Chapter 5
Primary Energy Consumption and CO_2 Emissions

5.1 Analysis of China's Future Primary Energy Consumption

5.1.1 Total Primary Energy Consumption

Based on the previous analysis of energy demand of end users in Chapter 3 and power sector in Chapter 4, the primary energy consumption under policy scenario, reinforced policy scenario, 2 °C scenario and 1.5 °C scenario is shown in Fig. 5.1. The comprehensive analysis data of various scenarios is illustrated in Tables A.1–A.4 which can be found in the appendices of the report.

Under the policy scenario, China's total primary energy consumption increases rapidly between 2015 and 2040 from 4.94 billion tce in 2020 to 6.06 billion tce in 2030, and to 6.10 billion tce in 2040. With the achievement of socialist modernization, China's industrial structure dominated by energy-intensive sectors will gradually shift to one driven by service and high-tech sectors, with further improvement in energy efficiency, total primary energy consumption in 2050 will slowly reach 6.23 billion tce.

Under the reinforced policy scenario, from 2020 to 2040, China experiences continuous growth of total primary energy consumption, followed by a dip from 2040 to 2050, which is consistent with the strategic goal of China's social and economic development. With the tightening of carbon constraints and the improvement of energy efficiency, China's total primary energy consumption would see a decrease as a whole, peaking at 6.02 billion tce in 2040 before dropping to 5.63 billion tce in 2050, 600 million tce less than the policy scenario.

Under the 2 °C scenario, with strengthened carbon constraint, enhanced energy efficiency and increased energy saving on the demand side, China's total primary energy consumption peaks at 5.64 billion tce around 2030 before transitioning to 5.20 billion tce in 2050. As short-term drastic improvement is seen in the level of

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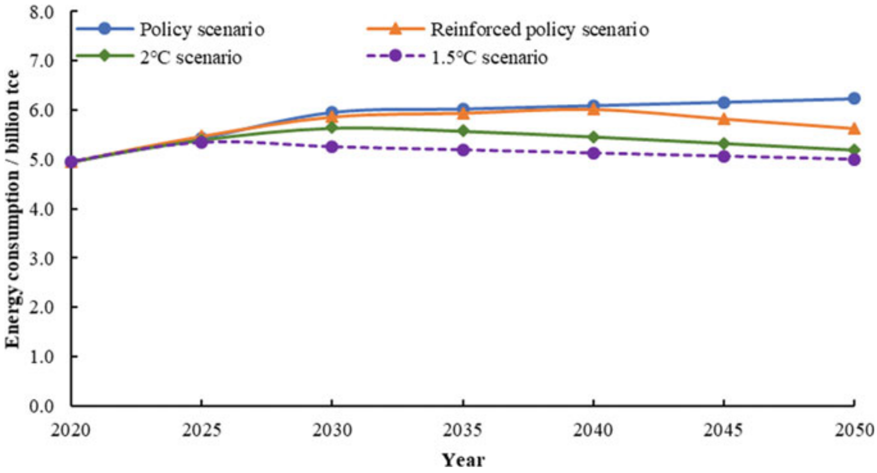

Fig. 5.1 Total primary energy consumption under the four scenarios

energy efficiency improvement and demand energy saving the 2 °C scenario, total primary energy consumption drops slightly under the 1.5 °C scenario compared to the 2 °C scenario between 2015 and 2030, hitting a peak of 5.34 billion tce in 2025 before a moderate decline to 5 billion tce in 2050.

