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The electricity, industrial, and agricultural sectors under changing climate: Adaptation and mitigation in China

Kaixuan Wang[#], Linqi Sun[#], Jiatai Wang[#] & Lirong Liu[*]

Centre for Environment and Sustainability, University of Surrey, Guildford GU2 7XH, UK

#These authors contributed equally to this work.

*Corresponding author (email: lirong.liu@surrey.ac.uk)

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Abstract: Climate change is a pressing global concern with far-reaching consequences that vary across sectors. Addressing the adverse impacts of climate change on various sectors is a challenging issue faced by countries worldwide, including China. It is imperative for China to address climate change to foster sustainable development and make meaningful contributions to global climate mitigation efforts. This paper presented a comprehensive analysis of the impacts of climate change on the electricity, agriculture, and industry sectors, which together account for over 80% of the greenhouse gas (GHG) emissions in China. Additionally, the strategies employed by these sectors to address climate change were reviewed, and potential future developments were explored. This review article could shine light on climate change practices and evidence-based policies aimed at addressing climate-related challenges across various sectors in China.

Keywords: Climate change, Electricity sector, Industrial sector, Agricultural sector, Mitigation, Adaptation.

INTRODUCTION

Climate change is a global issue that has affected various sectors in different ways. Its impacts are becoming more severe and widespread, posing significant challenges to many countries. China, as the world's most populous country and the largest carbon emitter, is no exception. The impacts of climate change on China can be felt across multiple sectors, including the electricity, agricultural, and industrial sectors. The severity of climate change has resulted in significant challenges for these sectors, meanwhile, these sectors are also actively taking adaptation and mitigation measures to combat climate change.

In the electricity sector, both demand and supply sides of electricity, as well as the transmission of electricity, will be affected by climate change. On the side of electricity demand, the increase in the global average temperature will increase the electricity consumption. More specifically, previous research shows that for every 1°C increase in global average temperature, the demand for electricity will increase by 9.2% and the peak electricity demand will rise by 36.1% [1]. When combining the effects of temperature and precipitation brought by climate change, the electricity demand will increase 8.53% under the worst-case scenario [2]. In terms of electricity supply, climate change will not only bring a rise in temperature and abnormal precipitation, but also cause climate disasters such as storms, rainstorms, and snowstorms, which can directly affect the supply of electricity. Electric transportation also suffers from the negative impacts of climate change. In China, overhead lines are used for long-distance power transmission in most regions, which may be interrupted by climate disasters easily [3]. Ice cover and heavy rain had the widest impact, accounting for 80% of the total. Meanwhile, the electricity sector is one of the largest sources of carbon emissions in China [4]. Addressing the impacts of climate change and reducing carbon emissions in the electricity sector are critical to achieving a sustainable energy future.

Agriculture is another important sector in China, accounting for 65% of freshwater consumption [5] and supporting over 20% of the world's population with only 8% of the global sown area [6]. Climate change has become a significant factor affecting the sustainable development of agriculture in China, as one of the countries most affected by natural disasters. Rapid development of the agricultural economy is accompanied by a large amount of agricultural GHG emissions. GHG emissions from agriculture account for about 14.5% of China's total emissions, which is much higher than the world average. Reducing GHG emissions from agriculture plays a crucial role in promoting sustainable agricultural development and achieving carbon neutrality by 2060. Therefore, in the face of climate change, China must actively take measures to cope with the potential damage that climate change and reduce emissions, while taking into account the food security of its 1.4 billion population as well as the livelihood of its 600 million farmers.

The industrial sector is the largest contributor to China's GDP (accounts for nearly 33.3%) [7], while it also accounts for about 50% of China's carbon emissions, including direct emissions from industrial processes and indirect emissions from energy use [8,9]. Within industrial sector, the iron and steel industry, cement industry and petrochemical industry accounted for a substantial proportion of the entire industrial emissions. For example, the iron and steel industry has a high level of energy consumption and a low utilization rate of secondary energy and solid waste, which is in stark contrast to the iron and steel industry in developed countries [10]. As the effects of climate change become increasingly severe, the industrial sector is also experiencing significant impacts. These include disruptions to supply chains, increased operational costs due to extreme weather events, and the need to adapt to changing regulations and consumer demands for sustainability. Therefore, paying attention to energy conservation and emission reduction, as well as increasing their resilience to climate-related risks in industrial sectors is of great significance to address climate change.

Overall, addressing climate change in various sectors is crucial for China to achieve sustainable development and contribute to mitigating climate change on a global scale. Thus, it is significant to investigate the impacts of climate change on the electricity, agriculture, and industry sectors, and identify strategies to mitigate its effects. As shown in Figure 1, this paper presented a comprehensive analysis of the impacts of climate change on the electricity, agriculture, and industry sectors. Additionally, the strategies employed by these sectors to address climate change were reviewed, and potential future developments were explored. This review article could shine a light on the climate change practices and evidence-based policies to address climate change challenges in China.

CLIMATE CHANGE AND ELECTRICITY SECTOR

A large number of papers on climate change and electricity were found in the Web of Science database. In

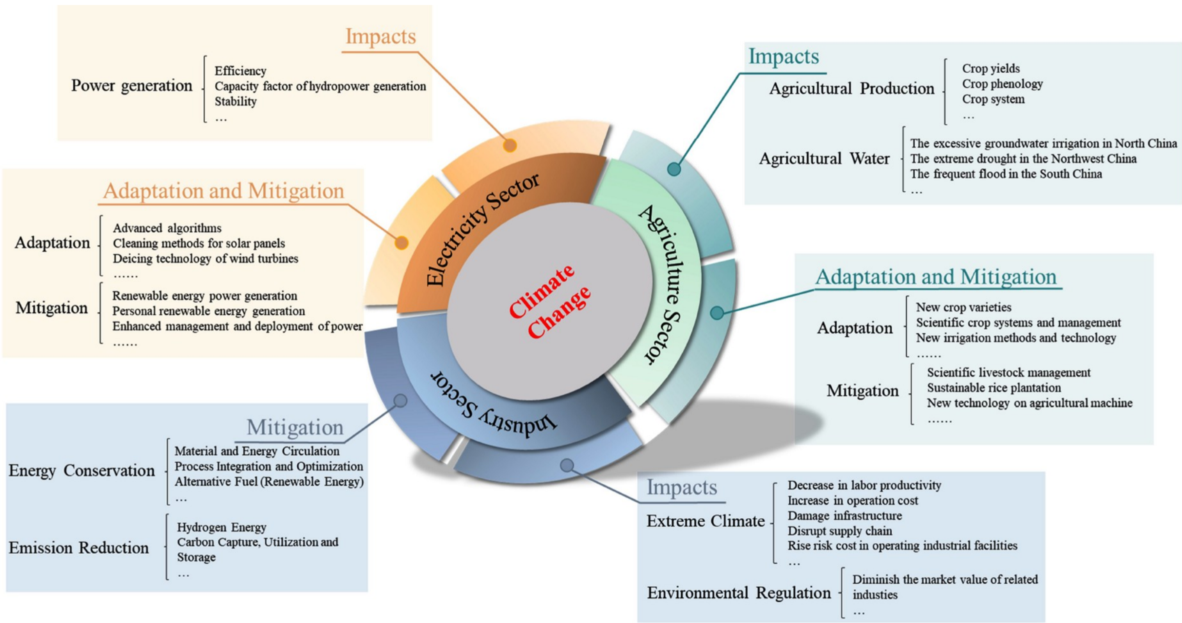

Figure 1 The figure abstract.

total, 1588 papers were collected (from 2013 to 2023), and finally, 445 nodes were analysed by the Cite-Space. In the keyword search of literature related to electricity and climate change (Figure 2), it can be observed that relevant influenced electricity sectors can be categorized into five parts that are influenced by climate change. The most significant part focuses on the effects of climate change, while renewable energy is the most frequently appearing keyword after climate change. In the grid segment, optimization appears most frequently. In the solar section, energy storage and batteries are crucial. In the wind segment, turbines are a key area of focus. In the bioenergy section, biomass is the most commonly mentioned keyword. Lastly, in the hydroelectric section, water is the most significant keyword. These keywords represent the crucial areas of research in studying the adaptation and mitigation of climate change in the electricity sector.

Impacts of climate change on electricity sector and adaptation measures

Impacts on power grid load and adaptation measures

Climate change is expected to bring changes in electricity demand and supply, which could lead to increased load on the grid. To address this issue, the optimal design of power grid systems is essential. One example is the autonomous collaborative control system for load dispatching, which has received considerable attention. This system coordinates the main, distribution, and microgrids (load aggregators) to achieve multi-layer coordinated control, resulting in a more stable power system. In addition, distributed energy generation and microgrids can be connected to the overall power grid to increase the total supply of electricity. The use of distributed, clean energy can also improve the redundancy space of the entire grid system [11]. Furthermore, accurate prediction of power generation, especially from clean energy sources, can help improve grid system stability. Ju *et al*. [12] have developed a new forecasting model based on convolution neural networks and LightGBM, which enhances prediction accuracy and robustness.

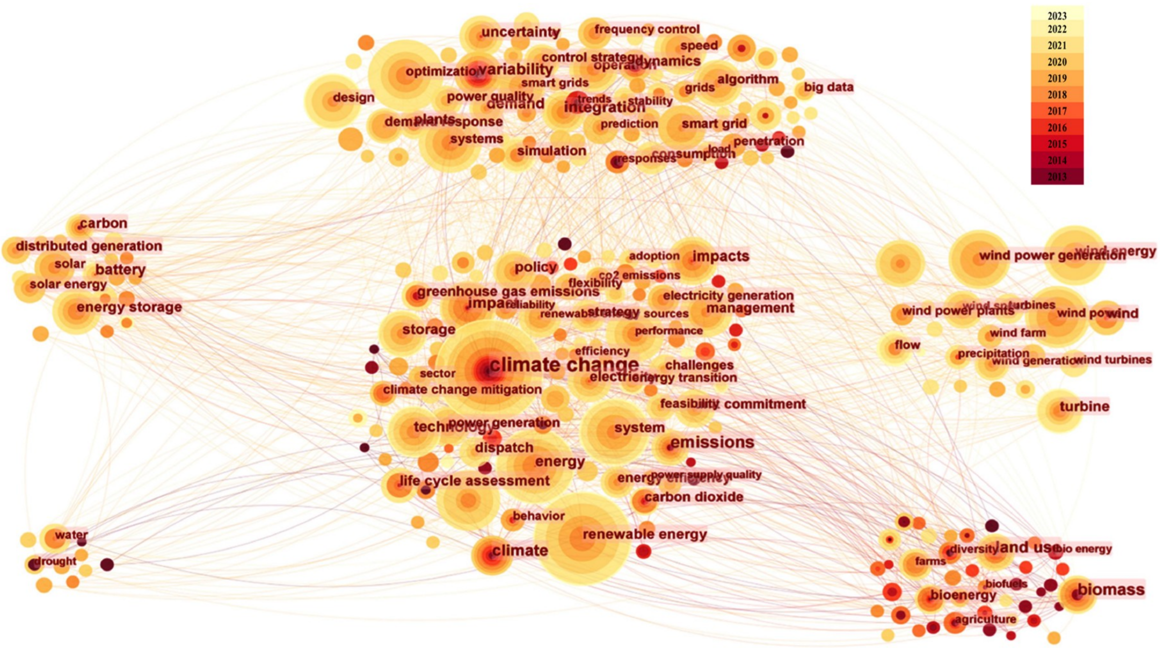

Figure 2 Keyword co-occurrence network analysis of electricity sector and climate change.

Impacts on various power generation facilities and adaptation measures

Climate change not only affects the overall supply and demand of electricity but also impacts the efficiency of specific power generation facilities. For instance, in north China, climate change is likely to reduce regional water availability, which could affect the heating efficiency of thermal power plants. These plants require a large amount of water for their operation, but due to the construction of mines, it has been challenging for them to obtain enough water in north China. Climate change may exacerbate this issue, leading to a decrease in the efficiency of thermal power plants [13]. However, it is important to note that the impact of climate change on traditional forms of electricity generation typically worsens when certain fixed conditions are established. In contrast, new energy generation, such as hydropower, wind power, and solar power, is more vulnerable to the impacts of climate change.

Hydroelectric power One of the impacts of climate change on hydropower generation is the capacity factor of hydropower generation through the amount of precipitation. For example, studies have shown that climate change could lead to a decline in the capacity factor of hydropower generation of 5.5%–17.1% in Colombia [14]. Based on different situations in China, studies also showed that weather has different impacts on hydropower generation in different regions of China. For instance, the effect of rainfall on hydropower generation was significant in the southern regions, but not in the northern region. The cooling degree day (CDD) had a significant effect on both the northern and southern regions, with the latter showing a greater impact (0.136%). In contrast, the northern region experiences a significant impact from heating degree day (HDD) [15]

To address the challenges posed by climate change on hydropower generation, researchers have investigated solutions related to reservoir management. Their research findings indicate that implementing adaptation measures to prevent overflow of the Three Gorges Dam during flood season could lead to a maximum increase in power generation efficiency of 4.4%–4.7% in 2046–2065, and 9.5%–12.4% in 2080–2099. From 2080 to 2099, the increase could range from 2% to 8.1%, thereby improving the power generation efficiency of the Three Gorges Dam [16]. Moreover, appropriate operational decisions for reservoirs are necessary to address the issue of power generation efficiency. For instance, some studies have integrated water supply systems, power generation systems, and environmental systems by using WPE models, which have enabled the dynamic operation of the reservoirs in an efficient and environmentally friendly manner [17].

