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Recent advances in carbon emissions reduction: policies, technologies, monitoring, assessment and modeling

Donald Huisingh [a], Zhihua Zhang [b, c, *], John C. Moore [b, c, d], Qi Qiao [e], Qi Li [f]

[a] Institute for a Secure and Sustainable Environment, University of Tennessee, Knoxville, TN, USA
[b] College of Global Change and Earth System Science, Beijing Normal University, Beijing, China
[c] Joint Center for Global Change Studies, Beijing 100875, China
[d] Arctic Centre, University of Lapland, Rovaniemi, Finland
[e] Chinese Research Academy of Environmental Sciences, Beijing, China
[f] State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, China

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ABSTRACT

Climate change and its social, environmental, economic and ethical consequences are widely recognized as the major set of interconnected problems facing human societies. Its impacts and costs will be large, serious, and unevenly spread, globally for decades. The main factor causing climate change and global warming is the increase of global carbon emissions produced by human activities such as deforestation and burning of fossil fuels. In this special volume, the articles mainly focus on investigations of technical innovations and policy interventions for improved energy efficiency and carbon emissions reduction in a wide diversity of industrial, construction and agricultural sectors at different scales, from the smallest scales (firm or household), cities, regional, to national and global scales. Some articles in this special volume assess alternative carbon emissions reduction approaches, such as carbon capture and storage and geoengineering schemes. Given the high cost and internal/external uncertainties of carbon capture and storage and risks and side effects of various geoengineering schemes, improved energy efficiency and widespread implementation of low fossil-carbon renewable-energy based systems are clearly the most direct and effective approaches to reduce carbon emissions. This means that we have to radically transform our societal metabolism towards low/no fossil-carbon economies. However, design and implementation of low/no fossil-carbon production will require fundamental changes in the design, production and use of products and these needed changes are evolving but much more needs to be done. Additionally, the design and timing of suitable climate policy interventions, such as various carbon taxation/trading schemes, must be integral in facilitating the development of low fossil carbon products and accelerating the transition to post-fossil carbon societies.

1. Introduction

Global warming is one of the greatest threats to human survival and political stability that has occurred in human history. The main factor causing global warming is the increase of global carbon emissions. The 2007 Fourth Assessment Report (AR4) by the Intergovernmental Panel on Climate Change (IPCC) of the United Nations indicated that most of the observed warming over the last 50 years was likely to have been due to the increasing concentrations of greenhouse gases produced by human activities such as deforestation and burning fossil fuels. This conclusion was made even stronger by the Fifth Assessment Report (AR5) released in 2013. The concentration of carbon dioxide (CO_2) in the atmosphere has increased from a pre-industrial value of about 280 ppm to 391 ppm in 2011. In 2014, the concentration reached more than 400 ppm. The continuous and increasing production of carbon emissions is therefore, a matter of global concern (Yue et al., 2015). Fortunately many countries have set ambitious long-term carbon emission reduction targets, e.g. the U.S. is committed to lower carbon emissions by 17% and 83% below 2005 levels by 2020 and 2050, respectively; the UK aims to reduce its carbon emissions by at least 80% of 1990 levels by 2050; China is now committed to abate

* Corresponding author. College of Global Change and Earth System Science, Beijing Normal University, Beijing, China.
E-mail address: zhangzh@bnu.edu.cn (Z. Zhang).

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its emissions per unit of economic output by 40–45% of 2005 levels by 2020; India is committed to decrease its emission intensity by 20–25% by 2020; and Brazil is committed to reduce its carbon emissions by 38–42% of BAU levels by 2020.

Globally, the growth in carbon emissions is largely from industry, transport and energy supply, while residential and commercial buildings, forestry/deforestation and agricultural sectors also contribute substantial quantities of carbon dioxide, methane and other greenhouse gases. Given the increasing risks to civilization of continuing with essentially unrestrained fossil fuel burning, an important question for all is what are scientifically sound, economically viable, and ethically defendable strategies to mitigate the global warming trends and to reverse the increases and to adapt to the present and anticipated climate risks? Many relevant approaches designed to investigate ways to reduce carbon emissions and to mitigate the impacts of climate change are included in about 90 articles contained in this special volume (SV).

2. Carbon emission reduction potentials in diverse industrial sectors

Reduction of fossil carbon emissions from diverse industrial sectors is central to efforts to reduce fossil carbon emissions due to the large material's flows they process and to the large quantities of energy they consume. If the energy is used inefficiently, this will lead to higher carbon emission levels. It becomes necessary to base the economic, the energy and the environmental policies on the efficient use of resources, in particular on energy efficiency (Robaina-Alves et al., 2015). Carbon emissions are generated in almost all activities of industrial sectors, extraction of materials from the earth's crust, production, procurement, inventory management, order processing, transportation, usage and end-of-life management of used products. However, as aggregate carbon emissions continue to rise, necessary improvements in industrial practices are lagging behind (Stål, 2015). Fortunately, some new carbon emissions reduction technologies, if effectively applied sector-wide, promise to help societies to make progress in alleviating the growing climate change crises (Slowak and Taticchi, 2015). Except for technical innovation, the design and timing of policy interventions is crucial for reducing innovation barriers and improvements in energy efficiency (Ruby, 2015). The authors of the articles in this SV investigated carbon emissions reduction potentials in a wide diversity of industrial sectors as highlighted in the following sections.

2.1. The iron and steel industry

Iron and steel production is one of the major sources of anthropogenic CO_2 emissions. Targeting a limitation of the global mean temperature increase in the range of 2.4–3.2 °C could result in drastic increases of the CO_2 prices if policies are developed to internalize the currently externalized impacts of CO_2 in the near future. Morfeldt et al. (2015) showed that significant energy efficiency improvements of current steel production processes, such as top gas recycling, can only meet the binding climate target if combined with carbon capture and storage (CCS). Moreover, a binding climate target tends to induce a regional differentiation of prices, indicating that regions such as China, India and South Korea may have difficulties meeting their domestic demand for steel, due to the high CO_2 price and their high dependence on fossil fuels for energy production.

China is the biggest iron and steel producer in the world. In 2012, it produced 658 Mt of pig iron and 716 Mt of crude steel, representing 59% and 46% of the world's production, respectively. The iron and steel industry in China accounted for 10% of total CO_2 emissions of China, therefore, the low fossil–carbon transition of the iron and steel industry is vital for meeting China's CO_2 emission reduction targets. Among different pathways to achieve CO_2 emissions reduction, more attention must be paid to industrial symbiosis, a system's approach which is designed to build upon win-win synergies between environmental and economic performances through physical sharing of 'waste' energy, exchanging of waste materials, by-products and infrastructure sharing among co-located entities. For China's integrated steel mills (ISMs), Yu et al. (2015a) showed that: 1) the three of the most effective symbiotic measures for CO_2 abatement were blast furnace gas recycled on site as fuel and/or sold off-site, coke oven gas recycled on site as fuel and/or sold off-site, and blast furnace slag sold to cement producing companies; 2) utilization of gaseous and solid waste/byproducts far outweighed the use of sensible heat in terms of their contributions to CO_2 abatement, which indicated the abundant potentials in sensible heat recovery; 3) cleaner production inside an ISM contributed more to CO_2 abatement than symbiotic measures with other enterprises did.