Power consumption by end users is converted into primary energy equivalent, producing a breakdown of primary energy consumption by sector under various scenarios, as shown in Fig. 5.2. If primary energy consumption of the power sector is separately calculated and only the direct use of primary energy by end users is taken

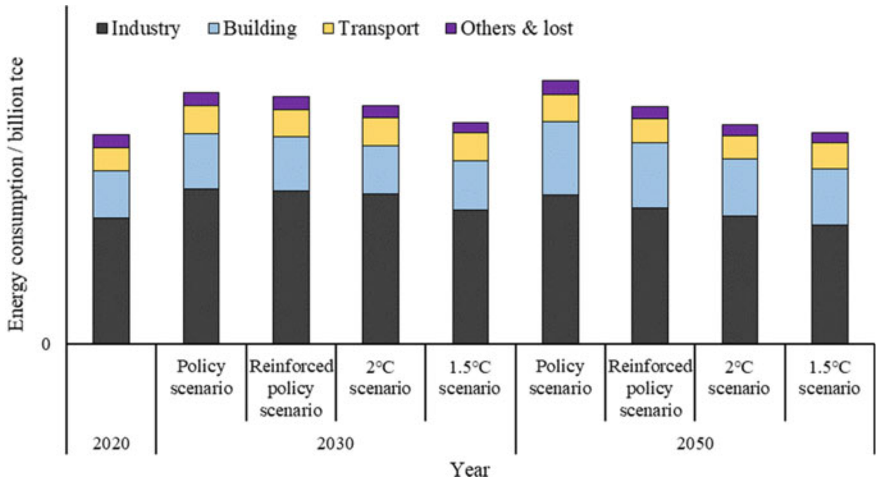

Fig. 5.2 Mix of primary energy demand under four scenarios

Table 5.1 Primary energy consumption under the reinforced policy scenario and the 2 °C scenario (Unit: billion tce)

		Reinforced policy scenario			2 °C scenario		
		2020	2030	2050	2020	2030	2050
Direct use of primary energy consumption by end users	Industry	1.62	1.88	1.23	1.62	1.73	0.69
	Building	0.55	0.51	0.37	0.55	0.41	0.26
	Transportation	0.49	0.55	0.40	0.49	0.53	0.30
	Other sectors and losses	0.12	0.22	0.5	0.12	0.09	0.04
Conversion of primary energy power generation		2.18	2.83	3.57	2.18	2.89	3.91
Total consumption of primary energy		4.94	5.98	5.63	4.94	5.64	5.20

into account, the reinforced policy scenario and 2 °C scenario would look differently in Table 5.1.

5.1.2 Mix of Primary Energy Consumption

Under the four scenarios, with the constraint of decarbonization, primary energy composition in China by 2050 features an overall trend of accelerated coal elimination and sharp rise in the share of non-fossil fuels. The composition of primary energy consumption in major years (2020, 2030 and 2050) under the four scenarios is shown in Fig. 5.3 and Table 5.2.

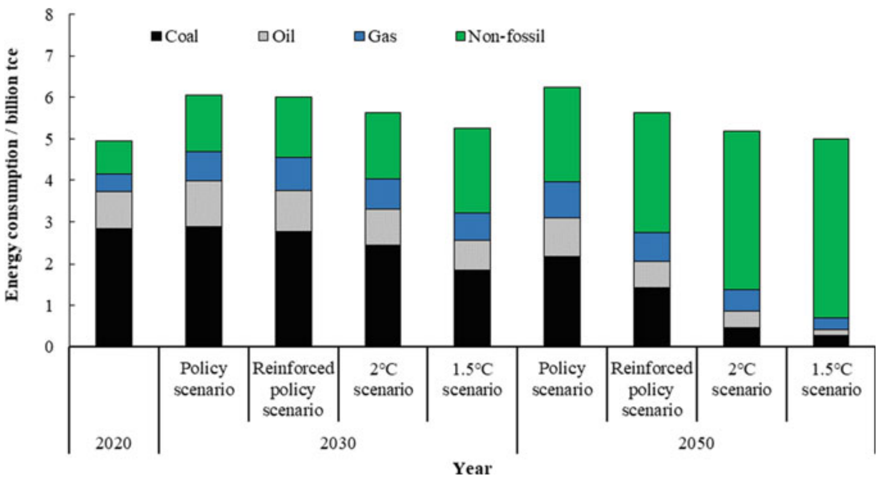

Fig. 5.3 Total primary energy consumption and its composition in major years under different scenarios