To improve the power generation efficiency of hydropower plants, researchers have investigated the use of advanced algorithms. One such algorithm is the PA-DDS algorithm, which has been studied for its application in hydroelectric power generation. According to these studies, Pareto solutions generated by the PA-DDS algorithm offer a wider and more optimal range of annual power generation and water supply, and the projection pursuit method can be used to select the best solution. By using adaptive operation rules focusing on power generation, these studies have found that the PA-DDS algorithm can significantly increase the annual power generation of cascade reservoirs, by up to 3.7% in GCM-BCC or 4.8% in GCM-BNU [18].

Improving hydropower station efficiency is undoubtedly important, but it is also crucial to prevent inappropriate hydropower station planning. The use of hydrological models to assess the potential of hydropower development is an essential research branch. For instance, some researchers have utilized simulations of eight global hydrological models (GHMs) driven by climate data from five general circulation models (GCM) based on two representative concentration pathways (RCP2.6 and RCP8.5) to predict future changes and related uncertainties of China's gross hydropower potential (GHP) and developed hydropower potential (DHP) [19]. To incorporate climate change into long-term hydropower planning, a framework has been proposed that encourages robustness in the planning, design, and operation of new hydropower schemes and helps avoid maladaptation to climate change. This framework involves modelling the linkages between climate change, watershed hydrology, and the future needs of the environment, agriculture, industry, and domestic users to test the sensitivity of the performance of new schemes to various climate change scenarios, among other uncertainties. This approach can ensure the correctness and rationality of hydropower planning [20]. Finally, it should be pointed out that the impact of climate change on hydropower generation also varies in different regions. Southwestern China is more affected by hydropower from climate change, while hydropower stations built in southeastern China are expected to be less affected by hydropower [21].

A complementary system of wind, solar, and hydro power (WSHCS) that incorporates multiple new energy sources have also been proposed. The system exhibited significant complementarity between the variability of monthly streamflow, wind speed, and solar radiation under changing climate conditions. This complementarity ensured the reliability and total energy production of the WSHCS under most future climate scenarios [22].

Solar power generation The efficiency of solar power generation is negatively impacted by storms caused by climate change. For instance, a dust storm can cover the surface of the solar panel with debris or residue, causing a significant drop in performance. This is primarily due to the inability of solar radiation to properly enter the panel due to residual particles. To address this issue, cleaning robots have been designed that can detect the power generation performance of the solar system and actively clean it when the performance drops [23]. There are also other cleaning methods for solar panels widely used worldwide, such as manual cleaning, vacuum cleaning, electrostatic dust removal, nanoparticle coating, automatic wiper cleaning systems, etc. However, actual situations should consider local climate conditions, labour costs, and other factors [24]. Solar cell performance decreases with increasing temperature, fundamentally owing to increased internal carrier recombination rates, caused by increased carrier concentrations. The operating temperature plays a key role in the photovoltaic conversion process [25]. Although the efficiency of solar power could be decreased, to mitigate climate change, it still remains one of the most promising ways to generate electricity. In this context, it is also necessary to consider the effects of climate change when planning solar power installations to ensure sufficient power generation in the future. In this regard, some studies suggest that by installing 7.46 TW of solar photovoltaic panels on about 1.8% of the country's land area (mainly in western China), based on 5% of climate change impacts, can help China to achieve a net-zero electricity system by 2050 [26].

Wind power generation The impact of climate change on wind power generation is mainly concentrated on the impact on the windmill equipment itself. Usually, if wind power equipment cannot get normal wind, their power generation efficiency will be seriously affected. The most bothering factors were wake turbulence and icing problems. The wake problem is mostly caused by the installation of power generation equipment too densely, but in some extreme climate conditions, it will be more difficult for wind turbines to meet the maximum efficiency of power generation. To solve this problem, some studies focused on making each wind turbine continuously adjust the rotor speed and pitch angle to achieve its maximum power coefficient at any wind speed and any wind direction [27]. This solution can effectively increase the upper limit of the actual operating power. In addition, extreme cold weather such as blizzards brought about by climate change can lead to more severe wind turbine icing problems. The icing of wind turbines can often cause efficiency losses of more than 20%. Therefore, more efficient de-icing technology is of great significance to improve the power generation efficiency of wind turbines [28].

Additionally, unlike the variable climate and geographical conditions on land, offshore wind turbines have higher stability. China has experienced a significant increase in installed offshore wind power capacity, becoming the country with the highest new offshore wind capacity in 2019 (2.4 GW) and the third-highest offshore wind market at the end of 2019 (nearly 7 GW of offshore wind capacity). China is expected to continue this growth in the coming years, surpassing the UK and Germany as the offshore markets with the largest total installed capacity by 2021. Since climate change has less impact on offshore wind power, it is advisable to prioritize offshore wind power in future wind power planning [29]. At the same time, the construction and operation of wind farms may promote vegetation growth and cause soil pollution [30]. This makes it more obvious to promote the development of offshore wind power from the perspective of environmental protection.

Overall, climate change will likely lead to a decline in electricity supply and an increase in demand [31,32]. In different regions, the impact of climate change on electricity supply and demand is different, but it will all have an impact on the matching of electricity supply and demand. In regions with low latitudes, the matching of energy system supply and demand will be negatively affected for both solar and wind energy systems. Despite supply increases at low latitudes, raised cooling demand reduces the matching of energy system supply and demand substantially [33]. This finding draws attention to energy security issues caused by climate change. The application of energy storage technology and the reasonable expansion of the deployment area of wind and solar power generation are potential solutions to this problem. Moreover, the current vulnerability of the energy system during its transitional phase to renewables might lead governments, in the event of energy deficits caused by natural disasters or political upheavals, to reconsider previously halted fossil fuel projects, thereby intensifying climate change challenges. Thus, it is crucial to consider incorporating a level of redundancy in the planning and development strategies for renewable energy deployment to mitigate energy security risks influenced by climate change [34].

GHG emissions and mitigation measures in the electricity sector

The electricity sector is responsible for a significant share of global emissions, highlighting the importance of reducing emissions in this sector to mitigate the impacts of climate change. To achieve this, researchers have proposed two schemes. The first involves retrofitting existing conventional energy power plants with carbon capture, utilisation and storage (CCUS) technology. In China, where over 80% of electricity is generated from coal-fired technology, installing CCUS devices in power plants could considerably reduce emissions from combustion, while still allowing for the use of abundant coal resources [35]. According to the IEA report, CCUS technology can contribute 14% of the emission reduction in the IEA's 2°C emission reduction target scenario (2DS). The second scheme involves promoting the use of renewable energy sources, which have relatively low emissions compared with conventional energy sources. Renewable energy power plants accounted for about 15% of power generation but contributed less than 1% of emissions quantity [36]. Among all kinds of renewable energy, wind power, hydropower, solar power, and biomass power generation are the most popular. According to the 2023 annual development report of China's electric power industry and China Biomass Industry Development Yearbook 2023, the latest power generation capacity of China's major renewable energy sources and the carbon emissions inferred based on the LCA method are shown in Table 1.

Renewable energy generation

Biomass power generation China's thriving agriculture industry provides abundant raw materials for biomass power generation. From 2000 to 2016, the estimated harvestable potential of domestic biomass resources, including crop residues, forest residues, animal manure, municipal solid waste, and sewage sludge, increased from 18.40 to 22.67 EJ. Taking into account energy crops, the total potential of biomass resources in China reached 32.69 EJ in 2016, which is equivalent to 27.6% of domestic energy consumption. Moreover, researchers predicted that, China's bioenergy could mitigate cumulative GHG emissions by 1652.73–5859.56 Mt CO_2 from 2020 to 2050 [37].

Wind generation Wind power is mainly generated by wind-driven turbine motors, and it can be divided into onshore wind power generation and offshore wind power generation based on the location of the wind turbines. In the current field of wind power generation, European countries and China will lead the wind power market [38]. Due to the vast land and long coastline, China has abundant wind energy resources.

Table 1 China's renewable energy power generation and carbon emissions in 2022

	Biomass	Wind	Hydropower	Solar
Power generation (billion kWh)	182.4	762.4	1351.7	427.6
Carbon emissions (g CO_2eq/kWh)	160	19.88	7.5	95

According to the evaluation results of wind energy potential, China's onshore potential is about 1400 GW, and its offshore potential is about 600 GW [39], which makes China has been promoting the construction of wind turbines. According to the World Wind Energy Association (WWEA), China's total installed wind power capacity reached 168,730 MW in 2016 and 187,730 MW in 2017. From 2014 to 2017, the annual growth rates of wind power installed capacity were 26%, 29%, 14%, and 11%, respectively [40]. At present, China ranks first in the world's cumulative installed capacity with a total installed capacity of 75.32 GW, accounting for 27% of the global total. The vast majority of onshore wind power in the world is concentrated in northern China. The "Three Norths" region has made a greater contribution to the current installed capacity and wind power generation, reaching 74% and 71%, respectively. The expansion of wind power has brought enormous environmental benefits. From 2008 to 2015, wind power contributed to a reduction of $66,854 \times 10^4$ t of CO_2 and 173×10^4 t of SO_2 [41]. Results showed that in 2019, the GHG emission intensity per unit power generation was 19.88 g CO_2eq/kWh (provincial intensity ranges from 13.59 to 34.50 g CO_2eq/kWh). The results indicated that onshore wind energy in China has an emission intensity more than 98% lower than traditional fossil fuels and the mitigation effect can reach 84%–98% compared with the energy mix in 2020 [42].

Hydropower Hydropower is one of the largest renewable energy sources in China, with a long history and abundant technical expertise. China has a theoretical hydropower potential of 694 GW, representing 15% of the global share and ranking first in the world. The technical exploitable installed capacity is 542 GW, a 17% global share, with an annual electricity generation of 2,474 TW. Hydropower resources in China have three main characteristics: uneven spatial distribution, uneven temporal distribution, and high concentration [43]. Among the various rivers suitable for hydropower generation, the endowment of hydropower resources in the Yangtze River Basin accounts for about 47% of China's total hydropower technology development potential and ranks first in the world. At present, the total installed capacity of large hydropower stations built in the Yangtze River Basin should have reached 132,000 MW, which can provide about 560 billion kWh of electricity per year [44], which could greatly contribute to reducing the need for fossil energy generation.

In addition to the large-scale hydropower stations located along the Yangtze River, China also has tremendous potential for reducing emissions through the development of small hydropower by 2016, more than 47,000 small hydropower (SHP) plants with an aggregate installed capacity of 77.91 GW had been built throughout the country. Around 300 million rural residents living in one-third of China's counties and 50% of its territories now have access to electricity thanks to the development of small hydropower projects. However, it is important to note that while these projects have helped relieve power supply pressures and reduce emissions, they have also caused ecological and environmental problems, such as river interruption, that require attention [45].

Finally, it is worth mentioning the hybrid use of hydropower technology with other renewable energy technologies. For example, integrating dispatchable hydropower with no dispatchable photovoltaic (PV) power is a promising way to enhance resource use efficiency. However, in the process, the hybrid generation of these energy sources may create more pressure on integrated water resources management. This problem can be effectively addressed by adopting corresponding adaptive operation rules. Some researchers have conducted case studies on the Longyangxia Hydro-Photovoltaic Hybrid Power Station in China as an example. The results showed that compared with the traditional operation mode, the annual average power generation and power supply reliability of the optimal rule curve increased to 7.3 billion kWh (4.3%) and

90% (47.5%), respectively, while the water shortage index dropped to 114 (6.6%) [46].

Solar Generation Solar PV technology is a clean way to generate electricity directly from solar radiation [47]. PV power generation also has the characteristics of regional differences. In 2015, China's photovoltaic power generation potential was 131.942 PWh, which was about 23 times the electricity demand of the whole Chinese society in the same period. The spatial distribution characteristics of photovoltaic power generation potential mainly showed a downward trend from northwest to southeast [48]. In recent years, there has been a difference with traditional solar photovoltaic systems. A technology called concentrated solar power (CSP) is receiving increasing attention. The ability of CSP systems to operate at extremely high temperatures and offer thermal energy storage integration gives them an advantage over other renewable energy sources. This is important to alleviate China's night-time industrial electricity demand [49]. Currently, CSP contributes less to renewable energy generation due to cost issues and technical issues, but it has great potential in the future [50]. Studies showed approximately 1.02×10^6 km^2 of land was available to support CSP development in China. If CSP was considered to replace the existing fossil energy power generation, CO_2 emission would have been reduced by 5.19×10^8, 5.61×10^8, and 6.24×10^8 t in 2017, 2018, and 2019, respectively. The vast majority of places suitable for CSP development were concentrated in the 5 provinces and autonomous regions in western China [51].

Similar to the previous renewable energy generation methods, solar power generation also has great potential for linkage generation with other renewable energy sources, such as wind power generation, to effectively increase average power generation. However, this combination requires a suitable energy storage system to achieve grid stability from the power generated [52].