2.2. The cement industry

Cement is the basic and most widely used building material in civil engineering, the quantity of which has increased dramatically because of vast and rapid urbanization. The cement industry is also one of the most significant carbon emitters. This sector accounted for about 1.8 Gt of CO_2 emissions in 2006, approximately 7% of the total anthropogenic CO_2 emissions worldwide (Gao et al., 2015). Ishak and Hashim (2015) reviewed the CO_2 emissions of all stages of cement manufacturing, including raw materials preparation, clinker production, combustion of fuels in the kiln and the production of the final cement products. They found that 90% of CO_2 emissions from cement plants were generated from clinker production while the remaining 10% was from raw materials preparation and the finishing stage of producing cement. They also reviewed various CO_2 emissions reduction strategies, including energy efficiency improvements, waste heat recovery, the substitution of fossil fuel with renewable energy sources, the production of low carbon cement and CCS. In addition, the use of supplementary cementitious materials, such as fly ash, silica fume, copper slag, sewage sludge, ground-granulated blast furnace slag, are often promoted as ways to reduce carbon emissions (Liu et al., 2015b; Crossin, 2015; Yang et al., 2015a).

China is the biggest producer and CO_2 emitter in the global cement industry. The cement industry accounts for 14.8% of total CO_2 emissions from China, thus it is a critical sector within which to help China to meet its national 40–45% carbon emissions reduction target (Chen et al., 2015a). Based on data from fifteen cement plants in China, Gao et al. (2015) showed that replacing carbonate-containing materials with non-carbonate materials and by changing the clinker ratio were the main ways to reduce CO_2 content in raw meal and process emissions, e.g. sulphoaluminate cement manufacture in a modern cement plant can give CO_2 emissions reductions of up to 35% per unit of mass of cement produced, relative to ordinary Portland cement manufacture.

2.3. The rubber industry

During all stages in the manufacturing processes of rubber products, large quantities of energy, water and other natural resources are consumed. Among rubber products manufacturing processes, the rubber material milling process, the extruding process and the rolling process all have a relatively high electricity consumption rate. Dayaratne and Gunawardena (2015) investigated three rubber-band manufacturing factories and revealed the overall emissions from the production of rubber band amounting to 1.16, 1.53 and 1.23 tonne CO_2-eq/tonne product respectively. Since carbon emissions in the rubber industry are closely connected to energy consumption, Dayaratne and Gunawardena (2015) suggested that rubber manufacturing should adapt cleaner manufacturing model and implement energy-efficient measures to achieve sustainable production and the corresponding financial barriers can be solved through the clean development mechanism.

2.4. The aluminum industry

The global primary aluminum industry is responsible for 1% of global carbon emissions. In the past decade, China's primary aluminum production increased sharply to nearly 22 Mt in 2013, thereby accounting for about 41% of world's total primary aluminum production. It is estimated that primary aluminum production in China will reach 24 Mt by 2015, but few researchers have performed detailed analyses on the CO_2 emissions of China's primary aluminum industry. Zhang et al. (2015e) developed a bottom-up calculation and scenario analysis model to estimate CO_2 emissions and reduction potentials for China's primary aluminum industry. For 2011, specific direct CO_2 emission from aluminum refining production amounted to 1.3 t-CO_2/t-Al_2O_3, around 46% less than that calculated for 2003. Indirect emissions related to power consumption were estimated to 11 t-CO_2/t-Al, which were twice as high as the average world level in 2005. In the next decade, China's aluminum industry will be confronted with restrictions on the high-quality bauxite import and degradation of domestic bauxite quality. It is expected that wide adoption of the Sinter-Bayer Series Process and improved Bayer Processes as well as further elimination of the lime-soda sinter process and the sinter-Bayer combination process, have the reduction potential of 6%, which is almost equivalent to the reduction effect of the standard Bayer process relying on external resources. For further CO_2 emission reductions, China should modernize existing smelters and eliminate smaller and outdated smelters. Moreover, it is necessary to accelerate technology evolution, such as lower electrolyte temperature, wettable cathodes and inert anodes. In addition, improving production concentration and implementing competitive electricity prices would facilitate the technology diffusion.

2.5. The paper industry

The pulp and paper industry is one of the most energy-intensive sectors and one of the largest carbon emitters among manufacturing industries with a direct emission of about 40 Mt of CO_2 per year in Europe. Conventional manufacturing of paper consists of processing wood fiber streams into planar structures (mixed raw material). With the development of future manufacturing concepts (FMC), the final paper product has a tailor-made layered structure: fibers and other materials are placed in the optimal position depending on the required properties and functionality. This kind of optimal positioning allows papermaking companies to manufacture paper products with equal or better properties while using less wood-fiber raw material and energy. Leon et al. (2015) quantified carbon emissions reduction potentials in super-calendered (SC) paper production and lightweight coated (LWC) paper production through the application of these innovative manufacturing strategies using advanced sheet structure design and fiber modifications. The FMC strategies applied to SC paper resulted in reduction of carbon emissions by 23%, with a total of 10.7 g CO_2-eq emissions saved per square meter of SC paper. In the case of the FMC strategies applied to LWC paper, carbon emissions were reduced by 20%, which were equal to a total of 19.7 g CO_2-eq saved per square meter of LWC paper. This means that the environmental benefits gained through the application of the FMC manufacturing in the paper industry are significant. Therefore FMC will play an important role in securing the future competitiveness of the paper industry in Europe and elsewhere throughout the world.

2.6. The oil sands industry

Exploitation of the oil sands can produce a variety of fossil fuel products, such as gasoline and heavy fuel oil. Products derived from oil sand's crudes face competition from lighter and often less expensive crudes in the global market. Rainville et al. (2015) investigated the potential for a Canadian product category rules standard to enhance the credibility of life cycle emissions estimates of products derived from Alberta's oil sands. Increasing comparability of Canadian crudes to those of other countries in such a way would make this an attractive tool with the potential to be adopted internationally. Their findings revealed that while there is a consensus on the need to further standardize life cycle assessment (LCA) methods and data quality requirements for crude oil products to make comparisons more accurate, participants in the standards-setting process may be unwilling to share the information that would make this possible. A credible standards-setting process may help to overcome this challenge, only if the ability to revise the standard can be anticipated in its initial development process, particularly with respect to its long-term effects on the development of new technologies.

2.7. The chemical fiber industry

Oil, natural gas and other low-molecular weight raw materials are used to synthesize polymers through chemical addition or condensation reactions. The polymers may then be spun into synthetic fibers that are further processed. Since 1998, China's chemical fiber production has ranked first in the world. In 2011, China's chemical fiber production accounted for about 70% of the world's total output. Therefore, energy saving and carbon emissions reduction are important for China's chemical fiber industry, and can provide immense benefits. Lin and Zhao (2015) revealed that GDP, R&D expenditure and energy price were the main factors which exert a great impact on energy consumption in the chemical fiber industry. With the help of the relationship between energy consumption and these influencing factors and possible future growth rate of these factors, Lin and Zhao (2015) predicted that the energy-saving potential for China's chemical fiber industry in 2020 would be 13–18 Mt coal-eq, accounting for about 28%–39% of total energy consumption in the Business-as-usual (BAU) scenario.