Table 5.2 Energy consumption composition by energy source in major years (Unit: %)

	2020	2030				2050			
		Policy scenario	Reinforced policy scenario	2 °C scenario	1.5 °C scenario	Policy scenario	Reinforced policy scenario	2 °C scenario	1.5 °C scenario
Coal	57.4	47.6	46.0	43.2	35.4	34.9	25.3	9.1	5.4
Oil	18.0	18.4	16.7	15.5	13.2	14.8	11.3	7.7	3.0
Gas	8.7	11.6	13.1	12.6	7	14.0	11.9	10.0	5.5
Non-fossil	15.9	22.4	24.3	28.6	38.7	36.3	51.5	73.2	86.1

- In the policy scenario, the total coal consumption decreases annually from 2.84 billion tce in 2020 to 2.18 billion tce by 2050, edging down 0.9% on an annual basis. Oil consumption rises from 890 million tce in 2020 to 1.1 billion tce in 2030 before falling to 920 million tce in 2050. Continuous growth is seen in natural gas consumption from 430 million tce in 2020 to 690 million tce in 2030 and 870 million tce in 2050. Non-fossil energy consumption experiences an annual growth of 3.6% from 790 million tce in 2020 to 2.26 billion tce in 2050. Under such scenario, by 2050, coal, oil, natural gas and non-fossil energy represents 34.9%, 14.8%, 14.0%, and 36.3% respectively in the energy mix.
- In the reinforced policy scenario, total coal consumption drops steadily since 2020 from 2.84 billion tce to 1.42 billion tce in 2050, an annual decline of 2.3%. Oil consumption grows from 890 million tce in 2020 to 980 million tce in 2030 before falling to 640 million tce in 2050. Natural gas consumption climbs from 430 million tce in 2020 to 770 million tce in 2030, then shows a downward trend and slides to 670 million tce in 2050. Non-fossil energy consumption jumps from 790 million tce in 2020 to 2.9 billion tce in 2050, averaging an annual growth of 4.2%. Under such scenario, by 2050, coal, oil, natural gas, and non-fossil energy each takes up 25.3%, 11.3%, 11.9%, and 51.5% respectively in the energy mix.
- In the 2 °C scenario, total coal consumption rapidly decreases from 2.84 billion tce to 470 million tce between 2020 and 2050, a 5.8% drop on an annual basis. Oil consumption falls from 890 million tce in 2020 to 400 million tce in 2050. Natural gas consumption, after a rise from 430 million tce in 2020 to 710 million tce in 2030, goes down to 520 million tce in 2050. Non-fossil energy consumption soars from 790 million tce in 2020 to 3.81 billion tce in 2050, growing at 5.4% annually. Under this scenario, by 2050, coal, oil, natural gas, and non-fossil energy comprises 9.1%, 7.7%, 10.0%, and 73.2% respectively in the energy mix.
- In the 1.5 °C scenario, total coal consumption foresees a steep fall from 2.84 billion tce in 2020 to 270 million tce in 2050, dipping 7.5% year by year. Oil consumption starts its drop since 2020 from 890 million tce to 150 million tce in 2050. In the wake of a climb to 660 million tce in 2030 from 430 million tce in 2020, natural gas consumption spirals down to 280 million tce in 2050. Non-fossil energy consumption, on the other hand, surges from 790 million tce in 2020 to 4.31 billion tce in 2050, an average annual growth of 5.8%. Under such scenario, by 2050, coal, oil, natural gas, and non-fossil energy makes up 5.4%, 3.0%, 5.5%, and 86.1% respectively in the energy mix.

Given the above analysis, in the transition from the policy scenario to 1.5 °C scenario, the decarbonization speed of the energy system continues to accelerate, non-fossil fuel energy becomes the main source in the primary energy consumption mix. However, to materialize these scenarios calls upfront strategic planning, as the earlier the transition, the better it is for the entire energy system.

