the future, with further improvement of cell structure and process and material utilization, the system could be used by up to over 7,000 times, and the electricity cost of power plant would be reduced to about 0.3 RMB/kWh by 2050, while meeting the need of large-scale commercial application of energy storage.

Key technology 4: Demand-side response technology. Demand-side response refers to users actively changing their inherent power consumption patterns to respond to power supply by reducing or shifting the power load in a certain period, so as to ensure the stability of the power grid. Demand-side response can be divided into two categories: price demand response and incentive demand response. It can make up for the poor flexibility and slow response of conventional units on the power-supply side, greatly enrich the dispatching resources of the power grid, and enhance the flexibility of power grid dispatching. This technology can regulate the load to a certain extent, bring about flexible adjustment of energy use on the demand-side, so as to improve the integration of new energy on the power supply side equivalently, and also increase the potential of the grid to absorb clean energy.

Research shows the cost of demand response technology is extremely low, standing at 0.001–0.004 RMB/kWh now due to the low investment required in hardware and software. In the future, with the tariff reform of power transmission and distribution, mature market mechanism, and cost reduction of communication technology, the cost of demand-side response can go down by another 20% by 2050.

7.2.2 Deep Decarbonization Technologies for Industrial Processes

CO_2 emissions in steel, cement and other industrial processes are difficult to reduce deeply, which requires the promotion of decarbonization technologies.

1. Hydrogen Steel Making Technology

Generally speaking, long-process steel production mainly consists of three processes. First, iron ore is reduced to iron (commonly known as crude iron or pig iron). Next, crude iron is further decarburized to create crude steel, which is finally formed into different types of steel. Since the greenhouse gas emissions of the steel industry mainly come from the crude iron and crude steel production processes, direct reduction technology based on hydrogen and CCS are two important options to reduce CO_2 emissions. Compared to the end-of-pipe solution of CCS, hydrogen steelmaking replaces coke and other fossil fuels for reducing iron ore to crude iron, which helps eradicate CO_2 emissions and becomes one of the best decarbonization technologies known to the steel industry.

If hydrogen itself is produced in a zero-carbon manner, either through water electrolysis or by applying carbon capture and storage (CCS) technology to methane steam reforming or coal chemical production of hydrogen, direct hydrogen reduction to iron can help enable carbon-free steel production.

Currently, there are three projects in Europe that are focusing on hydrogen steel technology: HYBRIT, SALCOS and H_2Future/Susteel. The first two are mainly based on the existing reduction technology, whereas the last one uses the plasma melt reduction technology, but none of which need CCS or CCUS. SSAB in Sweden has launched a hydrogen direct reduced iron (DRI) pilot plant, which aims to achieve zero carbon steel production by the early 2040s. Salzgitter Steel in Germany is also conducting a pilot project, and Arcelor Mittal, the world's biggest steel producer, is also brewing this technology. Japan, South Korea, the United States and China are all have hydrogen steel projects under planning or demonstration. In China, Baowu Group has collaborated with China National Nuclear Corporation and Tsinghua University on hydrogen steelmaking in 2019, and is planning to work with Rio Tinto group on low-carbon metallurgy innovations.

Studies showed the cost estimate of hydrogen steel is fuzzy. Researchers from Tsinghua University estimated the cost of nuclear steelmaking by referring to parameters of the direct reduction project of Japan JAEA. Although hydrogen reduction steelmaking has not been commercialized, it can be calculated from the price of direct reduction steelmaking. Using the 10-year average price of steel from 2000 to 2010 as a reference and setting $670/ton steel for coke blast furnace and $675/ton steel for natural gas reduction, then the estimated cost of nuclear hydrogen is $2.45/kg$H_2$, and that of hydrogen steelmaking through nuclear is $628/tons of steel. Some studies suggested that hydrogen steel will be well positioned to compete with conventional processes.

By the progress of major hydrogen steelmaking projects around the world, this technology has great potential in the future, but its implementation cost is relatively high (see Table 7.5). Chances are predicted to be slim for its massive scale-up by 2030, and its potential is set to be released around 2050.

In 2018, the global steel output stood at 1.8 billion tons. If taking CO_2 intensity per unit of steel product as 1.8-tons/ton steel, the carbon emission of the steel industry was about 3.2 billion tons. If the current direct reduction technology can achieve a 50% reduction in emissions, 1.6 billion tons of CO_2 emissions can be saved in the steel industry. By adopting the technological combination of EAF and zero carbon electricity, an overall reduction of 80% could be achieved (2.5 billion tons of CO_2).

On hydrogen energy demand, in 2018, China produced around 900 million tons of crude steel (including roughly 800 million tons of long-process steel). If 50 kg of hydrogen is required for reducing each ton of iron, with hydrogen-based technology utilized in the long-process steelmaking, then approximately 40 million tons of hydrogen is needed.

2. Low-Carbon Chemical Technology based on Electricity and Hydrogen

CO_2 emissions in the petrochemical industry mainly come from atmospheric pressure reduction, catalytic reforming, catalytic cracking, hydrogen production, ethylene, ammonia synthesis, and other installations and power engineering [6].