2.8. Hydraulic presses

Hydraulic presses are machine tools using a hydraulic cylinder to generate compressive forces, which are commonly used for forging, molding, blanking, punching, deep drawing, and metal forming operations in many manufacturing fields. Energy losses within hydraulic systems with high pressure and large flows are serious. However, the traditional classification of hydraulic press systems were not suitable for the analysis of energy flows, therefore, based on the characteristics of each component's energy conversion, Zhao et al. (2015a) divided hydraulic press systems into six parts: “electrical-mechanical energy” conversion units, “mechanical-hydraulic energy” conversion units, “hydraulic–hydraulic energy” conversion units, “hydraulic-mechanical energy” conversion units, “mechanical to deformation energy” conversion units and “thermal to thermal energy” conversion units. Using this classification, Zhao et al. (2015a) proposed an analytical approach for calculating energy flows in large and medium-sized hydraulic press systems and indicated that the main cause of low energy efficiency is that load characteristic is not properly matched with the drive mode, and the secondary is the lack of a energy storage unit in the hydraulic system, therefore energy storage and recycling units should be included in hydraulic presses.

2.9. Methanol production industry

Taghdisian et al. (2015) proposed an eco-design method for sustainable production of methanol by implementing a multi-objective optimization CO_2-efficiency model that was formulated to maximize methanol production and minimize CO_2 emissions, i.e., so-called green integrated methanol case (GIMC). In GIMC, the source of CO_2 is the methanol plant itself where injected CO_2 is supplied from reformer flue gas. Comparing GIMC with the conventional reference methanol case (RMC), using the multi-objective approach in the GIMC would lead to the reduction of 16% in the CO_2 emission with respect to the RMC at the expense of 5% decrease in the methanol production.

2.10. The logistics sector

International transportation is crucial to the development of world trade. Carbon emissions due to the logistics services sector ranged from a few percent to over ten percent, depending on the characteristics of goods and the mode of transport. Around 23% of total emissions are embodied in the traded goods (Lopez et al., 2015). To (2015) investigated emissions from the logistics sector in Hong Kong as an example. In 2012, the total cargo freight between Hong Kong and other places via air freight was approximately 4 Mt and produced approximately 22.6 Mt of CO_2-eq. The total cargo freight via sea freight was approximately 26.9 Mt and produced approximately 12.7 Mt of CO_2-eq. The total cargo freight via land freight was approximately 26.2 Mt and produced approximately 0.5 Mt of CO_2-eq. The total amount of carbon emissions was approximately 35.8 Mt of CO_2-eq. Switching air cargo movements to land freight or sea freight for transportation between Hong Kong and mainland China would, reduce carbon emissions by about 0.4 Mt/yr of CO_2-eq. In the long run, in order to slow down the growth of carbon emissions, the Hong Kong Government should consider building a dedicated rail for freight trains, or use some capacity of high-speed rail for high-value added cargo transport.

2.11. The trade sector

The carbon linkage caused by the intermediate trade among industrial sectors has typically been ignored. Zhao et al. (2015b) integrated the environmental input–output model with the modified hypothetical extraction method to investigate the carbon linkage among industrial sectors in South Africa. Results showed that the total carbon linkage of industrial systems in South Africa in 2005 was 171 Mt, which accounted for 81 Mt total backward carbon linkage and 90 Mt total forward carbon linkage. The industrial block of electricity, gas, and water had the largest total carbon linkage with internal and net forward effect, and the block of basic metal, coke, and refined petroleum products have the largest net backward effect. Zhao et al. (2015b) suggested that adjusting industrial structure, improving energy efficiency, developing new energy, and establishing clean energy mechanisms are conducive to reduce the carbon emission in South Africa and consequently achieve its domestic carbon emission reduction targets.

3. Carbon emissions reduction potential in the construction sector

The construction sector, as the primary contributor of global carbon emissions, plays a significant role in global warming. The construction sector is comprised of establishments primarily engaged in the construction of buildings and other structures, heavy construction (except buildings), additions and maintenance and repairs.

According to the Intergovernmental Panel on Climate Change (IPCC), the building sector is responsible for 40% of the global energy consumption and contributed a quarter of the global total carbon emissions. Although the construction phase in a building's life cycle is relatively short, the density of the carbon emissions in the construction phase is higher than that in the operations and maintenance phases. In the building sector, carbon emissions embodied in the manufacturing of materials and the energy to transform them into products for the construction and for the relevant equipment of the facilities accounts for 88%–96% of the total carbon emissions. Although some materials used during the construction process are negligible in terms of weight, such as polyamide safety nets and aluminum (<0.1%), they may have a considerable impact on carbon emissions (2–3%) (Hong et al., 2015). Improved energy efficiency standards and strict control of the increase in urban civil building floor areas will be the most effective ways to reduce carbon emissions in this sector. Although the building life span is also an important factor for carbon emissions, its influence is less sensitive than improved technology and energy efficiency standards (Ma et al., 2015). In order to monitor, evaluate and forecast carbon emissions for building construction projects better, Kim et al. (2015) developed an integrated CO_2, cost and schedule management (ICCSM) system for building construction projects using the earned value management theory. The ICCSM system can support faster and more accurate evaluation and forecasting of the project performance based on the construction schedule, so it can minimize CO_2 emissions and construction costs by considering the construction projection with the change of plans (e.g., change of design, and change of construction methods and materials).

For highway construction, Wang et al. (2015b) proposed an empirical method to estimate the total carbon emissions from different steps of the construction processes (raw materials production, material transportation and onsite construction) by different project types (e.g. subgrade, pavement, bridge, and tunnels). Their results showed that over 80 percent of the CO_2 emissions were generated from raw materials production, while the onsite construction and materials transportation only accounted for 10 and 3 percent of the whole CO_2 emission, respectively. Moreover, the CO_2 emissions from bridge and tunnel constructions were much larger than subgrade and pavement construction. Based on the collected data from 187 bridges and 13 tunnels in China, the total CO_2 emissions from road, bridge and tunnel constructions in China were 52, 36 and 42 t/m, respectively. In order to reduce these emissions, the focus should be strongly put on materials production processes in which low fossil carbon systems are preferred. Advanced techniques developed to decrease the emissions in material's production have the most potential.

In the hydropower construction industry, different types of hydropower schemes utilize different construction methods and have different carbon emissions. However, differences in carbon emissions between different schemes have been largely ignored when comparing environmental impacts for decision-making. Zhang et al. (2015d) studied and compared carbon emissions of two hydropower schemes: an earth-core rock filled dam (ECRD) and a concrete gravity dam (CGD). It was found that the ECRD reduced CO_2 emissions by approximately 24% compared to the CGD. With respect to each stage of the life cycle, the ECRD decreased CO_2 emissions by 46% for material production, 16% for transportation and 9% for operation and maintenance but increased emissions by 6% for construction due to the heavy workload. Operational maintenance was the greatest contributor to CO_2 emissions, followed by the production, construction and transportation stages.