Personal renewable energy generation In addition to the widely used renewable energy technology in power plants, the family-oriented miniaturized power generation technology has also gained increasing attention in recent years. For example, combining a domestic small wind turbine with a battery can provide stable self-power supplements for home use. This approach has shown economic benefits and supports practical application [53]. Coordination of different types of renewable energy generation and electrical energy storage devices has also been explored. For instance, research has shown that home photovoltaics in microgrids and wind turbines plus batteries in community grids were better configurations [54]. The commonality of this type of research is that wind turbines are often particularly suitable for detached houses. Therefore, there are also some researchers who have screened wind turbines suitable for home use, their research showed that the Savonius turbine and the Savonius-Darrieus Hybrid turbine were the most appropriate choices in most cases. Between these two turbines, the Savonius-Darrieus Hybrid turbine is often superior to the Savonius turbine [55].

Another renewable energy generation technology which is more suitable for household use is household photovoltaic energy technology. In recent years, with the promotion of new energy vehicles, the linkage between household photovoltaic power generation and new energy vehicle charging has become one of the issues of attention. In this field, vehicle-to-home (V2H) could be used to realize the connection between electric vehicles and home microgrids. V2H is part of a home smart microgrid, where EVs are connected to buildings via bidirectional inverters, and their charge and discharge states are optimized by a home energy management system (HEMS). The V2H system uses renewable energy and valley power to charge EV batteries as much as possible and supplies power to households during peak power consumption periods. This method can significantly improve power consumption efficiency [56]. In some special areas with sufficient sunshine, photovoltaics can be adapted to individual devices, such as solar cookers, solar water heaters, solar greenhouses, and photovoltaic devices for rural households on the Qingzang Gaoyuan. The use of these miniaturization devices can not only make the grid not have to extend too far, but also help reduce carbon emissions. The estimated positive effects of annual energy-saving and CO_2 abatement are 1.27 and 2.90 Mt, respectively, on the Qingzang Gaoyuan in 2009, which are about 15% of total energy conservation and CO_2 abatement based on solar energy in China [57].

Enhanced management and deployment of power

In addition to vigorously promoting renewable energy, the efficient management and deployment of electric energy generated by power plants will also indirectly improve the efficiency of electricity consumption, thereby indirectly reducing carbon emissions. China has always attached significant importance to the development of the smart grid. And many initiatives to build smart grids have already been implemented. For example, in 2011, China planned to build a Wide Area Monitoring System in a five-year plan and planned to implement phasor measurement units on all power generators above 300 MW and substations above 500 kV [58]. The continuous optimization and improvement of the power grid have always been one of the important research directions. For instance, China has the world's largest Ultra-high-voltage/ high-voltage (UHV/HV AC/DC) interconnected power grid. Because of the current interconnection, the Chinese national power grid has become a strongly interconnected power grid. The disturbance caused by an outage in one part of the grid is much more likely to spread to other parts of the grid. Based on this phenomenon, it is important for the manager of the grid system to find the faulty node conveniently and quickly. In this regard, digital twin technology was used to realize the online analysis of power grids. The method can track the operation state of, or mirror, a large-scale power grid in real time with only a sub-second delay [59]. Optimizing the design of the power grid can reduce the power loss of the power grid. For example, China's power grid loss was 372.4 billion kWh in 2019, a decrease of 7 million kWh compared with 373.1 billion kWh in 2018. This is equivalent to reducing carbon emissions by 602,000 t.

The area of research that has gained significant attention is the integration of renewable energy generation into grid systems. Renewable energy power generation is usually characterized by volatility and uncertainty, making it challenging to directly connect to the grid when the power generated exceeds the grid standard. This problem will be more obvious especially for distributed energy. Therefore, integrated energy system (IES) as an effective carrier of renewable energy was designed. The system could effectively integrate various distributed energy sources, loads, energy storage and other devices and control systems [60]. Also, research on renewable energy power generation, power supply and demand forecasting, and grid power load forecasting is also worthy of attention. In order to achieve more accurate predictions, the latest computer technology has been utilized. For example, machine learning (ML) and deep learning (DL) based forecasting techniques were considered to be effective and efficient methods for energy forecasting using historical data [61]. Their study showed that, for all predictive applications under consideration, hybrid DL algorithms achieve high levels of performance in terms of predictive accuracy. Furthermore, the hybrid DL scheme exhibits greater tolerance to data incompleteness compared with pure DNN-based DL. When the limitation of renewable energy is removed, the forecasting models for electric load will be even more diverse. A short-term power load forecasting model using a hybrid GA-PSO-BPNN algorithm has been built. This model is worthy of attention in power load forecasting in the processing industry [62].

Research on off-grid renewable energy systems is an important area to explore, particularly for rural areas in China. Researchers have conducted studies on the techno-economic feasibility of stand-alone hybrid renewable energy systems (HRES) in some villages in western China to meet the electricity and hydrogen loads of remote rural communities. Results showed that using HRES was more economical than extending the power grid and could significantly reduce carbon emissions. In fact, the reduction in CO_2 carbon footprint was estimated to be around 375.44 t per year, making it a viable option for remote communities [26,63].

In addition, there are a series of management system optimization schemes related to power generation, such as combined heat and power systems [64]; hybrid intermittent power generation systems [65], and energy storage related optimization schemes [66]. The unified feature of these systems is to improve energy utilization efficiency and indirectly reduce carbon emissions through reasonable planning.

Power storage technology

As mentioned previously, renewable energy generation technologies are often intermittent and unstable. Therefore, the adaption of energy storage technology to existing renewable energy technologies has gained research interest. Existing energy storage technologies other than battery energy storage mainly include compressed air energy storage technology, thermal energy storage technology, hydraulic energy storage technology, etc., among which pumping hydraulic power and compressed air are branches of mechanical energy storage systems [67]. Compressed air energy storage technology is an energy storage technology that is more suitable for wind energy and solar energy. This technology refers to the use of redundant electricity for compressed air, and when the demand for electricity rises, electricity is generated through compressed air for supply. Traditional compressed air energy technology still requires auxiliary fuel to participate in combustion, but the latest AA-CAES system can already realize air heating in a non-combustion state [68]. For storage media, it is now possible to heat storage through solar collectors [69].

Concentrated solar power (CSP) in solar energy utilization methods has giant potential. To compete with traditional thermal power generation technologies such as thermal power plants, CSP must meet electricity demand around the clock, even when the sun is not shining. Thermal energy storage (TES) is able to meet this demand by storing heat, providing a round-the-clock supply of heat for power generation [70].

In addition to the above energy storage solutions, battery energy storage, especially lithium-ion batteries, also has unique advantages in renewable microgrids including high energy density and power density, light weight and small size, high cycle efficiency, and low self-discharge rate [71] which makes further miniaturization. For renewable energy power generation sites, it is an expensive but reliable energy storage solution. In general, from the electrical storage category, the lithium-ion battery fits both low and medium-sized applications with high power and energy density requirements. Capacitors, supercapacitors, and superconductive magnetic energy devices are appropriate for high-power applications, while thermal energy storage is ideal for seasonal and bulk energy storage [72].

In addition to the aforementioned renewable energy storage solutions, ocean-based renewable energy storage technologies have also been developed. Referring to land-based energy storage technology, the energy storage technologies currently applicable on the ocean include pumped hydro storage (PHS), compressed air energy storage (CAES), battery energy storage (BES), hydrogen energy storage (HES), gravity energy storage (GES) and Buoyancy energy storage (ByES). Among them, the PHS and CAES technologies with the greatest potential are mainly due to the maturity of land based PHS and CAES [73]. Although GES and BYES technologies still need further design, their characteristics make their technologies have great potential to be suitable for marine renewable energy storage technology [74].

In summary, power storage technologies are crucial for increasing the efficiency of renewable energy generation and reducing energy waste, even though they cannot directly reduce carbon emissions. The development of power storage technology is a crucial step toward achieving the goal of mitigating climate change and achieving carbon neutrality. Some evidence from Texas, USA, shows that energy storage technology can enable renewable energy power stations to reduce carbon emissions by an additional 18% compared with fossil fuel power station [75].

Renewable energy related policies

China's policy tools related to renewable energy can be divided into four categories, which include total target planning; feed-in tariffs; cost sharing and tax preference. Those policy instruments provide an important foundation for promoting the healthy development of renewable energy industry [76]. These policy tools work together to promote the development of the new energy industry. But this does not mean that these policies are perfect. For example, the Chinese government's subsidy policies for various new energy industries will be gradually eliminated in the future. Therefore, this paper expects that subsequent policy formulation will mainly focus on the design of market mechanisms.

Chapter summary

Among renewable energy sources in China, hydropower, wind power and solar power are some of the most popular renewable energy power generation methods. These technologies are inherently sustainable, but they will also be negatively impacted by climate change. Therefore, many researchers have conducted research to solve related problems. Among them, anti-overflow technology related to hydropower generation; battery cleaning technology related to solar power generation; angle self-adjustment technology related to wind turbines and various new algorithms are important measures for various types of renewable energy power generation technologies to cope with climate change.

The main four types of policies are also listed in Table 2. The author speculates on possible changes and new development directions of future policies based on the current status of these four types of policies. The authors predict that the Chinese government will pay more attention to the commercial operation of sustainable energy development in the future. The design of market mechanisms will be the mainstream of future policy research. How financial capital is combined with industrial development will also be further studied. Also, a series of subsidy policies are more likely to be cancelled.

CLIMATE CHANGE AND AGRICULTURAL SECTOR

We identified papers on climate change and agriculture from all Web of Science databases by searching for

Table 2 Key technology and policies in electricity sector

		Literature	Measures	Evaluation
Adaptation to climate change	Key technology	Qin *et al*., 2020 [16]	Implementing adaptation measures to prevent overflow of the Three Gorges Dam	From 2080 to 2099, the increase could range from 2% to 8.1%, thereby improving the power generation efficiency of the Three Gorges Dam.
		He *et al*., 2020 [18]	PA-DDS algorithm	The PA-DDS algorithm can significantly increase the annual power generation of cascade reservoirs, by up to 3.7% in GCM-BCC or 4.8% in GCM-BNU.
		Hashim *et al*., 2019 [23]	Cleaning robots	Cleaning robots have been designed that can detect the power generation performance of the solar system and actively clean it when the performance drops.
		Sun *et al*., 2020 [27]	Adjust the rotor speed and pitch angle of wind turbines.	Achieving maximum power coefficient at any wind speed and any wind direction
Mitigation to climate change	Key technology	Yang *et al*., 2017 [41]	Wind generation	From 2008 to 2015, wind power contributed to a reduction of 66,854 $\times 10^4$ t of CO_2 and 173 $\times 10^4$ t of SO_2.
		Ming *et al*.,2019 [46]	The hybrid use of hydropower technology with other renewable energy technologies	The results showed that compared with the traditional operation mode, the annual average power generation and power supply reliability of the optimal rule curve increased to 7.3 billion kWh (4.3%) and 90% (47.5%), respectively, while the water shortage index dropped to 114 (6.6%).
		Qaisrani *et al*., 2021 [49]	Concentrated solar power (CSP)	The ability of CSP systems to operate at extremely high temperatures and offer thermal energy storage integration gives them an advantage over other renewable energy sources. This is important to alleviate China's night-time industrial electricity demand.
	Government policy	Song *et al*., 2022 [76]	Total target planning Feed-in tariffs Cost sharing and Tax preference	Those policy instruments provide an important foundation for promoting the healthy development of renewable energy industry.

the following keywords: agriculture, agricultural sector, climate change, adaptation, mitigation, impact. In total, 844 kinds of literature were collected from 2013 to 2023, and finally, 582 nodes were analysed by the CiteSpace after removing duplicates. In the literature keyword related to agriculture and climate change (Figure 3), it can be seen that the impact of climate change on agriculture is mainly on crop production and crop water consumption. The agricultural sector has implemented various measures to adapt to climate change. Meanwhile, agriculture also contributes to climate change through the emissions of different types of GHG such as CH_4 and N_2O. In light of this, the literature review also mentions that the agricultural sector is actively taking measures to mitigate GHG emissions and sequester carbon in the land, which could play a significant role in mitigating future climate change.