Table 7.5 Major global hydrogen steelmaking projects

NO	Project	Technology	Emission reduction	Investment cost	Notes
1	HYBRIT (Sweden)	Hydrogen reduction steelmaking	HYBRIT is on track to cut 10% of CO_2 emission in Sweden[a] and lower CO_2 emissions by 7% in Finland[b]	The pilot phase investment will cost SKr 1.4 billion (almost half from Swedish Energy Agency)	The production cost of HRBRIT is about 20–30% higher than traditional steelmaking processes, and the gap is expected to narrow as the cost of renewable energy falls and the cost of carbon dioxide emissions rises. HYBRIT requires lots of cheap renewable electricity, and what's special about the HYBRIT process is that all hydrogen is produced by electrolyzing water. Although the process is energy-intensive, the carbon emissions from the whole process would be negligible if the electricity needed could be renewable.
2	SALCOS (Germany)	Hydrogen reduction steelmaking	Down by 50–85%[c]		
3	Voestalpine	The development of groundbreaking green hydrogen to replace coke smelting technology	Ultimately reduce 80% of CO_2 emissions by 2050	18 million Euro	The project lasts for 4.5 years.

(continued)

Table 7.5 (continued)

NO	Project	Technology	Emission reduction	Investment cost	Notes
4	Projects of big four steelmakers in Japan	Test blast furnace operation with hydrogen	Down nearly 10% compared to average blast furnace operation[d]		Assuming the same scale as the fine pulverized coal injection equipment for the existing technology, it is estimated that each blast furnace would require an investment of several billion yen[e]
5	South Korean project	Successful development of hydrogen reduction steelmaking technique	Down by over 15%[f]	R&D costs 915 million RMB; each blast furnace costs around 250 million RMB	
6	MIDREX H_2® (US)	hydrogen reduction steelmaking	Emission reduction by 80%		

[a]http://www.worldmetals.com.cn/viscms/bianjituijianxinwen1277/20180906/245527.html
[b]http://www.sohu.com/a/293905313_313737
[c]https://salcos.salzgitter-ag.com/en/index.html?no_cache=1
[d]http://www.worldmetals.com.cn/viscms/bianjituijianxinwen1277/20170112/240018.html
[e]http://www.sohu.com/a/231443680_313737
[f]https://mp.weixin.qq.com/s/SXiB_i95fhcH8Rl5zTEYXA

Carbon emissions from heat and electricity consumption account for more than 60% while emissions from fossil energy only made up less than 40% [7]. CO_2 emissions of this industry are different from any other manufacturing sector. The contribution of fossil fuels is not only about the energy released by combustion, but also from the coupling process of chemical reaction and energy conversion, in which a large amount of carbon is fed into the products through chemical reaction.

In the future, there would be three major ways to reduce carbon emission in the petrochemical industry. The first and foremost is the adjustment of energy supply and raw materials, including the source of heat and electricity, raw material, and corresponding process update, i.e. reducing the source of carbon emissions from the process and techniques. The second is the improvement of energy efficiency and fundamentally reduce energy consumption. Finally, some processes in petroleum and petrochemical production are characterized by high CO_2 emission concentration, such as coal hydrogen production, ethylene glycol production, acrylonitrile production and methanol production, etc. Then, CCUS technology can be used to collect and store or utilize the carbon dioxide emitted.

In a word, developing low carbon chemical technology based on power and hydrogen, implementing technical processes to produce methanol, olefins, hydrocarbons, synthetic ammonia, refined oil, and other petrochemical products based on electricity and hydrogen, and reducing or replacing coal, petroleum, or other fossil energy as chemical raw materials, are of crucial importance to achieve deep decarbonization.

2.1. Technical Route of Producing Methanol by Electric Hydrogen

This technology is to use hydrogen and pure CO_2 to produce methanol. Table 7.6 shows the comparison of such technical process with the traditional one in terms of the technical parameters of energy consumption and emission. As is shown below, methanol produced by electric hydrogen has significant advantages in carbon emission reduction.

Compared with the traditional petrochemical route, the economic cost of this technology is relatively high. The main challenge lies with the fixed cost of electrolytic cells, which accounts for about 75% of the total fixed cost. Depending on different electrolysis technologies, the current methanol synthesis cost is approximately 6,000–13,000 RMB/ton, far higher than the current traditional technological pathways. The cost is expected to drop to 4,400 RMB per ton by 2050.

2.2. Olefin MTO/MTP Technology Based on Methanol Production from Hydrogen and Pure CO_2

Methanol to Olefins (MTO) and Methanol to Propylene (MTP) are two important new chemical processes. At present, MTO and MTP technologies in China are quite mature. In the current MTO/MTO processes, the yield of low carbon alkenes such as ethylene and propylene can reach more than 80%.

The attainment of the zero carbon target for this technological route primarily hinges on methanol synthesis. If the previous methanol synthesis route is considered, the olefin technological route can also achieve negative emission.

However, similar to the technological route of producing methanol based on hydrogen and pure CO_2, its economic cost remains high, and the key is to reduce the cost of electrolytic tank. Considering the price fluctuation of coal and oil, the current cost of coal to methanol olefin is about 4,000–5,000 RMB/ton, while steam cracking of traditional mixed oil costs approximately 5,000–8,000 RMB/ton. The olefin cost of methanol production based on hydrogen and pure CO_2 will be more

Table 7.6 Comparison of methanol production through electric hydrogen with traditional petrochemical technological pathway

Methanol per ton	Petrochemical route	Electric hydrogen route
Total energy consumption (GJ)	37.5	39.7
Carbon emissions induced by raw materials (t)	0.97	−0.79
Carbon emissions in process (t)	0.52	0.123
Total carbon emissions (t)	1.49	−0.67

than 10,000 RMB/ton. At the current methanol market price of 1600 RMB, the olefin cost of this technological route will still rise by more than 2000 RMB/ton even if future methanol cost based on hydrogen and pure CO_2 is reduced to 4400 RMB/ton.