5.1.3 CO_2 Emissions Under Different Scenarios

Analyzing from the macro perspective on the overall primary energy consumption and CO_2 emission from fossil fuel burning, in the transition from the policy scenario to 1.5 °C scenario, CO_2 emission from primary energy consumption would witness a steady decline, and carbon emissions from primary energy consumption under the four scenarios would fall from 10.25 billion tCO_2 in 2020 to 9.09, 6.18, 2.92, and 1.47 billion tCO_2 in 2050. CO_2 emissions from fossil fuel combustion under various scenarios are illustrated in Fig. 5.4 and Table 5.3.

The changes in CO_2 emissions from fossil fuel combustion under the four scenarios are mainly illustrated as follows:

- Non-fossil energy grows importance in primary energy consumption mix. By 2050, its consumption soars to 4.31 billion tce under the 1.5 °C scenario from the original 2.26 billion tce under the policy scenario, its share in primary energy consumption is 86.1% under the 1.5 °C scenario as compared to 36.3% under the policy scenario.
- There are striking differences in the year and level of CO_2 peak. In the policy scenario, energy-related CO_2 emissions will peak around 2030 at about 11.0 billion tCO_2. In the reinforced policy scenario, the peak occurs between 2025 and 2030 at around 10.6 billion tCO_2. In the 2 °C scenario, the peak will move up to 2020–2025, and reduced to about 10.3 billion tCO_2. To embark on the 1.5 °C pathway sooner, swift reduction in energy-related emissions is required around 2020.

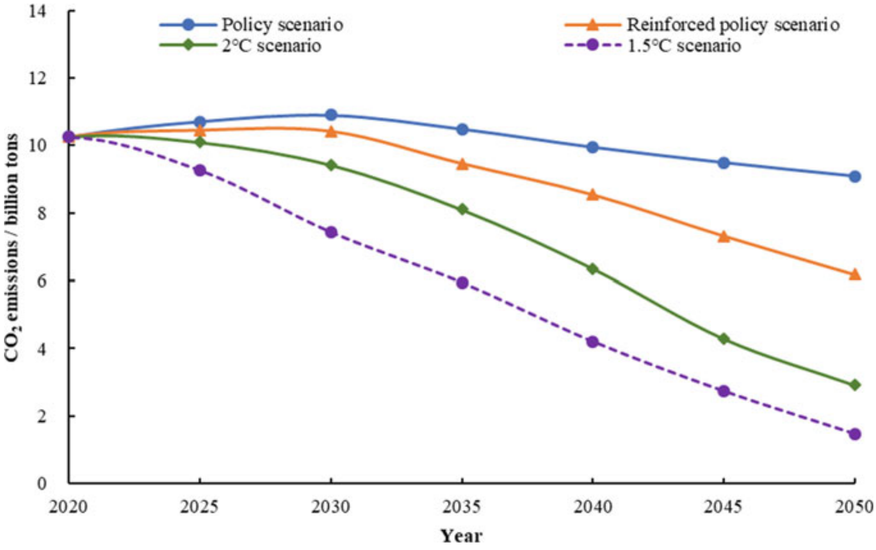

Fig. 5.4 Pathway of CO_2 emissions from fossil fuel burning under the four scenarios in China (excluding CCS)

Table 5.3 Primary energy consumption and CO_2 emissions in major years under four scenarios

	2020		2030		2050	
	Energy demand (billion tce)	CO_2 emissions (billion tCO_2)	Energy demand (billion tce)	CO_2 emissions (billion tCO_2)	Energy demand (billion tce)	CO_2 emissions (billion tCO_2)
Policy scenario	4.94	10.03	6.06	11.08	6.23	9.09
Reinforced policy scenario	4.94	10.03	5.98	10.61	5.63	6.18
2 °C scenario	4.94	10.03	5.64	9.42	5.20	2.92
1.5 °C scenario	4.94	10.03	5.25	7.44	5.00	1.47

- Great difference exists in the speed of total CO_2 emissions reduction. In the policy scenario and reinforced policy scenario, the average decrease of total carbon emissions after peaking in 2030 stands at 0.9% and 2.6% respectively, compared to 5.7% and 7.8% in the 2 °C and 1.5 °C scenarios.