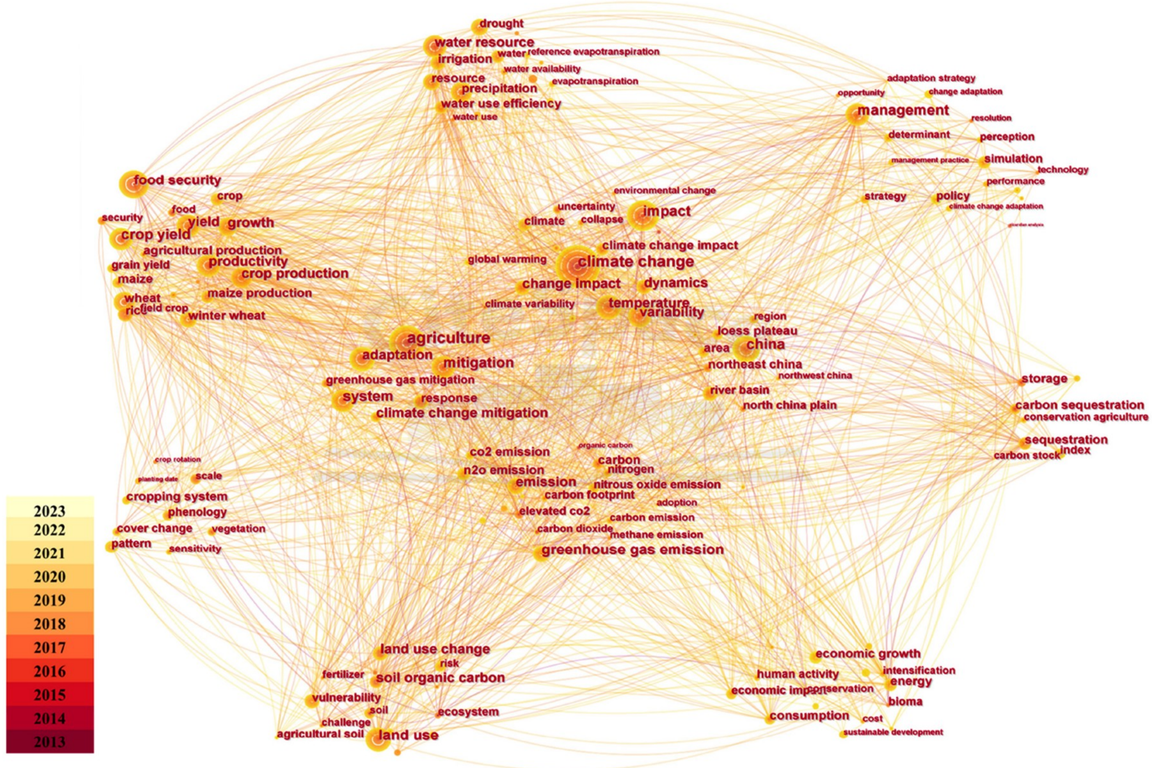

Figure 3 Keyword co-occurrence network analysis of agricultural sector and climate change.

Impacts of climate change on agricultural sector and adaptation measures

Impacts of climate change on agriculture

The agricultural sector is highly vulnerable to climate change. Climatic factors such as temperature, precipitation could directly lead to changes in light, heat, and water resources required for the growth of crops, resulting in changes in crop physiology, which in turn affects crop production [77]. China is the world's largest agricultural producer, and increasing attention was paid to the risks to Chinese agriculture from climate change, which not only affects the food security of the Chinese population but also the survival and development of Chinese farmers. The impact of climate change on agriculture and food production is broad and complex [78], with the most significant effects being on agricultural production and water consumption.

Agricultural production The impact of climate change on agriculture is reflected in the impact on agricultural production, including crop yields [79–81], crop phenology, crop systems, etc. In current studies, researchers have confirmed the historical climate change and its impact on crop production through the analysis of statistical long-term climate data. Most studies conducted in China have shown that the yield of major crops was sensitive to climate change. For instance, climate change has a positive contribution to wheat yield [81], but a negative contribution to maize yield [82]. Some studies also showed there were clear negative yield responses of main crops to increased growing-season temperature at the national level [79,83,84]. Additionally, other studies focused on the response of crop phenology to climate change, which also has a great contribution to crop production. The growth date and harvest date of different types of crops, as well as the various stages of the growth period would be changed due to changes in temperature, which would further cause changes in crop yields [85,86]. For example, the harvesting dates could be pushed later in the year and the entire growing would be correspondingly changed [87]. In addition, changes in cropping structure would also have an impact on crop production. Under the influence of climate change, cropping systems have also changed in many agricultural areas in China. For example, the growth stages of certain crops may change [88], and the planting patterns across the country may also change correspondingly. Studies demonstrated that the northern limits of multiple cropping systems had been shifted northward due to climate change, which means cereal production may have the corresponding changes [89].

Climate change in the historical period has changed the spatial and temporal distribution of temperature and precipitation, which has had a great impact on China's agriculture. GHG emissions are still increasing, and future climate change will still be an important factor affecting China's agricultural development. Researchers have applied climate models and crop models to simulate the growth of crops under future climate change to explore possible changes in agriculture in the future. Researchers suggested future global warming could exert pressure on the production of China's major crops [90–93]. Additionally, with global warming, extreme weather events are becoming more intense and frequent [94], such as drought [91,95], flood disasters [96,97] extreme high temperatures [98,99], which can seriously threaten crop production. Kang and Eltahir [100] found that the North China Plain had been threatened by deadly heatwaves due to climate change and irrigation.

Agricultural water consumption Water is the most critical resource for Chinese agriculture, and irrigated croplands account for half of the total cropland area and produce approximately 75% of food and more than 90% of industrial crops in China [101]. Water availability will be one of the limiting factors for the development of Chinese agriculture. With climate change, the precipitation, evaporation or surface runoff will change correspondingly, which in turn exacerbates the problem of water scarcity [102]. Therefore, in addition to agricultural production, the agricultural water use sector will also face enormous pressure from climate change. Another important issue facing China's agricultural water consumption is the mismatch between the distribution of water resources and the distribution of water-demanding agricultural areas. In this case, climate change will have different consequences for water use in different agricultural regions of China. For example, the North China Plain, an important agricultural region in China, accounts for about 40% of the country's cultivated land [103]. However, with the high density of the population, scarce per capita water resources, as well as the decreasing water resources caused by climate change, the lack of guarantee for agricultural water use has become a major problem in this region. Future climate change will pose a threat to the allocation of agricultural water consumption in North China Plain by increasing crop evapotranspiration [104] or exacerbating the frequency of drought events in this region [105]. The northwest region is a typical arid and semi-arid region in China with serious water shortage problems. However, it is also an important grain and cotton-producing area in China, with agricultural irrigation accounting for 91.8% of the total water use in this region [106]. Due to the fragile ecological environment in this region, irrigation water is heavily dependent on natural conditions, and climate change will increase the occurrence of extreme weather and hydrological events, increasing the instability of agricultural water supply. Under the future climate change, the water demand for agricultural crops in the northwest region would increase [107], the demand for irrigation water would rise [106], and the contradiction between water supply and demand would further increase [108]. For another important grain-producing area in China, the northeast region, research has also pointed out that by 2030, climate change is projected to increase the water supply and demand gap for irrigation in this region, leading to increased water scarcity [109,110]. Even in the relatively water-rich southern region of China, research has shown that future climate change would increase the occurrence of drought events, threatening agricultural irrigation projects [111,112]. Compared with drought events, the increase in flood events also poses a significant threat to agriculture. Liang *et al*. [113] and Wang *et al*. [114] predicted that more floods may occur in southern China in the future, which could have a significant impact on agriculture, affecting crop yields, soil quality, and the livelihoods of farmers.

Adaptation measures to climate change in agricultural sector

Numerous pieces of evidence have indicated that Chinese agriculture is currently and will continue to be affected by climate change. As for the major agricultural country, China must actively take measures to adapt to climate change. In response to the various impacts of climate change, an increasing number of researchers have started to focus on measures to address it from the perspective of agricultural production. With the development of new research technologies and strategies, both farmers and government departments have been actively adapting agricultural production to mitigate the agricultural losses caused by climate change.

Adaptations taken by farmers under the guidance of science For farmers, following scientific guidance by choosing improved varieties of seeds, reasonable planting dates and methods, and adopting scientific management practices will help them adapt to the constantly changing climate and reduce the pressure of climate change on agriculture. In order to minimize the adverse effects of climate change on crop yields, new crop varieties that are more tolerant and resistant to disasters have been discovered to cope with extreme weather conditions such as drought that may arise due to climate change. Some of these new genetically modified varieties have been introduced into the market and can be purchased by farmers at normal prices for production, such as drought-resistant rice [115,116], drought-resistant wheat, and cold-resistant wheat [117]. In addition, new late-maturing maize varieties with longer growth periods have made significant contributions to increasing corn yields under climate change [118]. Accordingly, local farmers have opted for longer-growing season crop cultivars to take advantage of the increasing temperatures. The current development of heat-tolerant and pest-resistant wheat varieties [119] is at least in part a response to the early effects of climate change. In terms of selecting crop types for cultivation, empirical analysis of [120] revealed that climate influenced the choice of crops that Chinese farmers make. For instance, the warmer temperature may increase the chance of farmers to choose maize, and the marginal increase in precipitation increases the choices of wheat. Furthermore, research focusing on adapting the cropping system could help identify potential benefits resulting from global warming [121]. Facing with the changes in crop phenology brought about by climate change, farmers have been actively adjusting the cropping systems and improving crop management practices by choosing sowing and harvesting dates, as well as management methods that are more suitable for current climate conditions. For example, Lv *et al*. [122] found that delaying the sowing date could help ensure the potential yield of maize in northeast China under climate change. In the North China Plain, delaying the harvest of maize and the rotation mechanism of delaying the sowing of winter wheat could help cope with the warming climate in the north and improve yields [123]. Farmers have also relocated their rice cultivation as a response to the warmer climate in the north of China [124]. On a global scale, different climate change adaptation measures in agriculture have been tried and identified as effective measures. For example, some researchers mentioned the importance of taking scientific measures to manage the farm actively [125–128]. Besides, Sloat *et al*. [129] also demonstrated the importance of crop migration in the process of climate change adaptation. It is necessary for China to reference and learn from these based on its agricultural realities.

In response to the pressure that climate change brings to water resources, the selection of irrigation methods and technology is also crucial for farmers. For example, the synergistic effect of late-maturing varieties and irrigation regulation could improve crop yields and water use efficiency under future climate conditions [130], and delaying sowing dates and adjusting irrigation times appropriately could mitigate the negative impact of climate change [131]. In recent years, a variety of water-saving irrigation technologies have been rapidly developed in China, which can overcome the limitations of water scarcity in agriculture by reducing crop irrigation water usage and improving water production efficiency, thus alleviating the pressure of climate change on agricultural water use. Scientific irrigation techniques can even help reduce soil salinization, protect soil, and improve land productivity [132]. Researchers discovered that in arid regions such as Ningxia Hui Autonomous Region, farmers are willing to invest in rainwater harvesting facilities such as water storage tanks [133]. In 2010, a survey conducted by Cremades *et al*. [134] showed that household-based irrigation technology was adopted by 99% of the sampled villages. However, community-based irrigation technology was only adopted by 47% of the villages. Therefore, the community-based irrigation technology still needs to be improved. On a global scale, new irrigation technologies such as advanced seawater desalination techniques [135] and deficit irrigation technology tailored for dry continental climates [136] are also highly worthy of China's consideration and learning.

Government efforts to the adaptation of agriculture to climate change Although many farmers have taken measures to adapt to climate change, such as adjusting crop varieties and optimizing cropping systems, there are still cases where farmers prioritize short-term profits over long-term solutions. Similarly, with the mitigation measures of climate change in agriculture, the laboratory and theoretical research and farmers' measures alone are insufficient to address both agricultural mitigation and adaptation to climate change. It is clear that government assistance plays an irreplaceable role in this regard.

Governments should develop climate adaptation strategies to provide policy and legal support for farmers in responding to climate change. For example, in 2007, the Chinese government introduced China's National Climate Change Programme, which prioritized agriculture as a key area for climate adaptation. Firstly, it is important for the government to invest in agricultural infrastructure, such as water-saving irrigation facilities, to reduce the economic losses that farmers may face when choosing water-saving irrigation methods. Secondly, support for scientific research and the promotion of new technologies are crucial for agriculture to adapt to climate change. The government should increase economic investment in agricultural research and the development of new varieties of agricultural products, which can bring new opportunities to agricultural production. The government can promote these varieties, for example, by providing subsidies for farmers to purchase seeds [137]. In addition, to help farmers prevent risks brought about by climate change, governments can establish meteorological monitoring systems to provide timely and accurate weather information to farmers. Meanwhile, given that farmers are more concerned about economic losses when coping with climate change, establishing crop and livestock insurance can help increase farmers' ability to withstand risks. Ref. [138] found that agricultural insurance income in China had increased significantly since 2000. However, due to reasons such as lack of policy support and insufficient awareness among farmers, the agricultural insurance mechanism in China is still imperfect. Therefore, government assistance and support are crucial in promoting agricultural adaptation to climate change.

GHG emissions and mitigation measures in the agricultural sector

GHG emissions in the agricultural sector

Although agriculture is greatly affected by climate change, it is undeniable that agriculture is also a huge carbon-emitting sector. As the world's largest carbon-emitting country, the agricultural production activities in China have higher carbon emissions than the world average. At the same time, due to natural and economic conditions, agricultural production in different regions of China varies significantly, leading to regional differences in agricultural GHG emissions. During agricultural production, a large amount of CH_4, N_2O, and CO_2 can be emitted. Researchers estimated agricultural GHG emissions based on different sources, including livestock and poultry farming [139–142], rice plantation [93,139,143], soil emissions and land management. These emissions are associated with the agricultural production process. Moreover, a considerable amount of GHG emissions are generated from the input of agricultural materials during the production process.

GHG emissions from agricultural production process China has become the world's largest meat consumption market and livestock producer [144]. Livestock production, particularly enteric fermentation (accounting for 26.2% of China's total agricultural emissions) and manure management (16.6%), generates large amounts of CH_4 and N_2O gases [145]. The western China is responsible for most of China's livestock production. From the perspective of livestock production, the western region exhibits the highest carbon intensityin China [140,146].