4. Carbon emission reduction potentials in the agricultural sector

After the industrial and construction sectors, the agricultural sector contributes substantial quantities of CO_2 and methane emissions. Improved energy use efficiency in agriculture, as one of the principal requirements of sustainable development, can reduce carbon emissions, help to minimize climate change risks, and prevent destruction of natural resources.

4.1. The mushroom production sector

Ebrahimi and Salehi (2015) studied energy use pattern and CO_2 emissions of button mushroom production in Iran. Results showed that the average total energy input and output in button mushroom greenhouses were 900 and 25 MJ m^{-2}, respectively, where the compost, diesel fuel and electricity were the most energy consuming inputs with amounts of 444, 409 and 37 MJ m^{-2}. The total carbon emissions of mushroom production were 23 and 32 kg CO_2-eq ha^{-1} for efficient and inefficient units, respectively, so the carbon emissions of mushroom production was reduced 27% in efficient units compared with inefficient units. Management of diesel fuel and electricity consumption in all mushroom production facilities helped the more efficient systems to achieve such reductions.

4.2. The lucerne production sector

To study an irrigated lucerne (Alfalfa) cropping system in Australia, Mushtaq et al. (2015) presented a novel integrated assessment framework, based on carbon and water accounting, which enabled them to analyze the potential trade-offs among water savings, energy consumption, carbon emissions and economic costs/benefits associated with the adoption of new water efficient irrigation technologies. Results revealed that efficient sprinkler technology not only saved water but also reduced energy use and carbon emissions. At the policy level, Mushtaq et al. (2015) indicated that on-farm infrastructure investment policies should prioritize the conversion from older, water-inefficient and energy-intensive sprinkler irrigation systems such as roll-line systems to center pivot sprinkler irrigation systems will help to make lucerne production more effective and efficient.

4.3. The cotton production sector

Visser et al. (2015) investigated ‘farm to ship’ cotton production in Australia and showed that the total carbon emissions of producing a bale of cotton from the farm to the ship's side or point of export was 323 kg CO_2-eq, which includes 182 kg CO_2-eq from the farm production phase, 73 kg CO_2-eq from the gin to port supply chain, and 68 kg CO_2-eq that resulted from emissions from the stock piled gin trash at the gins. If the waste is broadcast and incorporated into the soil at the farm level, Visser et al. (2015) showed that it could generate an emissions credit of 48 kg CO_2-eq per bale at the farm level, which will amount to a 27% reduction in the farm emissions footprint and a 15% reduction in the whole farm to ship carbon footprint.

4.4. The livestock production sector

The intensification of pig production has led to accumulation of increased quantities of livestock wastes in small and localized areas, where the use of manure as an organic fertilizer has sparked a rise in nutrient concentration in soils, groundwater, and surface water. Riano and García-Gonzalez (2015) estimated carbon emissions reduction of a swine manure treatment plant in Spain. Compared with conventional storage in anaerobic tanks, implementing the manure treatment plant could lead to a total annual carbon emission reduction of 62%, including CO_2 emission reduction 72%, CH_4 emission reduction by 69%, and no change of N_2O emission. Here we must notice that anaerobic digesters can be used to produce CH_4, which can be used as a renewable energy source or as a component in synthesis of other products.

4.5. The fisheries sector

Modern commercial fisheries are heavily dependent on the input of fossil fuels throughout their supply chains, particularly diesel inputs for their fishing vessels. Fuel use intensity of fisheries varies with regard to target species, equipment employed, region of fishing, technologies used, skipper behavior, and other factors. Globally, marine capture fisheries consumed 42 Mt of fuel in 2000, or 1.2% of global oil consumption, and released approximately 134 Mt of carbon dioxide (CO_2) into the atmosphere. Parker et al. (2015) measured fuel inputs to purse seining vessels targeting primarily skipjack and yellow fin tuna. These vessels burned, on average, 368 L of fuel per tonne of wet weight landings, which corresponds to a fuel-related carbon footprint of 1.1 kg CO_2 per landed kg of tuna, lower than that of average marine capture fisheries (e.g. 340–530 L/t for Atlantic cod, 471–490 L/t for haddock). These data represent 28% of worldwide landings of skipjack and yellow fin by purse seiners in 2009. Parker et al. (2015) found that the use of fish aggregating devices (FADs) in purse seine fisheries for tuna was found to be inversely correlated with efficiency, going against conventional logic that FAD use improves efficiency.

4.6. Agricultural tillage impacts

Scientific regulation of carbon flows under conservation tillage is of great significance for mitigating carbon emissions and for increasing carbon sequestration potential in soils. Chen et al. (2015b) investigated conventional tillage without residue retention (CT), conventional tillage with residue retention (CTS), rotary tillage with residue retention (RTS), and no-till with residue retention (NTS) in China. All the inputs of machinery, irrigation, herbicides, pesticides, fertilizer, seeds and other farm inputs were totally taken into account and were converted into equivalent carbon emissions. The annual increase in rates of soil organic carbon stocks were 452, 523, 1340, and 2385 kg ha^{-1} yr^{-1} from 2007 to 2011 under CT, CTS, RTS, and NTS, respectively. The annual carbon emissions under CT, CTS, RTS, and NTS were 1182, 1182, 1152, and 1139 kg C-eq ha^{-1} yr^{-1}, respectively. Among the treatments, NTS treatment had the lowest net carbon flux with −1246 kg C-eq ha^{-1} yr^{-1}. Taking CT as the baseline, the relative net C flux under RTS and NTS were −918 and −1976 kg C-eq ha^{-1} yr^{-1}, respectively. This means that widespread adoption of conservation tillage would be beneficial in the reduction of carbon emissions from these types of agricultural production.

Land use changes not only influence carbon storage in terrestrial ecosystems directly, but they also indirectly affect anthropogenic carbon emissions. Coastal regions usually have highly developed economies, which drive frequent changes of land use. Chuai et al. (2015) investigated land use changes in coastal Jiangsu of China and found carbon emission intensity in this region was much higher than the average for China as a whole. Total carbon emissions in coastal Jiangsu amounted to 822×10^4 t in 1985 and increased to 2931×10^4 t in 2010, which represented an increase of 2.57 times from 1985 to 2010. The transfer of cropland to built-up land accounted for the largest percentage of the total transferred area and contributed most to the increase of carbon emissions. Optimized land use policies and procedures can help to reduce carbon emissions in 2020 by 1542×10^4 t (Chuai et al., 2015). Tao et al. (2015) further assessed variations in soil carbon stocks across terrestrial land covers with different intensities of urban development, and quantified spatial distribution and dynamic variation of terrestrial carbon stocks in response to urban land use and cover change. They showed that carbon densities decreased with increasing intensity of urban development and urban land use change and soil sealing created hotspots for losses in carbon stocks, e.g. total carbon stocks in Changzhou of China decreased by about 30% during the past 25 years, representing a 1.5% average annual decrease. In addition, Wang et al. (2015a) presented a remote sensing approach to assess the impact of China's land use change on carbon emissions and revealed that the carbon emissions in half of the provinces of China are benign overall in terms of ecosystem circulation and there is fairness and economic efficiency of carbon emissions during 2000–2010.