The breakdown of carbon emissions by sector under the policy scenario, reinforced policy scenario, 2 °C scenario and 1.5 °C scenario is illustrated in Fig. 5.5. In all scenarios, carbon emissions from industrial sector makes up the largest share.

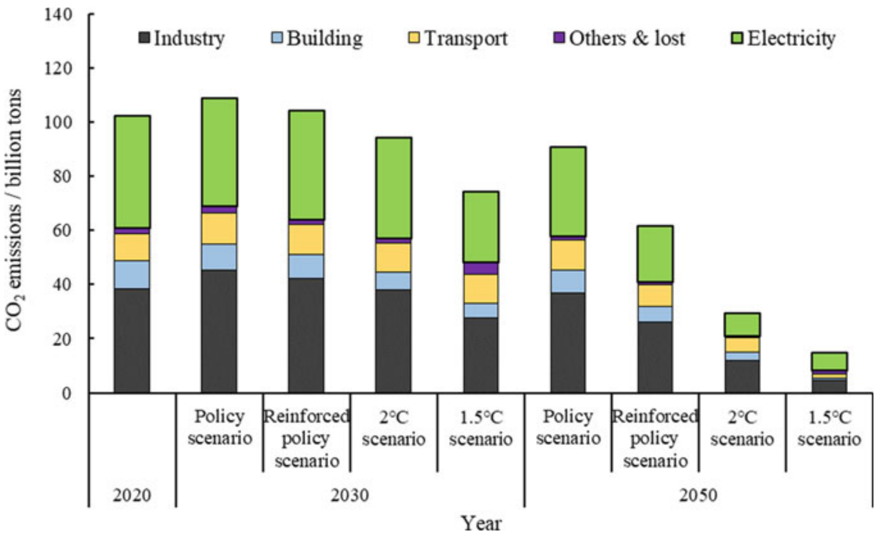

Fig. 5.5 Breakdown of CO_2 emissions under all scenarios

With the development of low-carbon electric power supply technology and negative emission technology, the power sector stands to be the biggest contributor to emissions reduction with a drop from 4.06 billion tCO_2 in 2020 to 3.29 billion, 2.09 billion, 490 million, and -150 million tCO_2 in 2050 under four scenarios respectively. Total CO_2 emissions from the building sector are curtailed, falling from 1.00 billion tCO_2 in 2020 to 830 million, 560 million, 310 million and 80 million tCO_2 in 2050 respectively. CO_2 emissions from transport experiences a minor growth before 2030, followed by an accelerated decline afterward to 1.11 billion, 800 million, 550 million and 170 million tCO_2 by 2050.

5.2 Economic Analysis of Emissions Reduction in the Energy System

5.2.1 Introduction of the Energy Economic Analysis Model

The Computable General Equilibrium (CGE) method can well characterize the correlation and interconnection between the economic and energy systems. This project employs the Global Energy Economy Computable General Equilibrium model (C-GEM) developed by the Institute of Energy, Environment and Economy of Tsinghua University to explore the socio-economic impact of China's low-carbon policy intervention from the perspective of global energy economy balance. As the world moves into a new phase of addressing climate change after the Paris Agreement, and as China embarks on supply-side structural reform amid the economic "new normal", the C-GEM team reintegrated sectors in the model, improved the power and energy-intensive industries, modified the energy substitution relationship, enhanced the automatic efficiency improvement factor, revised parameters of China's economic structure underlying the model, and updated and verified the data of global energy economy.