China is the world's largest producer and consumer of rice, responsible for approximately 40% of the total grain output [147]. In the past decade, agriculture has consistently been the second largest sector contributing to methane emission, following oil and gas leakage, with rice cultivation and livestock farming being the primary sources of agricultural methane [148]. CH_4 produced by rice plantations is one of the important sources of agricultural GHG emissions, the CH_4 emission of rice is 9.9 t CO_2 eq/ha, twice that of wheat and corn [149]. The middle and lower reaches of the Yangtze River are the main rice plantation areas in China, accounting for over 50% of the country's rice production, rice GHG emissions in this region account for 50.86% of the total GHG emissions from rice plantation in China [150].

When crops are planted, turning the soil causes CO_2 and N_2O in the soil to flow into the air, which releases too much GHG, especially the N_2O. Fertilized agricultural soils where N_2O is naturally produced through the processes of nitrification and denitrification have been believed to be a major source of annual global N_2O emissions [151]. In China, agriculture consistently ranks as the number one sector based on N_2O emissions by sector [148]. Due to the differences in land management and soil use conditions in different regions, the spatial distribution of nitrogen wet deposition is uneven in China, with higher value in the eastern, southeast coastal and central regions, and lower in the vast western regions.

GHG emissions from input agricultural production materials Agricultural production involves the use of a variety of materials such as mulch, chemical fertilizers and pesticides, as well as machinery and irrigation, all of which contribute to GHG emissions. China is the world's largest consumer of fertilizer, accounting for 36% of global consumption [152]. Zhang *et al*. [153] used the CGE model to simulate agricultural GHG emissions in China, the results showed that GHG from agricultural inputs accounted for

15.25% of total agricultural GHG in 2010. Additionally, the GHG emissions from the irrigation process are also considerable. Zou *et al*. [154] accounted that emissions from energy activities in irrigation (water pumping and conveyance) were equivalent to around 50%–70% of emissions from national energy activities in agriculture in 2010.

Mitigation measures in the agricultural sector

Agriculture is not only one of the main sources of GHG emissions but also plays a significant role as a key carbon sequestration. Therefore, the potential of agricultural carbon sequestration and emission reduction should be utilized effectively. Improving the soil carbon sequestration capacity of farmland and promoting agricultural emissions reduction is conducive to enhancing the ability of China's agricultural production to adapt to climate change. In this context, the FAO and the Chinese government jointly proposed the concept of "climate-smart agriculture" and put forward the goal of "carbon sequestration, emissions reduction, stable grain production, and increased income". In scientific research, researchers have proposed emissions reduction methods targeting different GHG emissions in agriculture.

Reduction in different types of green house emissions Firstly, CH_4 is one of the main GHGs emitted by agriculture, mainly from rice plantations and livestock farming. In research focusing on the reduction of CH_4 emissions from livestock farming, it was found that adjusting nutritional strategies, such as changing the type of forage [155] or the proportion of feed [156], could effectively reduce animal CH_4 emissions. Moreover, scientific intervention measures for animal wastes can also effectively alleviate CH_4 emissions [157]. To address the large amount of CH_4 emissions from rice fields, researchers have proposed various measures, such as changing plantation management practices [158,159], improving the harvest index [160], modifying irrigation measurements [161,162], and improving the crop varieties [163].

N_2O is another major GHG emitted from agriculture, with farmland soil being its main source. Therefore, effective farmland management and soil treatment are important measures to mitigate N_2O emissions. In response to distinct factors that affect N_2O emissions, there are currently various scientific measures to mitigate N_2O emissions. such as optimizing fertilizer application [164,165], adopting suitable crop rotation and intercropping systems [166,167], and implementing water-saving irrigation techniques [167,168].

In addition to reducing the emissions of CH_4 and N_2O, the above-mentioned emission reduction measures also correspondingly reduce the emissions of CO_2. Furthermore, the reasonable input and utilization of agricultural materials can also significantly reduce CO_2 emissions. For instance, reducing the use of pesticides [168], fertilizers, and agricultural mulch [169] and increasing the use of organic fertilizers [170,171] can effectively reduce CO_2 emissions. With the close integration of agriculture and energy sectors, the promotion of energy-saving technologies and the development of renewable energy has become a significant way to promote the reduction of agricultural GHG emissions, for instance, biochar on the improvement of soil quality [172,173] carbon sequestration, improving fertilizer utilization efficiency and enhancing crop yield has been widely reported [174]. The advent of modern solar-powered electric agricultural machinery [175] provides new choices for agricultural energy use. The document issued by the Chinese Ministry of Agriculture to address climate change also mentions strengthening the use of renewable energy in agricultural machinery (SCPRC). Other renewable energy use such as solar and wind can also be used in power irrigation systems and other farm machinery to help reduce GHG emissions.

Carbon sequestration roles of agriculture In addition to the above-mentioned human-driven emissions reduction measures, agriculture has the potential to play a crucial role in carbon sequestration by utilizing its inherent potential. Tao *et al*. [176] found that since the 1980s, the carbon sequestration in Chinese croplands has increased substantially, particularly in paddy soils and fluvo-aquic soils. This indicated that the reasonable utilization of farmland could unleash its full potential for carbon sequestration, thereby contributing to mitigating climate change. Currently, some common methods for carbon sequestration in farmland include the rehabilitation of degraded farmland and returning straw to the fields [177,178]. Zhang *et al*. [179] proposed the concept of conservation agriculture, which consists of four components: no-till farming, residue mulch, complex diverse cropping system and integrated nutrient management.

Government efforts to mitigate the GHG emissions in agriculture In addition to technological measures, government policy support is crucial for reducing GHG emissions from agriculture. The Chinese government has taken significant steps by introducing relevant policies, such as China's Policies and Actions for Addressing Climate Change, and established the National Leading Committee on Climate Change. In the agricultural sector, the government has taken action in multiple ways. Firstly, strengthening the establishment and implementation of laws and regulations is of great importance. Only with the support of legal policies can actions taken by various departments be firmly safeguarded. Secondly, ecological agriculture in regions with high levels of intensive agricultural production should be intensified, including land reforestation, prevention of agricultural pollution from fertilizers and pesticides, and promotion of the use of organic fertilizers. Furthermore, the government should strongly support the invention and promotion of technologies, such as supporting low-carbon management practices for rice farmers [168], providing subsidies to livestock farms for building feces treatment facilities to promote the production of organic fertilizers [180], and developing micro-organism technology to reduce methane emissions from rice paddies, as well as enhancing and refining the technologies for household-type biogas digesters [181].

Chapter summary

Future agriculture will face increasingly severe challenges posed by climate change, but it also holds tremendous potential to address climate change. In order to adapt the impact of climate change and reduce GHG emissions from agriculture, a range of technological and policy measures should be taken. As listed in Table 3, at the technical level, the selection of new crop varieties that are more climate change-adapted is continuously advancing. Besides, novel and scientific crop management such as adjusting planting times and methods, are also important to adapt to the changing climate conditions. On the other hand, to lower GHG emissions from agriculture, in livestock farming, China can learn from advanced technologies abroad such as altering feed types and proportions, as well as proper management of animal waste, which can be employed to reduce CH_4 and N_2O emissions. New technologies in agricultural management such as biochar on the improvement of soil quality, solar-powered electric agricultural machines tend to be popular in the mitigation role of agriculture. On the government side, the government plays a crucial role at the policy level. For instance, by providing subsidies to farmers for the adoption of new crop varieties, the government significantly alleviates the economic burden that comes with the higher cost of these new varieties. The increased yield and resilience to disasters associated with these new varieties also contribute to their economic benefits, thus driving the widespread adoption of these crops among farmers. However, given the large

Table 3 Key technology and policies in the agricultural sector

		Literature	Measures	Evaluation
Adaptation to climate change	Key technology	Huang *et al*., 2008 [115]; Yao *et al*., 2011 [116]	New genetically modified varieties resistant to climate disaster	New varieties will increase yields, which in turn increase farmers' income, but their spread among farmers needs to be assisted by government subsidies. In the future, it is necessary to learn advanced technologies and constantly update crop varieties that adapt to new changes.
		Wang *et al*., 2014 [118]	New varieties with changed growth periods	
		Lv *et al*., 2020 [122], Li *et al*., 2015 [124]	Scientific cropping systems and crop management practices	It is a relatively low input and high return measure because farmers are not required to buy. But the spread among many farmers requires government support through volunteers and other methods to bring laboratory research results to field practice.
		Zou *et al*., 2012 [132]	New irrigation methods and technology	The biggest difficulty is that it costs more to buy the equipment than it does to save water. It is necessary to continue to innovate technology, so that irrigation technology can bring other benefits such as the integration of water and fertilizer, and more experimental pilots need to be established.
	Government Policy		Investing in agricultural infrastructure	It will reduce costs for farmers and help spread new technologies.
			Supporting for scientific research	The progress of scientific research cannot be achieved without the support of the government, including adequate funding, cooperation between governments to improve international exchanges and so on.
			Meteorological monitoring systems	It can help farmers reduce their losses from climate disasters also increase their confidence in using new varieties and management methods.
Mitigation to climate change	Key technology	Na *et al*., 2013 [155]	Adjusting nutritional strategies of livestock	It is relatively low-cost, but needs the support of scientific research results. With the promotion of the government, it is promising to be widely used in the future.
		Bera *et al*., 2019 [172]	Biochar on improvement of soil quality	It provides a safe and economical waste disposal strategy, as well improves soil quality. Thus it has a promising prospect in the future.
		Gorjian *et al*., 2021 [175]	Modern solar-powered electric agricultural machinery	The cost is high and relatively difficult to promote, but the cost of photovoltaic modules has declined in recent years, and the economic opportunities for using solar energy to participate in agricultural tasks are increasing globally.
	Government policy		Strengthening the establishment and implementation of laws	It is an important task for the future government, which can promote farmers' environmental awareness.
			The contruction of ecological agriculture in regions	Ecological agriculture is an impressive development trend in the future, which requires the cooperation of the government and farmers.
			Supporting the invention and promotion of technologies	The government should and will continue to support for the new technology in the future.

number of farmers in China and the preference of many for traditional farming methods, the adoption of new technologies and management practices faces great challenges. The government should strongly support technological innovation and its dissemination, allowing researchers to bring laboratory findings to the field and truly benefit farmers.

In summary, future agriculture must actively address the challenges of climate change through the dual guidance of technology and policy. By implementing appropriate technological measures, optimizing agricultural practices, reducing GHG emissions, and harnessing the carbon sequestration potential of agriculture, sustainable agricultural development can be achieved. This will provide a solid foundation for food security, farmers' livelihoods, and ecological balance. Close collaboration between the government, farmers, and research institutions will be key to achieving this goal.

Climate change and industry sector

We identified papers on climate change and industry from all Web of Science databases by searching for the following keywords: climate change, industrial sector, impact, mitigation, low carbon, decarbonisation. In total, 1470 papers were collected (from 2013 to 2023), and finally, 489 nodes were analysed by the CiteSpace after removing duplicates. The keyword co-occurrence network of industry and climate change (Figure 4)

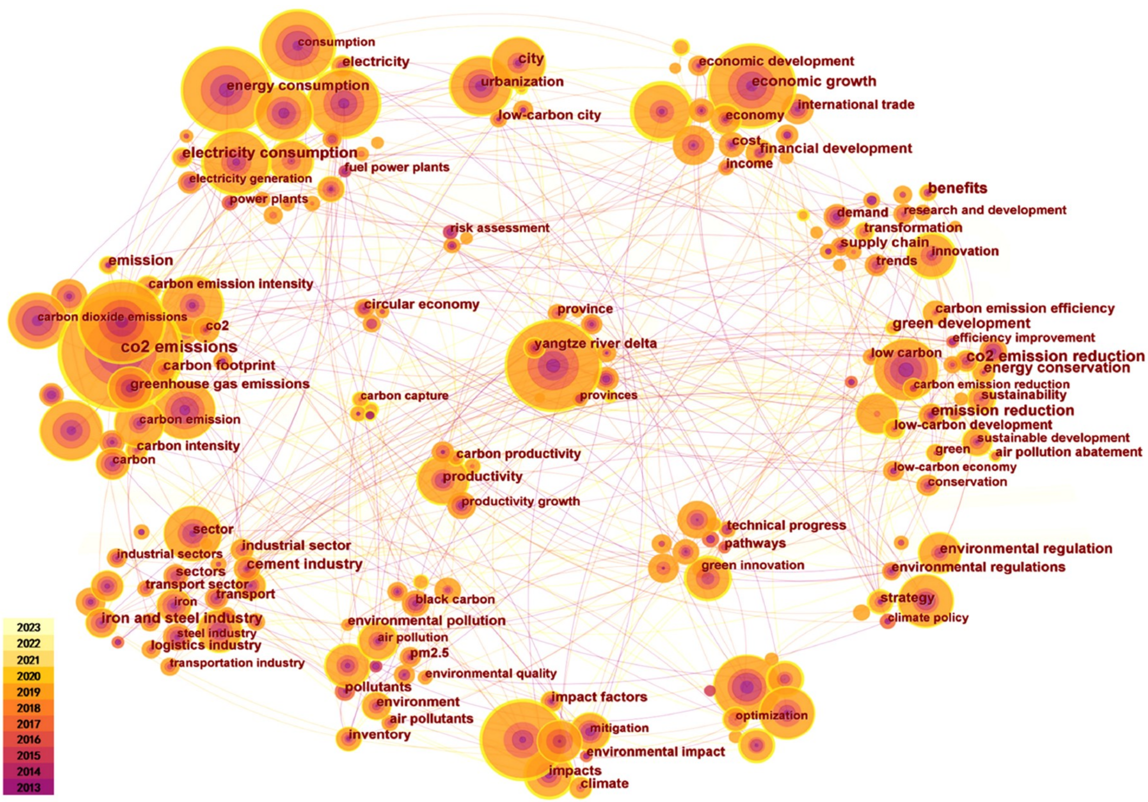

Figure 4 Keyword co-occurrence network analysis of industry sector and climate change.

reveals that the industrial sector exacerbates climate change primarily through the emission of GHG resulting from fuel and electricity consumption. Furthermore, industrial emissions have adverse environmental impacts, including air pollution. The literature review indicates that low-carbon development, such as energy conservation and emission reduction, is the predominant approach for mitigating climate change in the industrial sector. Economic considerations, such as cost-effectiveness, are also vital factors influencing decision-making while developing low-carbon technologies. Given that industry remains a crucial driver of China's economic growth, industries with high emissions and significant contributions to the national economy, such as steel, cement, and chemicals, have become the primary targets for emission reduction.