5. Assessment of carbon emissions reduction potentials is different societal scales

The articles of this SV not only focused on carbon emissions reduction potentials in certain industrial, construction, or agricultural sectors, but also assessed carbon emissions reduction potentials at different scales, from firm or household to national and global.

5.1. Firms

Climate change physical risks are likely to have a strong effect on the economic performance of firms since they can increase their costs significantly (Nikolaou et al., 2015). Industrial firms are central to the efforts to seek to achieve carbon emissions reductions due to the large materials flows they process. Building an effective management system for carbon reduction has become an important issue for a firm's survival in today's competitive environment (Liou, 2015). Most firms are willing to allocate resources and set a target for carbon emissions reduction projects (Rietbergen et al., 2015). By using international data consisting of 89 firms from 21 countries, Gallego-Alvarez et al. (2015) showed that a firm's reduction of emissions could enhance its reputation, attract investors and positively impact their financial performance. Liu (2015) further revealed that governmental regulations, awareness of consumers, company size have dramatic effects on firms' carbon emission intensities per unit of production, while the price of raw materials, governmental subsidies and pressure from international rules, as well as the leadership of the firms awareness of social responsibility slightly affected firms' carbon emissions. In addition, some tax policies, such as the export rebate policy in China, also affected firm's energy conservation and emission reduction policies, procedures and accomplishments (Fan et al., 2015).

Each firm needs to buy raw materials and fuels from other firms and to sell their products to other firms, so industrial symbiosis (IS) was introduced to promote carbon emissions reduction through effective use of resources and energy by substitution of byproducts and municipal solid waste for raw materials and fuels, waste heat and improved steam utilization. Yu et al. (2015b) studied IS performance on carbon emissions reduction in integrated steel mills and revealed the three most effective symbiotic measures for CO_2 abatement are blast furnace gas recycling, coke oven gas recycling, and blast furnace slag sold to the cement industry. They accounted for 69% of the total CO_2 emission reduction from all the symbiotic measures.

5.2. The household level

The need for the household sector to reduce its energy use and CO_2 emissions has been emphasized recently. A large proportion of energy consumption and associated carbon emissions is from the household sector. The UK's residential sector (excluding transport) is responsible for approximately 30% of all its carbon emissions – mainly due to high household energy consumption; in China, approximately 26% of total household energy consumption and 30% of CO_2 emissions are due to lifestyles and related economic activities; In Greece, a 44% increase in household expenditure between 1990 and 2006 was accompanied by a 60% increase in CO_2 emissions; and in India, CO_2 emissions from household consumption of goods and services increased 66% between 1993–94 and 2006–07 (Zhang et al., 2015f). Therefore, a major reduction of household carbon emissions is essential if global carbon emission reduction targets are to be met. The factors influencing household carbon emissions include household income, household size, age, education level, location, gender, etc (Zhang et al., 2015f). Han et al. (2015) further revealed that (i) household income is the most important contributor to the difference of household carbon emissions, and its positive effect increases as household carbon emissions rise; (ii) household house ownership and deposits contribute little to household carbon emissions, while household car ownership contribute more; (iii) young people and children will emit more household carbon emissions than adults, and the employed emit more than persons who are unemployed or retired; (iv) education increases household carbon emissions overall but mainly at the low quintiles. In order to cut carbon emissions, people should transform from luxurious to more frugal consumption activities, such as less use of air conditioning, reusing and recycling clothes and furnishings, purchasing low gasoline consumption and emission cars, and using more energy conserving and environmentally friendly home appliances. In addition, Pairotti et al. (2015) investigated energy consumption and carbon emission associated with the Mediterranean diet in Italy. They found that when compared with the national average diet, the Mediterranean diet produces an improvement in environmental performance of 95 MJ (2.4%) and 27 kg CO_2 equivalent (6.8%) per family.

5.3. The city scale

As home to over 50% of the world's population, cities are primarily responsible for production, consumption, trade of many energies and resources, as well as day-to-day human activities. During rapid urbanization, many environmental problems arise from the heavy dependence on energy, including energy shortages and excessive carbon emissions. The International Energy Agency estimated that 70% of the greenhouse gases are produced within the cities (Sethi, 2015). Therefore, it is essential to undertake accounting of carbon emissions for urban systems, particularly in developing countries with large quantities of energy and resources consumptions (e.g. China).

Economic activity in Beijing is highly concentrated and its total energy consumption has been increasing rapidly since 2000. In 2011, Beijing emitted about 50 Mt more carbon than in 2002, of which 93.8% was from energy consumption. Zhang et al. (2015g) evaluated the attributes of the energy consumption structure and determined the required carbon emissions reduction by each sector. From 2000 to 2010, the emission efficiency of Beijing's energy consumption structure fluctuated, but with an overall trend toward higher emission efficiency. More than 54% of the sectors had high consumption and low emission efficiency, versus 32% with low consumption and low emission efficiency, and the remaining 14% had low consumption and high emission efficiency. For the future, Mi et al. (2015) showed increasing the proportion of low energy intensive and low carbon intensive sectors including finance, information transmission, computer service and software, manufacture of measuring instrument, machinery for cultural activity and office work is an effective policy. On the contrary, the development of several high energy and high carbon intensive sectors must be strictly controlled - including scrap and waste, manufacture of textile and production and distribution of gas. If the average annual growth rate of GDP will be 8% from 2010 to 2020, these industrial structural adjustments can save energy by 39% and reduce carbon emissions by 46% in Beijing in 2020.

Guangyuan is a mountainous city in western China that was extensively damaged by the Wenchuan earthquake in 2008. Hao et al. (2015) investigated the effects of post earthquake reconstruction on the carbon cycle. They showed that the post-earthquake reconstruction influenced both the quantity and horizontal and vertical structure of carbon storage and fluxes, with a more apparent impact on the artificial rather than the natural carbon cycle. Although the big earthquake caused great losses in life and property, it provided an opportunity to promote low fossil-carbon development via the initiation of new construction. In Guangyuan, many programs were adopted along with the post-earthquake construction, such as soil nutrient management, agricultural methane gas utilization, natural gas utilization, energy saving light upgrades, and adoption of low-carbon traffic system, which respectively reduced 127, 499, 600, 4.5, and 4.2 Kt of carbon per year. These activities have made Guangyuan one of the major low fossil-carbon cities in China.

Feng et al. (2015) investigated Xiaolan, a typical town in south China. They found that the energy-related carbon emissions of Xiaolan in 2010 were 2 Mt CO_2-eq, where manufacturing is the biggest carbon emitting sector and represents 69% of the total emissions of the city. In 2010, the carbon emissions per capita in Xiaolan were lower than that in most Chinese cities, but higher than several Asian cities including Amman and Tokyo. To reduce carbon emissions, Feng et al. (2015) suggested improving energy efficiency; optimizing the energy structure and developing low fossil-carbon energy; updating the manufacturing infra-structure; as well as improving carbon emission management for the residential sector.