2.3. Technical Route of Synthetic Ammonia by Electricity and Hydrogen

Synthetic ammonia is the product of nitrogen and hydrogen under the joint action of high temperature, high pressure, and catalyst. At the moment, the existing technology relies on coal or natural gas to produce the hydrogen needed for ammonia synthesis. The most important source of carbon emissions from synthetic ammonia is hydrogen production processes. This ammonia synthesis technology is based on electric hydrogen, instead of coal and natural gas as the raw material to produce hydrogen.

Table 7.7 shows the comparison of such technological route and the traditional petrochemical route by technical parameters of energy consumption and emissions. It can be seen that the synthetic ammonia of hydrogen produced by electric power has significant advantages in reducing carbon emissions.

The economic cost of this technology is relatively high, which is roughly twice or more than traditional technologies. Some studies suggest that the cost per ton of synthetic ammonia in Chile and Argentina is around \$460–700, which is slightly higher than the \$300–600 per ton of synthetic ammonia produced from the existing steam methane reforming technology imported to Chile. The cost of synthetic ammonia based on electric hydrogen in northern Europe is likely to be 431–528 euros per ton in 2050, which is close to the market price.

2.4 Oil Products Produced by Hydrogen and Pure CO_2 via Fischer-tropsch (FT) Synthesis

In both crude oil refining and coal-to-oil technologies, hydrogenation process is neccessary, because the hydrogen content in crude oil and coal is insufficient to meet the demand of subsequent light oil products. As one ton of hydrogen is produced by water gas conversion, one ton of carbon dioxide would be emitted.

For every one ton of naphtha and gasoline produced by a traditional crude oil refinery, about 0.4–0.5 ton of CO_2 is emitted, and around 0.17–0.2 ton of CO_2 is discharged for every one ton of diesel [8]. For coal-to-oil technology, its carbon

Table 7.7 Comparison of technology of synthetic ammonia based on electric hydrogen and traditional petrochemical technology

Methanol per ton	Traditional petrochemical technology	Electric hydrogen technology
Total energy consumption (GJ)	35.04	45.1
Carbon emissions induced by raw materials (ton)	1.33	–
Carbon emissions in processes (ton)	0.5	0.12
Total carbon emissions (ton)	1.83	0.12

emission per unit oil product is very high without CCS technology, at roughly 5.5–6.9 tons of CO_2 [9].

The technology of producing oil products from hydrogen and pure CO_2 via FT synthesis relys on electric hydrogen, then use hydrogen and CO_2 to prepare syngas through the reverse water gas conversion reaction in order to synthesize oil products. Since hydrogen is produced without water and gas conversion, carbon emissions can be greatly reduced. Given that hydrogen production accounts for more than 25% of the carbon emissions from traditional technologies, carbon emissions per unit product of the technology can be reduced by more than 25%.

Compared with the traditional petrochemical technology, the economic cost of this technology is relatively high. The main challenge lies in the cost of electrolysis. Taking diesel as an example, the cost estimates of oil product synthesis based on different electrolysis technologies vary greatly. Some studies show that current cost is 4100–7000 RMB/ton, which is close to the traditional technologies, but the mainstream studies argue that the current cost is between 11,000–22,500 RMB/ton, which is much higher than the level of about 4,000 RMB per ton of traditional technology. The cost is expected to drop by 2050, but the cost per ton would still exceed 10,000 RMB.

3. Low-Carbon Cement Technology of Raw Material Substitution

Carbon dioxide is released in the process of calcining raw material into clinker to produce cement. The material ground to a certain degree of fineness after mixing in proportion by calcareous, clayey and a small amount of adjustment raw materials (sometimes mineralization agent and crystal seed are added; coal is also added to shaft kiln production) is known as cement raw meal. The substitution of raw materials has become a vital technology for low-carbon cement production.

As long as each chemical component in raw meal is proportioned properly, a variety of cement clinker conforming to standards can be produced. The traditional cement raw meal mix is shown in Table 7.8.

Producing clinker from alternative raw materials helps save raw material costs, reduce emissions, alleviate environmental pollution from all varieties of industrial by-products and save a bundle on the cost. The avaliable alternative raw materials are shown in Table 7.9, including calcium carbide slag, iron tailings, steel slag, silicon slag, silica sludge, and paper sludge.

Table 7.8 Content of main chemical substances in each component of traditional cement raw meal and burning loss rate

	Content of chemical constituents (%)					Burning loss rate (%)
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	
Limestone	5.58	0.42	0.31	50.58	1.51	39.75
Slag	34.72	10.86	1.85	38.4	9.67	1.2
Sandstone	66.09	8.9	4.06	6.66	3.5	8.37
Sulfate slag	10.51	2.84	65.21	8.69	3.64	5.52
Bauxite	39.18	32.00	12.38	0.92	0.14	14.35

Table 7.9 Content of main chemical substances of available alternative materials and burning loss rate

	Content of chemical constituents (%)					Burning loss rate (%)
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	
Carbide slag	2.29	2.45	0.36	68.35	0.78	23.48
Iron tailings	37.67	4.11	30.67	7.72	2.99	9.07
Steel slag	12.00	2.83	23.57	42.16	10.48	–
Silicon-calcium slag	22.07	2.41	5.00	57.75	0.81	10.84
Quartz sludge	85.96	3.73	1.57	0.51	0.26	4.51
Paper mill sludge	28	20	2.7	40.8	5.4	49.64

The chemical composition and content of various alternative materials are suitable for substitution, and some of them are even better than the original ones in terms of adjustment material content. When using alternative materials, it is necessary to pay attentions to the proportion of various raw materials and make appropriate adjustments to the subsequent processes.