Impacts of climate change on industry sector

In the industrial sector, extreme temperatures caused by climate change can lead to a decrease in labour productivity and an increase in operation cost, since high temperatures limit working hours of outdoor operations and rise the demand for air conditioning and other cooling systems. Both of these downsides lead to the reduction in production [182]. Studies based on Chinese industrial enterprises from 1998 to 2007 indicated an inverted U-shaped relationship between temperature and industrial production, which means that industrial production would increase with temperature until it reached an optimal temperature range and then decline sharply with further temperature rise [183,184]. Further studies revealed that high temperatures would indirectly affect industrial production by reducing total factor productivity (TFP), total fixed assets, investment, and innovation capabilities. Climate warming will cause a decline in Chinese industrial production by approximately 3.0%–14.6% in the medium term and 5.9%–20.0% in the long term [185].

Climate change has led to more frequent extreme climate in many regions of China, such as floods, drought and typhoons, which can damage infrastructure, disrupt supply chain and raise risk costs in operating industrial facilities [186]. Transportation system serves as a crucial service provider for industrial sector but is vulnerable to climate shocks [187,188]. Extreme weather events could cause traffic disruptions, which could affect the accessibility of raw material supply [189]. Water scarcity could happen due to the interruption of water supply caused by severe drought, especially in the regions where industrial sector highly relies on water usage.

Considering China's commitment to reducing GHG emissions and targets for transition to low-carbon economy, the government further restricts the proportion of energy-intensive industries, which diminishes the market value of related industries [186]. The continuous strengthening of environmental regulations can impact the revenue and performance of industries. Traditionally, it has been believed that environmental regulations imposed an additional burden on industries, requiring them to either incur extra costs for complying with regulations related to environmental protection or limit their output [190]. In 2017, China implemented a nationwide carbon market following a six-year trial of an Emission Trading System (ETS). The initial phase of China's national ETS focused on the petroleum, chemical, and non-ferrous industries, with both the upstream and downstream sectors of these industries facing considerable environmental pressure to reduce their emissions. Companies failing to meet the prescribed reduction targets will incur substantial abatement costs [186]. In short, climate change will lead to problems such as reduced output and increased costs in the industrial sector.

GHG emissions mitigation technology and strategy in the industry sector

For the industrial sector, the most important thing is to focus on how to reduce its impact on GHG emissions. As China's largest carbon emitter, mitigation efforts in industrial sector can help to reduce the impact of climate change not only on this sector but also on other sectors such as electricity and agriculture. Energy conservation and emission reduction in industrial processes have always been recognized as key strategies to address climate change, particularly in energy-intensive industries such as coal and washing, oil and gas mining, petrochemicals, chemicals, steel, cement, papermaking, nonferrous metals, and building materials. These industries rely heavily on energy and raw materials and are the primary targets for energy-saving and emission-reduction measures.

The section below mainly examines and analyses the energy-saving and emission-reduction technologies employed by these industries, with the aim of summarizing the measures taken by the industries to tackle the impact of climate change. The application of the mitigation technologies in the iron and steel industry is mainly introduced as an example.

Energy conservation

Material and energy circulation

Waste heat recovery Significant quantities of waste heat are produced during energy consuming processes in industrial sector, and the reusage of diverse forms of waste heat can notably curtail energy consumption. Research on waste heat recovery and utilization in the iron and steel industry commenced as early as the 1980s in China. This industry has tremendous potential for energy conservation through waste heat recovery and utilization, as numerous studies have shown [191].

In 2020, China produced about 890 million tons of pig iron and 1.06 Gtof crude steel [192], resulting in blast furnace slag and steel slag outputs exceeding 300 and 100 Mt, respectively. The molten slag was exhausted at a temperature exceeding 1400°C [193]. The contained waste heat resource reached 7.5×10^{17} J, which was equivalent to 25 Mt of standard coal. If this part of waste heat can be fully recovered, it is equivalent to reducing emissions by 67.5 Mt CO_2 per year.

Besides, the recovered heat may also be used for winter heating and waste heat power generation. Low-quality waste heat from quenching water of molten slag can be recovered by using Organic Rankine Cycle (ORC) power generation technology [194]. The ORC system realizes the conversion of heat in low-quality dust-laden steam to electricity, but the waste heat recovery efficiency is low. Recovered waste heat may be used for heating in winter time and power generation. At present, low-quality waste heat heating technology has basically matured and is suitable for heating demand in northern areas of China. Heating and waste heat power generation should be selected in parallel if funding permits, which not only overcomes the temporal and special limitation of heating, but also alleviates the problem of long payback period of power generation projects [195].

The chemical method of waste heat recovery uses endothermic chemical reaction to fix the heat contained in high-temperature slags into high-energy chemical bonds of the reaction products. This method is featured with less value loss, higher heat transfer efficiency and continuous recovery of waste heat [196]. Biomass utilization can be integrated with steel slag waste heat recovery as well, where slags not only provide heat energy for pyrolysis gasification reaction, but also act as the catalyst of the reaction [197].

Scrap reuse The reusage of recycled materials can also enhance the overall energy efficiency of the industrial process leading to substantial energy saving. For example, in iron and steel industry, scarp can be used in the electric arc furnace as a supplementary raw material to produce steel, which is widely regarded as a promising steel production method with substantial potential for reducing CO_2 emissions. Zhao [198] studied the melting process and yield rate of scrap steel with different material types by using laboratory hot melting test, and discussed the effects of different process parameters such as scrap material type, scrap preheating, scrap type and scrap shape on the scrap melting process combined with the numerical simulation of the scrap melting process.

Compared to the BF/BOF route, the CO_2 emission intensity of the Scrap/EAF route is merely a quarter, owing to the use of electricity instead of coke [199]. Moreover, the CO_2 emission intensity can be further lowered if low-carbon electricity sources such as wind power and solar energy are employed. The effectiveness of the high proportion Scrap/EAF steelmaking route has been verified in the United States, where 70% of the crude steel is generated through this route [200], with an emission intensity of 0.47 t CO_2/t cs (crude steel, cs) [201], already lower than the International Energy Agency's 2050 Sustainable Development Scenario of 0.6 t CO_2/t cs [202].

However, the proportion of scrap and electric furnace steel in China's crude steel output remains relatively meager, trailing behind the world's most cutting-edge standards. Over the last two decades, the percentage of Scrap/EAF crude steel production has witnessed a persistent decline, whereas the overall crude steel output has experienced an exponential surge. As of 2019, only 10% of crude steel emanated from the Scrap/EAF route. Conversely, concerning the world's top 20 steel-producing nations, the percentage of China's Scrap and EAF route lags behind the global average of 28% and is even lower than the 50% average of the world excluding China, depicting a profound disparity from the world's most advanced benchmarks, such as Italy's impressive 80% [203].

Presently, China's dearth of scrap supply impedes the support of such an enormous crude steel production, with a supply of merely 240 t of scrap compared to a staggering 995 t of crude steel production. The primary sources of steel scrap in China stem from social scrap and end-of-life steel products manufactured by the steel industry. It is noteworthy that during the interval between 2017–2018, society's supply of scrap steel experienced an unprecedented surge, primarily owing to the elimination of outdated and illicit production practices in China [204].

Process integration and optimization

Iron carbon agglomerates (ICA) In response to the global scarcity of high-quality coke and iron ore, a new low-carbon ironmaking charge called ICA has emerged as a potential solution. ICA offers several benefits: firstly, lower-quality coking coal and iron ore can be used, thereby expanding the range of available raw materials and reducing costs. Secondly, ICA exhibits high reducibility under the action of newly formed iron catalyst, which reduces the temperature in the heat storage zone, improves gas utilization and smelting efficiency, and enhances the gas permeability and droplet performance of the blast furnace. Additionally, ICA also facilitates the reduction of blast furnace ferrous load and improves shaft efficiency. Finally, only the metallic iron in the ICA needs to be melted to be brought into the blast furnace, which can reduce energy consumption and increase production [205]. The use of ICA also helps to reduce the coke ratio, thereby minimizing CO_2 emissions and production costs. Based on these advantages, the new ICA charge has become one of the important fields of low-carbon blast furnace ironmaking technology researched and developed globally [206,207].

Due to the increasing pressure to reduce energy consumption and emissions in China, the use of ICA technology has received widespread attention. This technology has been identified as a cutting-edge solution for energy conservation and emissions reduction in the "Steel Industry Adjustment and Upgrading Plan (2016–2020)" in China. Researchers from Northeastern University in China have conducted studies on the preparation, metallurgical performance optimization, and promotion of reduction of ICA with iron-containing feedstock, as well as its impact on the drip properties of blast furnace burden. They successfully employed the vertical furnace method, which established a complete process for the preparation and application of ICA. The results show that the emission of CO_2 can be reduced by 25 kg/tcs of crude steel, and the production cost can be reduced by about 12 ¥/tcs [208–210].

Blast furnace with top gas recycling (TGR-BF) Many countries and regions, such as Japan, Russia, the EU, and China have conducted tentative studies on small TGR-OBFs (Oxygen blast furnace with top gas recycling) since about 40 years ago [205]. The world's largest TGR-BF system in Japan has yielded a noteworthy CO_2 capture rate of 90% and reduced annual CO_2 emissions by a staggering 300,000 t. In China, multiple TGR-BF systems have been constructed and are operational, boasting a combined CO_2 capture capacity of 1.75 Mt per year. The TGR-BF technology functions to gather and segregate CO_2 from blast furnace top gas, allowing for the recovery and reuse of useful CO and H_2 components as a reducing agent in blast furnaces. This facilitates the reduction of coke utilization and its associated quantities. Moreover, TGR-BF technology can effectively diminish the presence of NO_x and SO_x in blast furnace gas, thus reducing air pollutant emissions. The cutting-edge gas cycle technology centres on the capture and separation of carbon dioxide from gases. In 2007, the TGR-BF process was pilot-tested on the experimental blast furnace of the LKAB plant in Sweden using four schemes. The ULCOS-BF test carried out in the test blast furnace proves that the newly developed furnace top gas recycling process has good operation safety, high efficiency and strong stability. Combining furnace top gas recycling technology with CCS (carbon capture and storage) technology, it should be feasible to reduce CO_2 emissions by 50% to 60% [211].

China is actively pursuing TGR-BF technology, with Baosteel Bayi Iron and Steel Company establishing a low-carbon ironmaking test base to conduct commercial tests on a 430-square-meter blast furnace [212]. The testing process has been carried out in four stages, with the first two already completed. By 2023, the entire commercial testing of the TGR-BF technology is expected to be finalized, with an overarching objective of reducing CO_2 emissions by 30%. TGR-BF technology is particularly well-suited for the steel industry and boasts high applicability.

Alternative fuel (renewable energy)

Electrification (renewable energy electricity) Switching to clean fuel is another direction for decarbonizing industrial sector. China intends to implement electrification, hydrogen, carbon capture and storage, and bioenergy to fully decarbonize heavy industry, including the steel, cement, and chemical (ammonia, methanol, high-value chemicals or HVC) sectors [213]. Direct electrification is best suited for industries with low to medium-temperature requirements, while hydrogen and bioenergy can be used for high-temperature requirements. Hydrogen can also be used as a reducing agent for steel and as a raw material for chemical production. Biomass may become another important chemical raw material [214].

Increasing the share of electrification in the industrial sector and using electricity from renewable sources can save energy demand from fossil fuels to a large extent [215]. In addition to the direct carbon emissions caused by the combustion of fossil energy, the carbon emissions of the petrochemical industry also include indirect emissions from purchased electricity, which account for about 10% of the total emissions of the petrochemical industry [216]. With the proposal of a clean power system construction target based on renewable energy, the power grid in China will continue to develop towards cleanliness, and the carbon emissions caused by electricity in the petrochemical industry will gradually decrease.

In 2021, coal-based thermal power generation accounted for about 71.13% of China's power structure [6]. It is predicted that after 2050 in China's power grid, the proportion of wind power and photovoltaic power generation will increase significantly, accounting for about 50%, while the proportion of hydropower and nuclear power remains at about 20%, and the proportion of fossil fuel without CCUS is less than 5% [217]. By 2060, the carbon emission factor of the State Grid will be reduced by about 97%, and the indirect carbon emissions caused by electricity in the petrochemical industry will be reduced by about 97% compared with the current level.