5.4. Regional scales

Carbon emissions in China are ranked the highest in the world and they are increasing rapidly. This has attracted attention throughout the world. The high carbon emissions in China are mainly due to its huge dependency on fossil fuels. Of all the energy resources, consumption of coal accounts for 66% while renewable and nuclear energy only accounted for 9% in 2012 (Liu et al., 2015e). At the same time, China is an extremely large country and there are obvious differences in the economic base, industrial structure, resource endowment, and energy utilization technology of each region. Relative carbon emissions have increased most from the Eastern provinces followed by the central and western provinces. The authors suggested that China should coordinate and balance the relationships between economic development and carbon emission reduction, further decrease the energy intensity of their production sectors, gradually adjust the economic and energy structures, and formulate carbon emission reduction policies to reduce regional disparities (Chen and Yang, 2015; Chang, 2015).

The Yangtze River Delta region is the fastest-growing economic region of China; it is the region with the largest total economic output, and the region with the most economic potential. The total primary energy consumption of the Yangtze River Delta region reached 420 Mtce in 2010; this is a 176% increase, compared to the 151 Mtce in 1995. Therefore, the Yangtze River Delta region has generated considerable volumes of greenhouse gases and so must bear responsibility for reducing its carbon emissions. Song et al. (2015) found that carbon emissions in the Yangtze River Delta region showed a rising trend, increasing from 107 Mt in 1995 to 289 Mt in 2010. The effects of various factors on energy consumption and carbon emissions in the Yangtze River Delta region were as follows: economic output, 144%; energy intensity, −60%; population size, 19%; and energy structure, −2%. In the Yangtze River Delta region, the energy intensity effect was the main factor for reducing carbon emissions. In every step of the production chain, such as mining, processing, conversion, storage, and end use, energy losses were large. Technical progress and innovation could become driving forces that would help improve energy efficiency. At the same time, energy consumption structures should be further optimized by accelerating the innovation of coal-utilization technology and increasing the proportions of oil, natural gas, and renewable energy sources that are used.

Shandong Province is a typical energy consumption province in East China. In 2009, the total energy production, consumption, and the net energy import were 146 Mtce, 345 Mtce and 196 Mtce respectively. Applying both the carbon-emissions-coefficient and the sector energy consumption method, Ren et al. (2015) predicted that in 2015 and 2020, the total primary energy consumption would be 1.57 times and 1.85 times higher in Shandong Province than it was in 2009, and the carbon emissions are estimated to be 1.48 times and 1.67 times higher, respectively. Ren et al. (2015) suggested that in the future, Shandong Province needs to gradually increase the supply of natural gas and renewable energy, improve a multi-channel energy supply network, develop and implement clean coal technology, and put its products into widespread use in order to reduce carbon emissions.

With China's increasing participation in global production chains, the country's inter-regional economic ties have grown closer. Liu et al. (2015c) analyzed the characteristics of virtual carbon flows among regions of China which is essential to deploy effective regional mitigation strategies. Results indicate that inter-regional carbon flows in China grew from 136 MtC in 2002 to 377 MtC in 2007. The proportion of total national emissions represented by inter-regional carbon flows rose from 15% in 2002 to 21% in 2007. The carbon flows from the Central and Northwest regions to the Eastern Coastal region were the greatest contributors to both the total inter-regional carbon flows in 2007. Liu et al. (2015a) revealed further that the net transfer of emissions caused by economic growth was decreasing in China.

Quantitative and binding targets have been set for energy-efficiency improvement and carbon emissions reduction in China. Zhang et al. (2015b) presented a framework for provincial-level disaggregation of energy-saving targets in China, e.g. in the capability preferred scenario, Application of this framework to burden-sharing within China would result in increased insight among the regions concerning differences in regional circumstances and their roles in high-level energy-saving strategy. Shanghai should receive a target share of 19% and ranks first among all provinces of China, and Beijing (18%), Jiangsu (18%), and Guangdong (18%) occupy the following three places. In addition, Yan and Fang (2015) investigated carbon emissions of the Chinese manufacturing industry and found that the smelting and pressing of ferrous metals, manufacture of raw chemical materials and chemical products, and manufacture of non-metallic mineral products were the top three sectors, combining to account for approximately 60% of the total carbon emissions. Carbon emissions mitigation, in the future, will mainly depend on decreases in energy intensity, declines in emission coefficient of electricity and upgrades in the economic structure - their additive effects on CO_2 emissions reductions will be about 5400 Mt by 2020.

5.5. *National & global scales*

Accompanying the boom in the global economy, the developing world exhibits higher carbon emission growth rates than the developed world. Emissions transfers between/among countries, which represent a significant fraction of total emissions, are assumed to be a primary factor contributing to this difference. It is important to understand these transfer figures and resulting consumption-based emissions in order to evaluate the emissions drivers and establish suitable climate policies. To broaden the existing carbon emission data coverage and to further analyze their impacts on total emissions in the long term, Yang et al. (2015b) developed a new model called the Long-term Consumption-based Accounting model (LCBA) to estimate consumption-based carbon emissions for each of the 164 countries from 1948 to 2011. LCBA is good at estimating consumption-based emissions in the national scale, while traditional input–output models specialize in sectoral analysis and supply chain analysis. Current climate policies such as Kyoto Protocol are being seriously jeopardized by the soaring emissions transfers and increasing contribution of the Non-Annex 1 signature countries, so together with LCBA model and traditional input–output model, consumption-based emissions inventories will play an increasing role in future climate negotiations and can help to achieve solid progress in future climate policies.

6. Implementation of low fossil carbon energy systems

Large scale exploitation and utilization of energy resources, especially fossil fuels, has contributed significantly to the development of world civilization. Currently people use unsustainable energy sources that yield benefits in the short-term but contribute to disadvantages in the long-term such as climate risks. A possible measure to mitigate climate change is to provide incentives for the implementation of renewable energy systems, which can produce power with much lower amounts of fossil carbon emissions than conventional fossil fuels. Substantial carbon emission reductions necessary for limiting a rise in global average surface temperatures to less than 2 °C are possible through widespread implementation of low fossil carbon energy systems. Mainstream low fossil carbon renewable energy sources include biomass, wind power, hydropower, solar power, ocean thermal, wave, tidal and geo-thermal energy sources.