The following obstacles, nonetheless, impede the extensive and continuous use of alternative raw materials in the cement industry.

Raw material supply. The global reserve of alternative materials is a technical challenge that hampers the wide use of alternative materials in cement plants. For example, the global output of granular blast furnace slag and fly ash in 2008 and 2007 was approximately one billion tons per year, which was insufficient for the high utilization rate of the global and cement industries.

Properties of cement products. Compared with the ash produced by fossil fuels, some alternative materials have different composition and content. The clinker composition produced by these materials in the kiln features has tremendous fluctuations. If the phosphorus in clinker exceeds the limit, the early strength of cement produced will decrease and the setting time will also be longer. In addition, the use of alternative materials can affect the long-term strength of the cement.

Economic challenge. Adjust the cost of purchasing, handling, and transporting raw materials to cement plants may result in additional costs.

In short, tapping into low-carbon cement technology based on alternative raw material, developing and applying alternative materials, and optimizing the mix of the raw materials, are all serve to reduce carbon dioxide emissions. But the cost of these technologies constitutes a major barrier, which calls for more technological breakthrough.

7.2.3 Deep Decarbonization Technologies for Transport Sector

The use of electricity and hydrogen instead of fossil fuels in the transportation sector represents a crucial deep decarbonization technology. It is essential to accelerate the development and proliferation of technologies for electric vehicles and hydrogen fuel cell vehicles.

1. Electric Vehicle Technology

Electric vehicles mainly consist of battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV). The former is driven by electric motors with electricity as the power source, while the latter is driven by internal combustion engine and motor separately or simultaneously, and the power is generated from gasoline, diesel or electricity. Many countries are actively taking measures to promote the strategic transformation of traditional gasoline vehicles and vigorously develop electric vehicles.

Despite the rapid progress in technology and performance, electric vehicles are yet to be competitive in terms of comprehensive cost. Breakthroughs have been made in key components such as electric motors, electronic controls, and battery management systems, with continuous improvement in system integration, vehicle performance and comfort as well as power consumption. At present, the volumetric energy density of lithium-ion batteries for cars is 200 ~ 300 Wh/L, and the battery cycle can reach 1000 times. The light vehicle battery market is dominated by NCM lithium batteries with high energy density, whereas lithium iron phosphate with higher cycle life and safety performance is the mainstream for medium and heavy vehicles. On the whole, the total cost of electric vehicles is currently higher than that of traditional internal combustion engine vehicles, which is largely driven by the high battery cost. With the breakthrough of key battery material technology, the cost of battery is on the decline.

The technologies and comprehensive performance of electric vehicles will witness tremendous improvement in the future. The comprehensive efficiency of powertrain and energy efficiency of vehicle will see significant improvement, with a dramatic reduction in vehicle power consumption, and the driving range will be equivalent to that of gasoline vehicles. Car bodies and parts and components will be much lighter through steady expansion of aluminum-magnesium alloy, high-strength steel, and carbon fiber materials, etc. The energy density and safety of lithium-ion batteries will be greatly enhanced, and innovative batteries will be gradually applied and commercialized on a large scale. In addition, with breakthroughs of Internet, big data and artificial intelligence and their rapid penetration into the automotive industry, new technologies and models, such as telematics, vehicle-to-grid (V2G), autonomous driving, vehicle-road collaboration, and intelligent manufacturing, will get flourished.

In the future, the comprehensive cost of electric vehicles will keep decreasing, and narrowing the gap with gasoline vehicles. With more stringent global regulations for car emissions, traditional internal combustion engine (ICE) technology will be further complicated, prompting rising cost for gasoline vehicles. In comparison, with the improvement in energy density of electric vehicle batteries, performance enhancement, and lower cost of comprehensive research, development, and manufacturing, the cost of electric cars will keep falling. Therefore, the comprehensive cost of electric vehicles will be superior over traditional internal combustion engine vehicles by 2025, and the cost will be competitive over gasoline vehicles and PHEVs by 2030, and the best comprehensive value/performance will be achieved by 2050.

The charging infrastructure for electric vehicles (EV) is undergoing rapid development. With surging sales and ownership of electric vehicles, charging facilities also show a rising trajectory. Countries vary in their priorities in supporting charging infrastructure. For instance, the United States provides incentives primarily in the form of tax relief and direct investment; Japan concentrates on supporting technology R&D and innovation; while China employs a mixture of policy instruments, covering planning, finance, infrastructure, technology, electricity, etc. Countries also vary in their charging technologies and standards, with diverse models of commercial operation for charging facilities. The comprehensive scale-up of high-power charging technology is now underway.