Biomass Biomass can be considered a carbon-free resource under certain conditions. Therefore, biomass steelmaking is an attractive solution to reduce emissions during steel production [218,219]. Replacing fossil-based reducing agents with biomass can decrease CO_2 emissions by up to 50% in the integrated steelmaking process [220]. Biochar is also a viable substitute for the sintering process, while charcoal presents a promising alternative for blast furnaces [191]. Moreover, the iron and steel industry can mitigate carbon emissions through the utilization of other renewable sources, given its reliance on electricity and heat for steelmaking [221–223]. However, compared to other low-carbon technologies such as CCS and hydrogen energy steelmaking pilot projects, biomass steelmaking is currently the least considered option in the research on the low-carbon path of China's steel industry. The research and development of using biochar instead of coke for steelmaking is still in its early stages, and the supply of biomass resources such as agricultural and forestry residues is limited. As China aims for carbon neutrality, bioenergy technologies may be more critical for long-distance transportation such as shipping and aviation.

For chemical industry of China, the coal-based chemical production route will remain dominant in future unless there is a clear economic advantage to power conversion and a biomass-based production route. The clean utilization of coal in the chemical industry has been listed as China's strategic development policy, and the overall planning scale of coal chemical industry will be further expanded. However, the scale of the coal chemical industry needs to be significantly reduced on the basis of existing plans, not only for the consideration of carbon emissions, but also for the protection of water resources and the prevention of air quality deterioration. Among the seven provinces and autonomous regions with concentrated coal chemical production capacity, including Shanxi, Henan, Shaanxi, Inner Mongolia, Xinjiang, Qinghai and Ningxia, six provinces and autonomous regions are already facing the problem of water shortage or even severe water shortage, in addition to serious air quality problems. Therefore, it is crucial for China to implement effective measures to mitigate the negative environmental impacts of the coal chemical industry, while exploring cleaner alternatives for the production of chemicals [213].

Emission reduction

Hydrogen energy

Hydrogen can be generated from multiple sources, and have high calorific value, excellent combustion performance, good thermal conductivity and fast reaction rate, which makes it the most promising energy in 21st century [224–228]. The utilization of clean hydrogen as a primary energy carrier and feedstock holds great potential for reducing carbon emissions in "hard-to-abate" (HTA) industries like iron and steel, cement, and the chemical industry. Implementation of a feasible clean hydrogen scenario that achieves 65.7 Mt of production by 2060 has the capacity to save US$1.72 trillion in new investment compared to a scenario without hydrogen usage [229].

Blast furnace ironmaking using coke as a reducing agent is the main carbon emission process in steelmaking. According to the statistical data of China Iron and Steel Industry Association in 2020, the coke rate of blast furnace ironmaking was 355.19 kg/t, and the carbon emission generated in the ironmaking process was 1.3 t of CO_2 per ton of pig iron. In blast furnace ironmaking, the use of coke can be reduced by means of technical process optimization and coke oven gas injection, thereby achieving the effect of emission reduction. For example, replacing 15% of coke with hydrogen injection can reduce carbon emissions by about 10% [230]. Based on the overall goal of carbon neutrality, compared with 2.0 t of carbon emissions per ton of steel using traditional BF-BOF technology [231], the carbon emissions per ton of steel using green hydrogen-based direct reduction technology are only 0.15 t, reducing carbon dioxide emissions by more than 85%.

For high-grade iron ore, direct reduction and electric arc furnace routes are available. These routes offer a potential reduction in carbon emissions of up to 47% compared to the existing blast furnace converter route. By using 80% green hydrogen in the direct reduction process and 20% scrap steel production, carbon emissions can be reduced by 75%. And when 100% green hydrogen is used for both DRI and EAF routes, carbon emissions can be virtually eliminated.

In 2019, notable iron and steel enterprises in China commenced significant investment in hydrogen metallurgy research and initiated independent projects [232]. Several Chinese companies and universities have established strategic partnerships and research institutes to promote the development of hydrogen energy and metallurgy technology. Baowu Iron and Steel Group has collaborated with China Nuclear Power Corporation and Tsinghua University to develop hydrogen production using nuclear energy and metallurgy processes. Hebei Iron and Steel (HBIS) Group, China Iron & Steel Research Institute (CISRI), and Northeastern University have jointly established the "Hydrogen Energy Technology and Industrial Innovation Centre" to encourage innovation and industrial development. Jiuquan Iron and Steel (Group) Co., Ltd. (JISCO) has established the Hydrogen Metallurgy Research Institute to conduct research in the field of hydrogen metallurgy. Rongcheng Iron and Steel Group, Shaangu Electric Power, Hanhai Hydrogen Energy, and the Seoul government have partnered to establish a nationwide hydrogen energy development and distribution hub. Additionally, HBIS Group has signed an agreement with Tenova to establish the world's first hydrogen metallurgy demonstration project capable of producing 1.2 Mt of output. Furthermore, China Shanxi Taihang Mining Co., Ltd. has proposed a coke gas technology-based Direct Reduced Iron (DRI) method in collaboration with Beijing University of Science and Technology, and Inner Mongolia Saixipu Technology is investing 1 billion yuan in a high-purity pig iron project that uses hydrogen-rich melting technology [45].

Despite being in its early stages in China, the hydrogen energy industry holds immense potential for future applications. Serving as a zero-pollution reducing agent, it has the capability to substantially decrease carbon emissions and modernize conventional manufacturing processes, ultimately leading to a mutually beneficial outcome for both industry and energy structure [233].

Carbon capture, utilization and storage (CCUS)

Capture The techniques used for capturing CO_2 include post-combustion capture, pre-combustion capture, and oxy-fuel combustion capture. Separation technologies for CO_2 include absorption, adsorption, membrane separation, low-temperature distillation, and other methods [234–236].

According to different absorption principles, carbon capture absorption technology can be divided into chemical absorption and physical absorption [237,238]. In China, the iron and steel industry and the petroleum industry are the main application fields of chemical absorption technology. For example, during 2004–2008, Baoshan Iron& Steel Co., Ltd. (Baosteel) recovered CO_2 from lime kiln flue gas for the research on bottom blowing of converter steelmaking. The project uses the chemical absorption method, based on the improved MEA chemical absorbent, and carried out a small-scale research with a scale of 40 L/h flue gas. Jingtang Iron and Steel Co., Ltd. used the national project to cooperate with Beijing University of Science and Technology to carry out the converter bottom blowing CO_2 experiment. The follow-up plan is to establish a lime kiln flue gas capture CO_2 device. The first-stage design is 50,000 t/year [239]. Shenhua Group has equipped a CO_2 capture device for the direct coal liquefaction project in Ordos, Inner Mongolia, using a chemical absorption method using MEA as the absorbent. In January 2010, China Power Investment Corporation completed and put into operation the Chongqing Hechuan Shuanghuai Power Plant, which can capture 10,000 t of high-purity CO_2 per year, and also adopted the chemical absorption method using MEA as the absorbent; Baosteel conducts CCUS research to explore mature modular technologies that can be used for reference. Through discussions with World Steel experts on the maturity of CCUS process technology, it is believed that Baosteel's CCS modular technology has reached the conditions for industrialization [240].

However, the application of carbon capture and absorption technology in the steel industry has encountered a bottleneck. For a long time, the iron and steel industry has usually used amine-based absorbents. Although they have strong absorption and selectivity for CO_2, they also lead to high stability of such absorbents combined with CO_2, thereby increasing the energy consumption in regeneration process. China's iron and steel enterprises have conducted decades-long research in order to solve the problem of high energy consumption in the regeneration of such absorbents. Recently, iron and steel enterprises such as Baosteel have developed four new types of absorbents with low regeneration energy, including blended amine solvents, non-aqueous amine-based absorbents, biphasic amine absorbents, and catalyst-aided amine absorbents [199,241].

Adsorption technology is another carbon capture technology besides absorption technology. It is mainly divided into pressure-swing adsorption (PSA) and temperature-swing adsorption (TSA) according to the different adsorption principles. Among them, PSA technology can operate in a wider temperature and pressure range, and consumes lower energy and cost, so it has become the main adsorption technology considered by China's industrial sector. Although PSA technology has many advantages mentioned above, it has not been widely applied in China's steel industry. The key factor determining the effective application of

PSA is whether a significant amount of highly selective CO_2 can be adsorbed in the flue gas, and whether the maximum desorption after adsorption is completed can be achieved. Activated carbon, zeolites, silica gel, and activated alumina are all commonly used adsorbents in PSA technology [237,242,243].

Utilization Carbon dioxide utilization technology involves using carbon dioxide for high-value production through various means, such as chemical, biological, and geological processes. In the industrial sector of China, carbon dioxide utilization currently focuses on chemical production, biological utilization, and resource utilization during the production process [240].

There are many ways to use CO_2 in the iron and steel industry after extraction. First, CO_2 can be used in converter steelmaking. Since the 1980s, researchers in China and other countries in the world have begun to develop new technologies for bottom-blowing CO_2. Its metallurgical value lies in: (1) strong dynamic stirring required for dephosphorization; (2) reducing argon consumption; (3) inhibiting the peroxidation of molten steel. Europe, Japan, and Australia are mature countries and regions that use CO_2 for reblowing, and China Baosteel Iron and Steel Group has also tested this technology [241].

In addition, chemical conversion of carbon dioxide can yield valuable chemicals including methanol and ethanol. In January 2020, China inaugurated its first-ever 1000-t liquid solar fuel synthesis demonstration project, which utilizes CO_2 hydrogenation technology for methanol synthesis, developed by the esteemed Dalian Institute of Physical Chemistry, Chinese Academy of Sciences (CAS). The project enables solar energy to be converted into methanol fuel, achieving a noteworthy efficiency of over 14%. Upon commencement, the project anticipates an annual production capacity of 1440 t of “liquid sunshine” methanol. Moreover, in September 2020, the world’s inaugural 5000 t/year CO_2 hydrogenation to methanol industrial pilot plant, engineered by China National Offshore Oil Corporation (CNOOC), achieved stable operation and successful industrial demonstration [244]. In addition, CO_2 can also be used to synthesize formic acid [245] and olefins [246], and there are many other CO_2 conversion technologies, such as electrocatalysis [247], and photocatalysis [248], which are currently in the basic research stage.

Furthermore, bioutilization of carbon dioxide involves two main technologies: biological fermentation technology and microalgae carbon sequestration technology. Carbon dioxide can be converted into ethanol by biological fermentation technology through microbial fermentation to produce fuel. China launched a demonstration project of this technology as early as 2014. Baosteel and LanzaTech New Zealand cooperated to use microbial gas fermentation technology to convert blast furnace/converter gas and other gases into fuel ethanol, with an annual output of 300 t [241]. Microalgae carbon sequestration technology is another very promising carbon dioxide utilization method besides biological fermentation technology. Microalgae can fix carbon dioxide by absorbing it as a raw material for photosynthesis, and the large amount of carbon dioxide contained in the flue gas emitted by the industrial sector can be used as an effective source of raw material. In addition, there are air pollutants containing other elements in the flue gas, such as nitrogen oxides, sulfur oxides, heavy metal elements, etc., which also provide other nutrients needed for the growth of microalgae. In the process of photoautotrophic growth, microalgae shows unique advantages such as high photosynthetic efficiency, fast growth rate, and strong adaptability. Organic matter is produced through photosynthesis [249], as well as high-value products such as lipids, proteins, and carbohydrates [250,251]. China’s main research and demonstration projects include: Inner Mongolia coal-to-methanol production base to establish a bio-carbon sequestration demonstration project and Baosteel’s microalgae high-efficiency carbon sequestration and wastewater purification pilot platform. Although China has made significant progress in the research of microalgae carbon sequestration technology, the problems of carbon sequestration efficiency and carbon sequestration speed in the technical process are still major challenges in the application of this technology [252].

Storage Carbon dioxide storage refers to the process of capturing and compressing CO_2 emissions from large sources and transporting them to designated locations for long-term storage, rather than releasing them into the atmosphere. The technology for CO_2 storage, particularly geological storage, is receiving increasing attention and research, with the United States, the European Union, Japan, Australia, and other countries and regiones developing corresponding research plans to conduct theoretical, experimental, demonstration, and application research on CO_2 storage technology. Large-scale CCS methods mainly include geological storage, surface storage, and ocean storage. China has a huge geological storage potential of about 12.1–41.3 Tt [253]. In June 2022, the equipment for China's first offshore CO_2 storage demonstration project was completed at Offshore Oil Engineering (Qingdao) Co., Ltd. The offshore CO_2 storage module weighs approximately 750 t and its core equipment includes a CO_2 compressor sled, molecular sieve, and cooler. It is an important device on the Enping 15-1 central platform and will serve the Enping 15-1 oilfield in the Pearl River Mouth Basin in the South China Sea.

In summary, CCUS has become a popular area of research and development in China's iron and steel industry, as it offers potential benefits in terms of energy conservation, emission reduction, and production enhancement. Many Chinese iron and steel enterprises, including Baosteel, Huaneng Shidongkou Power Plant, Pioneer Hengyang Steel Tube of Peking University, Sichuan Dagang, Beijing University of Science and Technology and Shougang Jingtang, etc., are taking blast furnace gas as the research object, combining CO_2 and Modular technology for the utilization of coal gas production. These companies are building their own experimental platforms to conduct research, perform numerical simulations, and design systems, aiming to achieve effective CO_2 utilization in various processes, including coal gas production, power generation, steelmaking, microalgae farming and carbon sequestration, and partial replacement of nitrogen with CO_2.