The C-GEM model can depict in detail the flow of elements, goods and services in economy and energy systems. Through factor input and intermediate product input, producers churn out domestic final products under certain technical conditions, some of which are supplied domestically to meet domestic market needs, while others are exported to the international market. Apart from domestic supply, total domestic demand for goods also comes from imports. Residents, governments, and other consumers, through production factor sales and taxation, obtain disposable income that is partly used for personal consumption and partly placed in saving, which then translates to investments, the combination of personal consumption and investment makes up the total domestic demand. Energy input (as part of the intermediate input) and carbon emissions allowance (as a scarce input) also enter the production process, thereby linking the economic system and the energy system. Given a perfectly competitive market, producers seek maximized profits through cost minimization with given production technologies. At a given income level, consumers maximizes their utility through preference selection. Given certain output level, domestic products and import and export commodities generate maximized sales revenue through the pricing mechanism. Production factors are best allocated for supply and demand in the production process.

C-GEM uses GTAP 10 as the basic database embedded in the model, with 2014 as the base year, putting together data from economy, energy, and bilateral trade in 65 industrial sectors across 141 countries and regions. A global computable general equilibrium model is then formulated, while accommodating the sectoral breakdown of official energy and economic statistics in China, capturing 17 regions and 21 sectors globally (19 production sectors and 2 consumption sectors). Furthermore, the policy scenario, reinforced policy scenario, 2 °C scenario, and 1.5 °C scenario are built within the model to diagnose carbon price changes and GDP losses in the low-carbon transition.

5.2.2 Carbon Price

Carbon price levels from 2020 to 2050 under the four scenarios are shown in Table 5.4. Noted that carbon price incentive mechanism in this study contains all policies for emission reduction adopted by the entire energy and economic system except the policies for renewable energy development and natural gas utilization. Carbon price, in this context, represents the marginal cost of abatement in the process of CO_2 emission reduction, thus reflecting the force of policy measures under different scenarios. Under policy scenario, reinforced policy scenario, 2 °C scenario, and 1.5 °C scenario, carbon price gradually climbs from RMB 46/ton in 2020 to RMB 265, 510, 1364, and 5,701/ton in 2050. By 2050, carbon price in the 2 °C and 1.5 °C scenarios is 5 times and 21 times of that in the policy scenario, and 3 times and 11 times of that in the reinforced policy scenario. This means that in order to fulfill the most stringent emission targets, the whole society would have to bear a very high cost.

Table 5.4 Carbon price under different scenarios (Unit: RMB/ton, at constant 2011 prices)

	2020	2025	2030	2035	2040	2045	2050
Policy scenario	46	73	99	139	192	245	265
Reinforced policy scenario	46	79	106	152	238	351	510
2 °C scenario	46	86	126	199	344	583	1364
1.5 °C scenario	46	106	166	285	622	1609	5701