In the European Union, the share of renewable energy has increased significantly over the past few years. In 2012, renewable energy was estimated to have contributed 14.1% of gross final energy consumption in the EU, compared with 8.3% in 2004. The largest increases during this period were recorded in Sweden (from 38.7% in 2004 to 51.0% in 2012), Denmark (from 14.5% to 26.0%), Austria (from 22.7% to 32.1%), Greece (from 7.2% to 15.1%) and Italy (from 5.7% to 13.5%). Among renewable energy options, bioenergy is considered to be the dominant energy source. Muench (2015) thoroughly analyzed the greenhouse gas mitigation potential of biomass systems for electricity generation and showed that electricity from biomass can be an appropriate measure for greenhouse gas mitigation in the European Union. Muench (2015) recommended to promote the employment of (1) non-dedicated lignocellulosic biomass with thermochemical conversion, (2) dedicated lignocellulosic biomass with thermochemical conversion, and (3) dedicated lignocellulosic biomass with direct combustion, because these biomass systems yield the highest carbon mitigation. For wind power, Hacatoglu et al. (2015) introduced a new approach for assessing the environmental sustainability of wind-battery systems. A wind-battery system produced less potential global warming, stratospheric ozone depletion, air pollution, and water pollution impacts compared with a gas-fired power plant. The wind-battery power plant generates 87% less life-cycle carbon emissions and 78% less life-cycle ozone-depleting substance emissions than a gas-fired power plant.

For implementation of low fossil-carbon energy systems in urban areas, Lund et al. (2015) analyzed the hourly temporal and spatio-temporal energy demand and supply patterns in Delhi, Shanghai and Helsinki to understand how energy systems respond to high renewable electricity shares, and to determine realizable levels of renewable electricity power. Results indicated that if we limit the use of the renewable electricity output for the instantaneous power demand, a 20% yearly share of electricity could be reached. Increasing the renewable electricity beyond this limit without a smart design adds only limited benefit. Adding short-term electrical storage capacity could increase the renewable electricity share of power in Shanghai to 50–70%, in Delhi to 40–60%, and in Helsinki to 25–35%.

Brazil is undoubtedly a country with considerable renewable energy generation capacity. The structure of the Brazilian energy matrix defines Brazil as a global leader in power generation from renewable sources. In 2011, the share of renewable sources in electricity production in Brazil reached 88.8%, mainly due to the large national hydro-electrical power potential. The current composition of Brazilian energy matrix has outstanding participation of hydropower, even though Brazil has great potential for the exploitation of other renewable energy sources such as wind, solar and biomass. Although the Brazilian energy model presents a strong potential for expansion, the total energy available from current renewable technologies often outweighs the national demand (Guerra et al., 2015).

7. Assessment of carbon capture & storage and geoengineering approaches

Currently, rising energy production is associated closely with increasingly carbon emissions. Despite concerns about carbon emissions in the atmosphere, fossil fuels will probably remain the main source of primary energy for a long time. Therefore, carbon capture, utilization & storage (CCUS) to reduce CO_2 levels in the atmosphere is being addressed by governments around the world. CCUS involves technologies which separate CO_2 from the energy and industrial emission sources and transports and stores it underground. With CCUS the energy supply cost must include not only the fuel cost, but also the CO_2 capture, transportation and storage costs (Wennersten et al., 2015). Currently, CCUS is still in the early stages of technological development, and the high cost and several internal & external uncertainties makes the role of CCUS unclear in future emission reduction, especially for developing countries. Zhu et al. (2015) made a comprehensive evaluation of CCUS's potential for future development and contribution to carbon emissions reduction in China with the help of a regional energy-economy-environment integrated assessment model.

Results showed that CCUS technology will take about 30 years before effective systems for carbon emissions reductions are found, and although there will be development of CCUS after 2040, its contribution to emission abatement will always be lower than that of energy substitution. Zhu et al. (2015) suggested that in the short and mid-terms, the Chinese government should emphasize incentives for non-hydro renewable energy so as to increase the energy supply, while strengthening the demonstration and technology learning for CCUS, and in long-term (after 2050), the Chinese government may promote CCUS adoption in coal-fired power plants through subsidies, or other policy measures to achieve greater CO_2 emissions reductions.

7.1. Carbon capture

Coal combustion alone accounts for about 20% of global carbon emissions, and coal produces the most CO_2 per unit energy of all fossil fuels. However, the world's reliance on coal-based power will continue to grow, irrespective of the improvements achieved in efficiency and the growth of renewable energy sources. Therefore, the development of carbon capture and storage technologies at coal-fired power plants requires urgent attention. Various worldwide projects have tried different industrial approaches adapted to carbon capture. Aqueous Ammonia and Monoethanolamine (MEA) are the popular solvents used to capture and separate CO_2 from the flue gas stream. Aqueous Ammonia is a better solvent because its CO_2 loading is greater than MEA. However, aqueous ammonia is highly volatile since it can become gaseous and leaves the absorption column with the treated gas. The use of membrane contactor can limit ammonia loss and can widen the operational ranges of temperature, pressure and ammonia concentration (Molina and Bouallou, 2015; Khalilpour et al., 2015). In addition, Gopalakrishna (2015) suggested using hydrotalcite like compounds and metal-based oxides for CO_2 capture.

Co-firing coal with renewable energy sources coupled with carbon capture is researched as a promising potential solution. Fogarasi and Cormos (2015) evaluated the technical and economic aspects of biomass co-firing electricity production with and without CO_2 capture using different mixtures of coal and sawdust. CO_2 emissions and net electrical efficiency only changed by 1% between the case studies with 100% coal and 100% sawdust. Coal and sawdust direct co-firing based power generation offers a potential solution for increased global energy demand with simultaneous preservation of natural fossil fuel reserves and decrease in net CO_2 emissions. In addition, Andric et al. (2015) studied the maximum supply distance of biomass that allows the co-firing of coal and biomass to be more environmentally efficient than the pure coal combustion systems.

7.2. Carbon dioxide storage

Geological storage is a possible step after CO_2 is captured from various energy or industrial sectors. Different from traditional approaches, Li et al. (2015c) assessed geological storage of CO_2 by combining it with deep saline water/brine recovery (CO_2-EWR), which was proposed to help to solve the dilemma between the increasing carbon emissions from the coal industry and the national energy and water security in China. Compared with traditional CO_2 geological storage, CO_2-EWR can control the release of reservoir pressure and water production by a reasonable engineering design of pumping wells to achieve the security and stability of the large-scale geological storage of CO_2. Moreover CO_2-EWR can collect and process deep saline water for drinking, industrial and/or agricultural utilizations to alleviate water shortage situations. As a promising solution for energy/water 'nexus', the research and pilot demonstration of CO_2-EWR is under prudent development in China, where the sealing integrity of the caprock plays a key role in CO_2 geological storage in a saline aquifer over the long period. Caprock, as a sealing layer, is defined as water-saturated formation with a sufficient capillary entry pressure to prevent the upward migration of a buoyant fluid. Most caprocks are shales, mudstones, or carbonates with moderate or low porosities and very low permeabilities. These properties are naturally anisotropic. When the capillary entry pressure of the caprock is smaller than the pressure exerted by the buoyant CO_2 plume, CO_2 gradually penetrates into the caprock. Sealing efficiency may be lost if the caprock is not water-wet or the water is lost through dehydration and CO_2 sorption. Hence, the effect of CO_2 sorption-induced anisotropic swelling on the caprock may heavily impact the sealing efficiency. Wang (2015) developed a numerical model for the investigation of the sealing efficiency of anisotropic caprocks. Wang's model is capable of describing the transport properties of anisotropic shale caprocks, including gas flow and sorption, rock deformation, directional porosity and permeability modifications.