With increasing ownership of EVs, the relationship between vehicle charging/discharging and power grid has become another point of interest. EV energy storage can meet the needs of load regulation, frequency modulation, and grid connection of renewables by participating in auxiliary services and demand-side response. Especially with the increasing integration of renewable power in the future electric power system, EV energy storage will become a major flexible resource for the power system.

In short, the rapid development of EV technology and industrialization, declining cost, booming development of charging infrastructure, and the increasingly competitive overall cost over traditional ICE vehicles, will underpin deep decarbonization of the transportation sector.

The following obstacles hinder the development of EVs which needs particular attention:

1. The EV market is still primarily driven by policy factors, and market forces should promptly come into play to drive the market growth. There is also a dilemma as to which one should take the precedence over the other: infrastructure or vehicles. And the foundation of the EV industry remains fragile.
2. With the growing EV penetration, the sustainable supply of lithium, nickel, cobalt and other key resources needed for batteries is facing severe challenges, and the environmental pollution from the recycling and disposal of batteries is another issue for concern. In China, for example, the lithium reserve is around 3.2 million tons, or roughly 20% of the world's total reserves. However, due to the poor resource endowments and lack of industrial competitiveness, 70% of lithium supply in China depends on import. Nickel and cobalt resources are extremely scarce, accounting for only 3.4% and 1% of global reserves respectively, with over 60% and 90% of import dependency. With the massive scale-up and usage of EVs in the future, the scarcity of key battery resources will be

exacerbated. Moreover, the production, scrapping and recycling of batteries may cause serious pollution to the environment, such as the discharge of waste water, waste gas and waste liquid from the production process, electrolyte leakage in the process of recycling, the spread of heavy metals, and dust from materials dismantling, etc. The current battery recycling technology and the market are underdeveloped, and disposal processes are immature. The efforts to establish the recycling system have just started, and the legal framework is far from enough.

2. Hydrogen Fuel Cell Vehicle Technology

Hydrogen fuel vehicle technology represents the key technology pathway for low-carbon transformation in the field of automobile transportation. It involves the production, storage, transportation, filling, and final use of hydrogen energy for vehicles, including hydrogen energy supply, fuel cell system, stack, and fuel cell vehicle related technologies.

Regarding hydrogen production, storage, transportation, refueling technologies and infrastructure construction, countries have formulated the technology roadmap for hydrogen production and corresponding infrastructure plans in light of their respective resource endowments, which are in line with hydrogen fuel cell vehicles (FCV) development and scale-up plans.

Hydrogen production: mainstream technologies are fossil fuel reforming hydrogen production, industrial by-product hydrogen (chlor-alkali industry, coal, coke oven gas production), biomass gasification/fermentation hydrogen production, water electrolysis, etc. The technologies and equipments for hydrogen production from coal, natural gas and alkaline water electrolysis, are all ready for commercialization, and currently hydrogen production from fossil fuels represents the overwhelming mainstream. The capacity of China's hydrogen production exceeds 20 million t/a, of which direct hydrogen production from fossil fuels such as coal gasification and natural gas reforming accounts for about 70%, industrial by-product hydrogen production takes around 30%, and water electrolysis and other technologies cover less than 1% [10, 11]. Now, more than 90% of hydrogen in the world is used in petrochemical and ammonia synthesis industries. With growing demand brought by the development of hydrogen fuel cell vehicles, great changes might take place in the technology mix of hydrogen production [12].

Hydrogen storage: The mainstream technologies include compressed gas hydrogen storage, liquefied hydrogen storage, metal hydride hydrogen storage, and adsorption hydrogen storage, etc. Compared with other technologies, compressed gas hydrogen storage and liquefied hydrogen storage are relatively mature, but fall short of industrialization. At present, the technology of gas hydrogen storage with steel hydrogen cylinder below 45 MPa in China has been very mature, and the international R&D and demonstration efforts are all moving towards 70 MPa. Liquid hydrogen storage with high efficiency is the R&D priority of all countries. However, as liquid hydrogen storage and transportation require ultra-low temperature equipment with certain technical barriers, liquid hydrogen for civilian use is mainly applied in Europe, Japan and the United States, whereas China uses liquid hydrogen primarily for aerospace and military purposes.

Hydrogen transportation: road, waterway, and pipeline, etc. are common approaches for transport. Road and waterway transport technologies are subject to the development of hydrogen storage technology and relatively suitable for short-distance and small-scale transport. Gas hydrogen pipeline suits large scale and long distance transport for cost reduction. Pipeline transport is well developed in foreign countries, with Europe and the United States having built 1,500 km and 2,400 km of pipelines for hydrogen transport respectively. In contrast, the length of hydrogen pipeline in China is only 300–400 km, and the longest is the "Baling-Changling" pipeline, which extends about 42 km with a pressure of 4 MPa [13].

Hydrogen fueling: According to statistics of Germany organization (H2stations.org), there were 369 hydrogen fueling stations in operation worldwide by the end of 2018, including 273 of which were open to the public, and the others were in-house stations owned by institutions and enterprises. Germany, Japan and South Korea have all announced plans to build hundreds of refueling stations by 2030, and have each set up joint ventures for this purpose. China has 17 hydrogen refueling stations in operation and 38 stations under construction.

Fuel cell system and the electric reactor technology both meet the demand for vehicle applications. At present, the power system of hydrogen fuel cell vehicles features a cell-fuel cell hybrid system. Aside from cell and fuel cell technologies, atmospheric/variable pressure gas technology, battery management technology, braking energy recovery technology, and battery thermal management technology also serve important roles.