The CCUS of Chinese iron and steel enterprises mainly includes the following steps: (1) comparison and selection of modular technologies for separating CO_2 from blast furnace gas by pressure swing adsorption and chemical absorption; (2) CO_2 is used in the coke oven combustion chamber to replace high calorific value gas for combined cycle power plant (CCPP) units in power plants to increase output; (3) CO_2 is used in steelmaking processes, including applications in converter blowing and continuous casting systems; (4) CO_2 is used in microalgae technical solutions for farming and carbon sequestration to obtain biofuels; (5) technical solutions for partial replacement of nitrogen by CO_2.

Chapter summary

The industrial sector is poised to remain the primary contributor to climate change in the foreseeable future. Consequently, the strategies employed by this sector to address climate change are primarily oriented towards its mitigation. To curtail carbon emissions originating from industrial activities and alleviate the impact of climate change, various industrial domains must embrace innovative low-carbon technologies. Moreover, governments should formulate pertinent policies to bolster emissions reduction within the industrial sector. The table presents key technologies and policies that will come to the forefront in the future. Concerning technology, the integration of Carbon Capture and Storage (CCS) with industrial production processes holds great promise in substantially diminishing direct carbon emissions arising from production. Given the enduring indispensability of fossil fuels as a source of industrial energy and raw materials for the foreseeable future, CCS technology assumes paramount importance for industries encountering challenges in emissions reduction and the transition to alternative energy sources. While the system's complexity is undeniable, and its overall maturity remains incipient, select CCS technologies have already entered practical application and pilot phases. Furthermore, the utilization of hydrogen will emerge as a pivotal avenue for industrial emissions reduction. For instance, within the iron and steel industry, hydrogen can serve not only as a fuel but also as an auxiliary reducing agent during the iron-making process. The deployment of green hydrogen, generated via electrolysis from renewable energy sources, in hard-to-abate processes can yield substantial reductions in carbon emissions. Notwithstanding the manifold advantages of hydrogen energy, it is imperative to acknowledge that current hydrogen energy technology is in an immature stage, characterized by drawbacks such as elevated costs, intricate value chains, storage challenges, and substantial infrastructure prerequisites. In addition to the above, promoting industrial electrification and augmenting the share of renewable energy sources in industrial electricity consumption stand as pivotal measures for emissions reduction within the industrial sector. The recycling of waste materials, furthermore, can efficiently foster the circular economy, abate raw material consumption, and reduce the environmental impacts associated with raw material extraction.

In the terms of policies, it is worth noting that the policies presented in the Table 4 are all derived from the "2022 Annual Report on China's Policies and Actions to Address Climate Change" issued by the Ministry of Ecology and Environment of the People's Republic of China [254]. In the face of climate change's impact, the Chinese government is resolutely committed to fostering green, low-carbon, and high-quality development within the industrial sector, with an overarching objective of establishing a sustainable green manufacturing system. Through judiciously curbing the blind development of "high-energy-consumption, high-emission, low-level" projects, the government has achieved notable reductions in energy demand. Furthermore, the Chinese government has championed the enhancement of quality and efficiency across the industrial sector. It has elevated industry-wide energy efficiency by endorsing exemplar enterprises, advocating for the comprehensive utilization of industrial solid waste, bolstering the recycling of renewable resources, and strengthening demand-side management of power within the industrial sector. These initiatives have effectively culminated in a reduction of energy consumption per unit of added value within the industrial domain. Moreover, the government has taken active measures to address non-carbon dioxide greenhouse gas emissions, targeting primary emission sources within the industrial sector. These actions include refining pertinent policies, standards, and technical specifications systems to non-carbon dioxide greenhouse gas emissions control. It becomes manifestly evident that the effective mitigation of climate change necessitates a confluence of both technological and policy interventions.

CONCLUSIONS

This paper provides a review of the adaptation and mitigation efforts in three important sectors in China in response to climate change: the electricity sector, agricultural sector, and industry sector. We identified papers on climate change and agriculture from all Web of Science databases by searching for the following

Table 4 Key technology and policies in industrial sector

		Literature	Measures	Evaluation
Mitigation to climate change	Key technology	Li Zheng *et al*., 2021; Wang *et al*., 2021 [255,256]	Carbon capture, utilization and storage (CCUS)	For sectors grappling with emission reduction and the shift towards cleaner energy sources, CCS technology assumes a pivotal role in their future progress. The evolving landscape of CCS technology is anticipated to facilitate a remarkable reduction of approximately 390 Mt of emissions per annum in China by the year 2030.
		Yang *et al*., 2022 [229]	Hydrogen (zero-carbon energy system)	Within the context of the ZERO-H initiative, the BF-BOF share is projected to decrease to 34% by the year 2060. Meanwhile, electric arc furnaces are poised to claim a 45% share, and hydrogen-DRI will constitute the remaining 21%. Clean hydrogen is slated to fulfill 29% of the industrial sector's overall final energy requirements.
		Wang *et al*., 2023 [257]	DRI-EAF (Electrification and Scrap Use)	Owing to reduced steelmaking expenses, decreased CO_2 emissions, and elevated CO_2 prices, the overall cost of direct reduced iron-electric arc furnace (DRI-EAF) technology will be more competitive than the blast furnace-basic oxygen furnace (BF-BOF) method.
	Government policy	Ministry of Ecology and Environment of the People's Republic of China, 2022 [254]	Support the green, low-carbon and high-quality development of industry and build a green manufacturing system	Vigorously regulate the unchecked proliferation of high-energy-consuming, high-emission, and low-tier (two high and one low) projects. The issuance of environmental impact assessment approvals for construction projects within associated industries in 2021 witnessed a year-on-year decline exceeding 30%, thereby curbing the initiation of over 350 "two high and one low" undertakings and curtailing the demand for new energy by 270 Mt of standard coal.
			Vigorously promote the improvement of quality and efficiency in the industrial field	Identify 43 companies at the forefront of energy efficiency across 14 pivotal sectors, encompassing petrochemicals, chemicals, and steel, to spearhead advancements in the overall industry's energy efficiency.
			Controlling non-CO_2 greenhouse gas emissions	In compliance with pertinent regulations, the Chinese government intensifies its oversight of HFC emissions. It mandates rigorous supervision of select HFC chemical manufacturing and construction initiatives, bolsters environmental governance for associated construction projects, and prohibits companies from direct discharge of the by-product trifluoromethane.

keywords: climate change, agricultural sector, impact, adaptation and mitigation. In total, 3896 papers were collected (from 2013 to 2023), and finally, 639 nodes were analysed by the CiteSpace after removing duplicates. This paper aims to summarize the existing research on their adaptation and mitigation measures. From the keyword co-occurrence network analysis (Figure 5), it can be seen that previous studies focused on adaptations to cope with climate change, the contribution of these sectors to climate change, and future measures to mitigate climate change. In detail, the electricity sector mainly focused on measures to cope with and mitigate climate change, with keywords mainly related to different types of power generation such as wind, biomass, solar, and electricity generation. Similarly, the agriculture sector is affected by climate change and produces a large amount of GHG that contribute to climate change, and previous studies mainly focus on adapting to climate change. The keywords related to the agriculture sector include crop yield, crop water consumption, and crop growth and development. Unlike the above sectors, although the studies of industrial sector focused on climate change mitigation, it is also affected to a certain extent by climate change. In addition to the main sectors such as the iron and steel industry, cement industry, and building industry, the literature keywords of the industrial sector mainly focus on efficiency improvement and energy efficiency.

In the electricity sector, this paper mainly reviews the design of grid systems and the design of various renewable energy generation methods. Over the past five years, research on climate change adaptation in the power industry has focused primarily on improving distribution efficiency, while research on climate change mitigation has focused primarily on expanding renewable energy generation. In this area, there is a strong focus on exploring advanced equipment, materials and algorithms to improve the efficiency of renewable power plants. Although these studies yield valuable insights, the limitations of this review still deserve attention. Most literature reviews of the electricity sector focus on the principles of technologies and why they can reduce carbon emissions. There has been insufficient discussion of the integrated application of

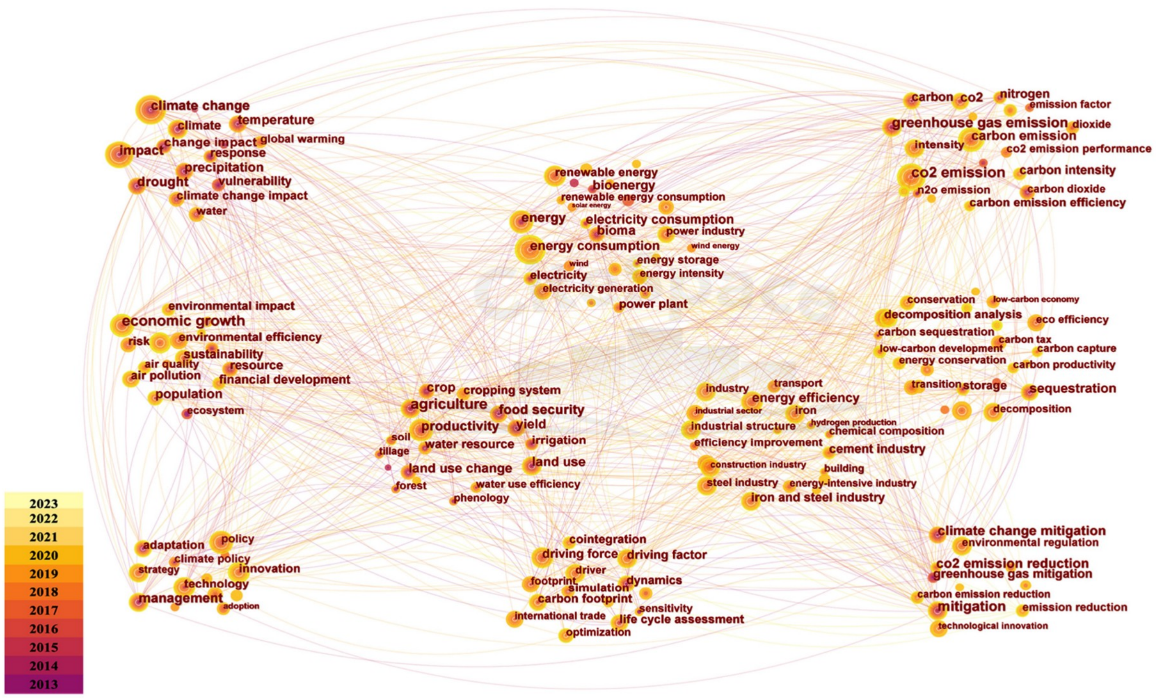

Figure 5 Keyword co-occurrence network analysis of three sectors and climate change.

these technologies in different locations. For example, there is not enough discussion about the integration of multiple forms of renewable energy generation. The challenge of generating electricity in remote areas is also a subject that requires further investigation. In the agricultural sector, most of the reviewed studies in this research discussed the adaptation and mitigation measures of agriculture towards climate change separately. However, as one of the most sensitive sectors to climate change and a significant source of various types of GHG, few studies have comprehensively considered the unique characteristics of agriculture. By solely emphasizing a certain aspect, the overall impact of climate change on agriculture and the contribution of agriculture to climate change are easy to be overlooked. In this review, both adaptation measures and mitigation measures for climate change in the agricultural sector were analyzed simultaneously. However, the emphasized summaries of this research were mostly based on results of experiments or crop models, but less attention to the practical implications for actual agricultural practices. In the industrial sector, studies about mitigation measures of industrial sector were mainly reviewed and discussed. The long-term impacts of climate mitigation efforts in the industrial sector are difficult to be analyzed and predicted due to the complexity of industrial processes and frequent changes in the government policies and regulations. Moreover, much research had limited access to high-quality and up-to-date data related to the industrial emission, energy consumption and other operational parameters, which hindered the accuracy and comprehensiveness of research. Interdisciplinary nature of industrial sector also requires collaboration of researchers to guarantee systematic thinking of the research.

Future research inquiries in the electricity sector are expected to integrate local geographical characteristics and population settlements. For instance, one potential avenue of exploration involves achieving the automatic adjustment of solar-wind-hydro hybrid power plants based on real-time weather conditions, which promises to enhance the stability and efficiency of power generation. Another promising direction involves the design of microgrids tailored to local population distribution and lifestyle habits. Microgrids devised in this manner tend to entail lower initial capital investments and reduced energy losses. The significance of these research efforts is that they have the potential to empower policymakers and local governments to develop more targeted policies based on unique natural attributes and local requirements of specific regions. As for the future study on the agricultural sector, it is crucial to comprehensively discuss the impact of climate change on agriculture and the contribution of agriculture to climate change simultaneously. How to apply experimental data to actual production should be a key focus of future research. Finally, for future studies on industrial sector, it is recommended that advanced modelling and simulation techniques should be utilized to analyzed the effects of different mitigation measures and policy scenarios based on interdisciplinary collaboration and transparent data collection and sharing. Policy analysis should also draw attention besides technological discussions to identify policy gaps and recommend improvements.

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Author contributions

K.W., L.S. and J.W. analysed the data, wrote the manuscript and revised the manuscript. L.L. conceived the idea and revised the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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