Mineral sequestration of waste materials provides another promising method for CO_2 storage by the transformation of CO_2 into calcium, magnesium and other forms of stable carbonates (Ukwattage et al., 2015; Kainiemi et al., 2015). Coal combustion fly ash contains alkaline oxides such as CaO and MgO which can be carbonated in the presence of CO_2. This process is similar to the chemical weathering of alkaline earth minerals in the presence of atmospheric CO_2 dissolved in rain water. In order to enhance the carbonation reaction for mineral CO_2 sequestration, Ukwattage et al. (2015) studied the mineralization of Australian coal fly ash for CO_2 sequestration at the laboratory scale. Different water-to-solid ratios (from 0.1 to 1) and reaction temperatures (20–80 °C) were tested under a moderate initial CO_2 gas pressure of 3 MPa. Their results showed that a 0.2–0.3 water-to-solid mix ratio recorded the highest sequestration potential for coal fly ash and was identified as the optimum for mineralization. The increase of reaction temperature resulted in a faster rate of initial CO_2 transfer into the fly ash material but did not have a significant impact on the overall sequestration. In addition, lime mud from papermaking processes has also been suggested for use for CO_2 storage (Zhang et al., 2015a).

7.3. CO_2 resource utilization

Due the widespread use and consumption of traditional fossil fuels, mankind not only faces increasing environmental pollution and greenhouse effect, but also requires new resources. Captured CO_2 can be used as a feedstock for chemical production. Currently the catalytic conversion of CO_2 into useful and value-added chemicals is an important field in green chemistry (Zhou et al., 2015; Zhang et al., 2015c). Yang and Wang (2015) reviewed various technologies for the utilization of CO_2, including (i) hydrogenation to methanol, dimethyl ether, methane, alkene, formic acid, etc. (ii) reaction with hydrocarbons, including CO_2 reforming of methane to syngas; hydrocarbons oxidation to alkene, aldehyde and carboxylic acid; C1–C3 hydrocarbons and aromatics carboxylation. (iii) reactions with oxy-organics, such as methanol, propylene glycol and epoxide, to obtain valuable chemicals and materials.

7.4. Geoengineering schemes

In addition to CCUS, some scientists have proposed to use geoengineering (or climate engineering) to artificially cool the Earth. Geoengineering, which is the intentional large-scale manipulation of the environment, has been suggested as an effective means of mitigating global warming from anthropogenic carbon emissions. Most geoengineering schemes proposed to be performed on land or in the ocean are to use physical, chemical or biological approaches to remove atmospheric CO_2. These schemes can only sequester an amount of atmospheric CO_2 that is small compared with cumulative anthropogenic emissions. Most geoengineering schemes proposed for the atmosphere are based on increasing the planetary albedo. These schemes have relatively low costs and short lead times for technical implementation, and can act rapidly to reduce temperature anomalies caused by anthropogenic carbon emissions. However, the costs and benefits of these geoengineering schemes are likely to vary spatially over the planet with some countries and regions gaining considerably while others may be faced with a worse set of circumstances than would be the case without geoengineering (Zhang et al., 2015h).

8. Carbon taxation/trading schemes

Carbon emission trading schemes and carbon taxation schemes are the main approaches adopted by countries and regions to seek to achieve their emission reduction goals (Du et al., 2015). Both schemes may potentially result in similar emission reductions, and neither scheme seems to lead to lower emissions than the other (He et al., 2015; Bing et al., 2015). Developed countries have high carbon emission abatement costs compared with large developing countries (Li et al., 2015a). Higher carbon pricing levels can reduce the economic advantage for high carbon emitters (Wu et al., 2015). In addition, for household carbon emissions reductions, personal carbon trading (PCT) is a progressive scheme in which the poorer consumers are mostly 'winners', as their levels of emissions are generally lower (Li et al., 2015b).

Under cap-and-trade regulations, firms may buy permits for production, or sell surplus permits, or buy and sell no permits at all, depending on the value of the initial cap. Under carbon tax regulations, firms are charged for their carbon emissions at a constant tax rate. Currently, emission-trading schemes (ETS) have been established in several regions of the world, such as Australia, the EU, Kazakhstan, New Zealand and Switzerland as well as in Québec in Canada and California, Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont in the United States. China has publicized plans to initiate the demonstration of carbon emission trading in seven regions as of 2013 (Liao et al., 2015). There is already an agreement aimed at linking the EU ETS and the Australian ETS, which is a step towards an international CO_2 pricing system. Liu et al. (2015d) showed that the tax rate significantly negatively affects a company's policy choice preferences, which is consistent with the intuitive understanding that a lower tax rate is more acceptable for the businesses. In theory, when introducing carbon taxation/trading schemes, the product cost increases will dissatisfy the potential buyer. If the enterprise wants to keep their profit margin constant, it has to improve production efficiency, product efficiency, decrease product cost, or a mix of all three. So the producer must improve the product design and manufacture, lower the cost and improve the product's performance (Xu et al., 2015). Based on a duopoly model, Wang and Wang (2015) quantitatively explored the impact of a carbon offsetting scheme on both emission trading participants' profits and industry's output. They found that the introduction of a carbon offsetting mechanism would reduce the equilibrium carbon price to some extent regardless of how the proportion ceiling of offset quota is designed, relieving the production losses caused by the carbon emission constraints, but to different degrees.

9. Discussion and conclusions

Climate change is now widely recognized as the major environmental problem facing human societies. Its impacts and costs will be large, serious, and unevenly distributed globally. The main factor causing climate change and global warming is the increase of global carbon emissions. However, negotiations on carbon emissions reduction have largely failed because of lack of international trust and the unwillingness of most governments to pursue anything except blind short-term self-interest. The Kyoto Protocol and subsequent emissions reduction negotiations have been obstructed repeatedly, particularly by representatives of the US government, but also by much of the developed world, which has consistently failed to acknowledge their historical contributions to climate damage, and in some cases they continue to deny basic science in the field.

Currently, rising energy production is associated closely with increasing fossil-carbon emissions. Despite concerns about carbon emissions in the atmosphere, fossil fuels will probably remain the main source of primary energy for a long time. In order to prevent or to minimize climate crises in the long run, there are three main approaches: 1) Improved energy use efficiency in industrial, construction, agricultural, transportation and all other sectors, 2) widespread implementation of low fossil carbon renewable energy systems, 3) CCUS and geoengineering schemes. Given high costs and internal/external uncertainties of CCUS and risks and the unanticipated and uncontrollable side effects of various geoengineering schemes, improved energy use efficiency in industrial, construction or agricultural sectors and widespread implementation of low fossil carbon energy systems are clearly the most direct, and safe approaches. This means that we have to radically transform our societal metabolism towards low/no fossil-carbon economies. However, design and implementation of low/no fossil-carbon production will require fundamental changes in the design, production and use of products and these needed changes are evolving but much more needs to be done. Additionally, the design and timing of suitable climate policy interventions, such as various carbon taxation/trading schemes, must be integral in facilitating the development of low fossil carbon products and accelerating the transition to post-fossil carbon societies.

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