In terms of FCV technology, the overall performance has measured up to commercial scale-up. Fuel cell buses and trucks are under demonstration. Hydrogen fuel cell vehicles will see greater potential in the field of heavy-duty vehicles. *The Technology Roadmap for Energy Efficient and New Energy Vehicles* specifies a timetable for the development of hydrogen fuel cell vehicles. By 2020, 2025 and 2030, China aims to have 5,000, 50,000, and over a million FCVs on the road respectively.

In short, the development of hydrogen fuel cell vehicles entails a robust industrial chain consisting of hydrogen production, storage, transportation, refueling, and the production and management of fuel cell and car body, etc., together with the improvement of infrastructure. At present, fuel cell systems and stack technology could reach automotive level and the performance of FCVs, on the whole, is up for commercialization. Fuel cell buses and trucks are also under demonstration and enjoy a broad prospect for development with mature technology and cost reduction.

The following challenges hinder the development of hydrogen fuel cell vehicle development and merit particular attention:

1. High cost, energy consumption, and carbon emissions in hydrogen production process.

   As CCS technology has not been widely adopted, its effect on carbon emissions from fossil fuel hydrogen production is not immediately apparent compared to direct hydrogen production from fossil fuels. The purity of industrial hydrogen by-products cannot meet the needs of fuel cells, thus a purified process with separation technology such as pressure swing adsorption (PSA) is needed, which causes a huge amount of energy consumption. Given the mainstream adoption of thermal power in China, clean electric hydrogen remains a long way off.

2. The industrial foundation of hydrogen storage, transportation, and refueling remains weak, with stunted growth in related industries and inadequate technologies.
   The infrastructure of hydrogen refueling stations and hydrogen transport pipelines is seriously underdeveloped in the world. It is estimated the full-fledged hydrogen infrastructure costs at least $2 trillion. At present, worldwide investment in this connection still caters to the pilot stage, and large investment is not yet in sight. The efficiency and safety of the existing hydrogen storage and transport equipment need further improvement. Taking the double-layer vacuum spherical hydrogen storage device as an example, its daily evaporation rate is between 0.2% and 0.5%. Vehicle-mounted hydrogen storage materials also require further development to enhance their capacity weight ratio.
3. Urgent improvement is needed for key fuel cell technologies of China, as well as localization of key components.

While being commercialized, hydrogen fuel cells fall short of meaningful mass production. The design of electric reactor, battery cost, battery power density, conversion efficiency, and service life are all hinder the industrialization of hydrogen for automobiles, and further breakthroughs are essential. Furthermore, localization of key materials and components is another impediment. Key components such as membrane electrode catalyst, proton exchange membrane, air compressor, and hydrogen reflux-pump all rely on import. Besides, the technical capability of fuel cell companies needs further improvement.

7.2.4 *Negative CO_2 Emission and Carbon Geoengineering Technologies*

CCS and geoengineering are important alternatives for achieving deep decarbonization. Under the deep emission reduction target, CCS can be applied to fossil energy power generation, coal chemical industry, and petrochemical industry to secure deep decarbonization of fossil energy utilization. BECCS is able to capture and store carbon dioxide emissions from biomass power generation and thermal utilization, making for a CO_2 negative emission technology.

1. CCS Technology

CCS technology consists of three steps: capture, transport, and storage. Step one: capture. First adopted in oil refining and chemical industries, etc., carbon capture refers to the process of separating and purifying carbon dioxide to a high concentration state. Three CCS technologies widely accepted are pre-combustion capture, post-combustion capture, and oxygen-enriched combustion. Step two: transport. Mainly through pipeline and low-temperature storage tank, this step involves the transport, in a leak-proof manner, of high concentration CO_2 to the designated venue for storage. The last step: storage/sequestration. By sealing saltwater layer, deep unexploitable coal seam, and waste oil and gas reservoir, this step embeds and stores CO_2 in the deeper stratum of the earth, so that it would be completely isolated from the atmosphere.

Research on CCS cost and demonstration projects have suggested such technology requires huge investment and high operating costs, and call for more breakthroughs in order to be competitive.

Despite being a later mover on CCS, China attaches great importance to its R&D and demonstration, and has committed tremendous amount of funding for its development over the past decade. In terms of the technologies of carbon capture, utilization and sequestration, China is already on par with developed countries. In August 2018, the CCS facility in Jilin province had reached a storage capacity of 600,000 tons of CO_2. Meanwhile, SINOPEC's Qilu CCS project and Yanchang Petroleum's coal chemical CCS facility in northern Shaanxi province are able to capture 400,000 tons and 410,000 tons respectively. In the future, with strengthened efforts in CCS technology demonstration, cost reduction, and steady scale-up, China may stand at the forefront of low-carbon technology.

Despite its huge volume, carbon emissions in China are concentrated and easy to capture. Given the sheer size of China, geographical sites for carbon sequestration are readily available with enormous storage potential. Data show that the carbon sequestration potential of China can reach 3,088 billion tons in theory, and the capacity of sequestration in deep brine layer is 3,066 billion tons, or 99% of the total theoretical capacity. Sun et al. [14] evaluated the theoretical storage of CO_2 in China's sedimentary basins, and concluded that China has a broad prospect for CO_2 sequestration, which is about 184.1 billion tons, over 190 times of total CO_2 emissionsof 2015 in China. Li Xiaochun et al. [15] estimated the CO_2 storage capacity of China's saline aquifer at 1.43505×10^{11} tons by using solubility method.

Several barriers may hold down the progress of CCS in the future:

1. High costs. The high cost of CO_2 capture largely determines the cost of CCS, whose further reduction hinges on the development and maturity of the technology. It's crucial to make full use of exchanges between domestic and foreign R&D institutions, and lay equal emphasis on independent R&D and international cooperation for continuous CCS technology development [16].
2. Lack of relevant policies and legal systems. Nowadays, there are few policies and laws available for CCS, prompting government efforts to ramp up the formulation and implementation of these policies and laws.
3. Leakage risk. CO_2 leakage is a key concern of safety. Human health and life would be under immediate threat in case CO_2 mass fraction exceeds 8%. Even though the possibility of leakage is very small, precautions in all respects should be made [16].
4. Insufficient public awareness. Currently, the notion of CCS remains a novelty to most Chinese people. It is important to promote CCS best practices at home and

abroad through education and publicity. It will alleviate public concerns about CCS leakage, building up popular support, and paving the way for its future development [16].

5. Lack of a sound evaluation system. Many components of CCS technology need to be evaluated. For example, the site selection for CO_2 geological sequestration should be reevaluated in a holistic manner based on the existing assessment system. Only with proper assessment can the best storage site be selected.

2. BECCS Technology

BECCS refers to the technology that combines biomass and CO_2 capture and storage to achieve negative GHG emissions. The difference between BECCS and fossil fuel CCS is that the latter could only contribute to zero emissions goal, while the former could further achieve negative emissions [17]. The technological progress of BECCS involves biomass utilization and CCS. Large-scale biomass utilization technologies, such as biomass power generation, central heating, cellulosic ethanol production, and F-T synthesis, can be installed with CO_2 capture devices to make for potential BECCS.

Statistics show that to date, there are 27 BECCS demonstration projects around the world, and many of which have been called off or shelved. Largely concentrated in the United States and Europe, these projects are based on existing plants of ethanol, cement, pulp and paper, biomass mixed combustion, and biomass pure power [17, 18]. The BECCS Project (IL-ICCS) currently implemented in Decatur, Illinois of the US is the largest project so far. The project, launched in April 2017, captures one million tons of CO_2 each year in the process of converting corn into ethanol. After compression and dehydration, captured CO_2 is injected into a sandstone formation about 2.1 km deep at Mount Simon for permanent storage [19]. Currently, China has not yet built BECCS demonstration project.

Many advanced biomass technologies for large-scale utilization, such as cellulosic ethanol, F-T synthetic biofuels, and biomass gasification combined cycle (BIGCC), are still under R&D and demonstration, and uncertainties abound for their future development. Many CCS projects are also in the stage of demonstration, with multiple challenges ahead in terms of large-scale technology implementation.

BECCS is faced with four different uncertainties, including biomass availability, technology maturity, economic viability of scale-up, and uncertainties of social and ecological impact, which will greatly weaken the contribution of the technology.

The cost of BECCS also primarily depends on the cost of biomass and CCS. BECCS is still under technology demonstration and has not been massively deployed globally. So its cost analysis is mainly conducted based on certain assumptions.

Studies have shown that the cost of CO_2 capture may not support CCS for small biomass energy devices, thus R&D and demonstration are required in the future. First, the carbon chain is very long considering the cost of biomass and CCS; second, biomass and CCS technologies come in great varieties, and great variance exists regarding biomass cost and CCS technologies; third, growing energy crops will result in a shortage of land needed for food production, pushing up food prices. The combination of biomass power generation and CCS has great potential for large-scaleapplication.

Based on biomass availability and the uncertainty of BECCS, estimates [20] on 2050 emission reduction potential have been conducted on the low, median and high level as well as upper limits. The result suggested that the ceiling of CO_2 removed by straw in 2050 in China is 830 million t/a; by forestry residue, 957 million t/a; and by energy plants, 963 million t/a, which add up to a ceiling of 2.75 billion t/a CO_2 removal by BECCS. It's expected that on the way toward the 2 °C and 1.5 °C targets, the potential of emissions redcution by BECCS in China would be 0 ~ 27.51 billion tCO_2 per year, of which the medium-value and high-value are 650 million ~ 1 billion tCO_2.

The following efforts must be made to support the future development of BECCS in China:

First, it is important to build up the scientific understanding of BECCS under the targets of 2 °C and 1.5 °C. Scaled-up implementation of BECCS-related negative emission technologies can reduce costs and help to achieve the temperature targets. However, further research is needed to strengthen the scientific understanding, and take appropriate measures to reduce potential risks in the development of BECCS.

Second, promoting BECCS research and demonstration to enhance scientific understanding and public acceptance. China should strengthen the technical reserve by boosting BECCS demonstration. So far, China has launched commercial demonstration of biomass and CCS, and the future priority is to integrate the two for negative emission. Research and demonstration in such areas as BIGCC+CCS should be to enable future emission reduction.

Third, BECCS should be incorporated into the framework of China's climate change strategy. Although BECCS still faces high uncertainty for its development and application, it's a safe bet that massive deployment of BECCS would be required to achieve the 2 °C and 1.5 °C targets. That is, BECCS should be a possible option for climate change mitigation. Meanwhile, the potential risks of BECCS should be well awared.

3. Geoengineering Technology

Geoengineering is generally defined as "the planned, large-scale human intervention in the climate system in response to global climate change". A growing number of international literatures are using "climate engineering" or "climate intervention" to replace geoengineering to distinguish it from large-scale human activities for other purposes.

In general, geoengineering techniques and methods include carbon dioxide removal (CDR) and solar radiation management (SRM). CDR removes or converts carbon dioxide in the atmosphere, and reduces the greenhouse gas concentration in the atmosphere through biological, physical or chemical methods, such as afforestation and forest ecosystem restoration, biological energy with carbon capture and sequestration (BECCS), biochar for increasing soil carbon content, enhanced weathering or ocean basification, direct air capture and storage (DAC), marine fertilizers, etc. SRM, on the other hand, does not directly reduce the content of carbon dioxide in the atmosphere, but reduces the solar radiation reaching the ground to alleviate the earth's warming through methods such as stratospheric aerosol injection (SAI), increasing cloud albedo modification over land or surface oceans, and increasing the surface albedo modification on land or ocean surfaces.

In the latest *Special Report on Global Warming of 1.5 °C*, IPCC makes a distinction between CDR and CCS. According to the report, CDR refers specifically to the removal of carbon dioxide directly from the atmosphere or the reduction of atmospheric carbon dioxide by artificially increasing ocean or terrestrial carbon sinks. The application of carbon capture, storage and utilization (CCS/CCUS) in the energy and industrial sectors is classified as emission reduction technology, rather than CDR in geoengineering (IPCC, 2018). Thus, in contrast to CCS, CDR stresses the removal of carbon dioxide directly from the air or through enhanced biological or geochemical methods. BECCS belongs to a special CDR technology, which combines biomass and CO_2 capture and storage to bring about negative GHG emissions.

Currently, no example can be found in large-scale geoengineering in the world. Technologies in this regard vary in mechanism, characteristic, and level of maturity, and are under varied stages of development. The most controversial SAI technology in SRM is under theoretical and computer simulation research, and is very sensitive to outdoor environment. The backlash from NGOs has forced such experiments to be postponed or halted. The progress of SAI R&D has been very slow, primarily because of its high risk and hugely uncertain global ramifications from artificially altering the climate system through its massive adoption. Therefore, there has been a groundswell of support for ramping up the international geoengineering governance. Other technologies of SRM are sporadically tested on a small scale, hence limited impact.

In contrast, the research and development of CDR related technologies have boomed, and some technologies have seen commercial demonstration. About 6 operational projects and over 12 construction projects on BECCS can be found worldwide. Professor David Keith from Harvard University actively supports and promotes the commercial application of DAC. As a partner, he founded Carbon Engineering to try out the application of DAC. The Canada-based Carbon Engineering has been running a pilot CO_2 extraction plant for direct air carbon capture since 2015. The company uses a solution of hydroxides to capture carbon dioxide, which must then be heated to high temperatures to release the carbon dioxide and store it and reuse the hydroxide. The process employs available technology and is considered to be relatively low-cost. Based on its design and economic assumptions, it costs between $94 and $232 to capture a ton of carbon dioxide from the atmosphere. The Swiss company Climeworks has opened a commercial facility using amines in small modular reactors. Some experts believe that commercial competition has unfolded in the space of DAC, which can be rapidly and extensively deployed once the cost barrier is shattered.

According to a paper published in Nature Communications in July 2019 by Italian, British and other academics, in spite of the two different technologies, capturing CO_2 directly from the atmosphere and burying it underground is a viable option. Using DAC means global emissions are likely to remain chronically high until 2050, with heavy use of negative emissions only later in the century. Annual negative emissions in the 2080s would be about 30 billion tons (Gt/year), close to this year's global emissions of around 40 billion tons/year. That would mean building approximately 30,000 large DACCS factories. In comparison, there are less than 10,000 coal-fired power stations in the world today. The technology will require as much as a quarter of the world's energy supply by 2100, up to 300EJ (10^{18} J) a year, equivalent to the current annual energy demand of China, US, EU and Japan, or the global supply of coal and natural gas in 2018 [21].

Marine fertilization is also a controversial CDR technology. For ecological and ethical reasons, the Convention on Biological Diversity (CBD) explicitly stipulated in 2010 that geoengineering activities affecting biodiversity and climate are prohibited except for small-scale scientific research.

Geoengineering sparks tremendous controversies worldwide, especially SRM, for its high risk and great uncertainty. CDR is an unavoidable pathway of emission reduction in the near and medium term under the 1.5 °C target, so it is imperative to accelerate research and development and demonstration. Although CDR has entered the commercial demonstration stage, large-scale application may also threaten land use, water resources, and food security, and international governance needs to be strengthened.

China's medium- and long-term low-carbon strategy must attach great importance to geoengineering. First, geoengineering should receive its due attention. Appreciating the importance of geoengineering is, by no means, easing or weakening mitigation and adaptation efforts. Secondly, the research of geoengineering should be strengthened to inform scientific decision-making; the complementation and integration of natural science and social science should be encouraged; and the comprehensive research and talent training relative to science, technology, policy, ethics, law and other aspects should be reinforced. Thirdly, the key technologies of geoengineering CDR and SRM should be distinguished; and the geoengineering technology development strategy should be carefully crafted from a strategic perspective of vision and foresight. Fourth, China should actively participate in the international governance of geoengineering.

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