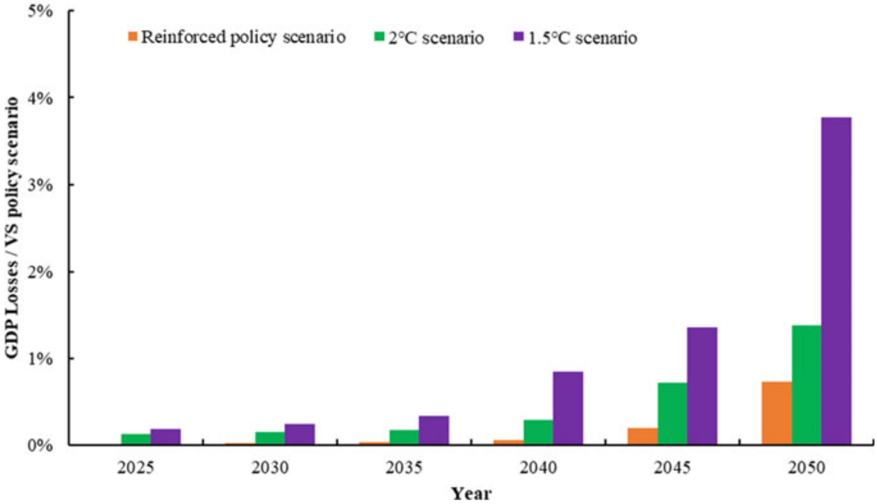

Fig. 5.6 GDP losses under different scenarios

5.2.3 GDP Losses

To promote deep decarbonization while securing sustainable economic and social development, it is essential to strengthen policy measures and ensure sufficient flow of investment. For the economic system, a cut in CO_2 emissions entails costs and sacrifices. Figure 5.6 provides the GDP losses of the reinforced policy scenario, 2 °C scenario and 1.5 °C scenario as opposed to the policy scenario. The reinforced policy scenario features relatively minor GDP losses of less than 1% by 2050, or approximately 0.7%. By contrast, the 2 °C and 1.5 °C scenarios are characterized by greater GDP losses, which grow to 1.4% and 3.8% by 2050, almost 2–5 times larger than in the reinforced policy scenario, reflecting to fairly high economic losses by China for the sake of the most stringent emission targets.

5.3 Synergy Between Deep Decarbonization and Environment Improvement

Cutting back on fossil energy consumption reduces CO_2 emissions while reducing SO_2, NOx, $PM_{2.5}$, and other conventional pollutants at the source, facilitating achievement of environmental standards and the "Beautiful China" target [1]. China's mid-long term environmental targets indicate that by 2035, all major cities and regions should meet the national standard of $PM_{2.5}$ concentration below no more than 35 $\mu g/m^3$ [2] and by 2050, $PM_{2.5}$ concentration below 15 $\mu g/m^3$ for all regions.

The Jing-jin-ji (Beijing-Tianjin-Hebei, respectively) Region and its periphery areas, Fenhe-Weihe Plain and Yangtze River Delta are the key regions for China's environment improvement programs. In 2015, the average concentration of $PM_{2.5}$ at all monitoring stations in China stood at 53.1 $\mu g/m^3$, and the three regions reported 81.3, 60.4, and 55.0 $\mu g/m^3$ respectively. Only 29.1% of Chinese cities fell within the standard [3].

In the policy scenario, the national $PM_{2.5}$ concentration falls to 19.2 $\mu g/m^3$ by 2030, down 63.8% from 2015. Jing-Jin-Ji Region and its periphery areas, Fenhe-Weihe Plain and Yangtze River Delta witness a decrease estimated at 59.8%, 65.4%, and 65.5% respectively. By then, air quality will see a dramatic shift across the country, with the Fenhe-Weihe Plain and Yangtze River Delta no longer being major $PM_{2.5}$ pollution areas. 96.6% of Chinese cities would have been met the Class two of environment quality standard of 35 $\mu g/m^3$ on an annual average. Though one third of cities would have reported a concentration level less than 25 $\mu g/m^3$, over 30% of cities in Beijing-Tianjin-Hebei Region and its periphery areas would fall short of the target. The level of $PM_{2.5}$ pollution in 2050 remains at par with that in 2030, with most regions far behind the 15 $\mu g/m^3$ target and some places in Jing-Jin-Ji Region and its periphery areas still struggling with $PM_{2.5}$ pollution. By 2050, the national $PM_{2.5}$ concentration is reduced to 14.0 $\mu g/m^3$, and that in Jing-Jin-Ji Region and its periphery areas, Fenhe-Weihe Plain and Yangtze River Delta drops to 24.9, 14.6 and 14.0 $\mu g/m^3$respectively. Only 76.0% of the cities in China and 4% of cities in Jing-Jin-Ji Region and its periphery areas measures up to the Class one standard of 15 $\mu g/m^3$. In general, the policy scenario foresees a great decline in national $PM_{2.5}$ concentration, but big gaps still exist if China is to achieve 35 $\mu g/m^3$ by 2030 and 15 $\mu g/m^3$ by 2050.

The reinforced policy scenario sees notable reduction in $PM_{2.5}$ concentration as compared to the policy scenario. By 2030, $PM_{2.5}$ pollution is somewhat improved in key areas such as Jing-Jin-Ji Region and its periphery areas compared to the policy scenario. China as a whole, Jing-Jin-Ji Region and its periphery areas, Fenhe-Weihe Plain, and the Yangtze River Delta is down to 17.3, 29.7, 19.8 and 16.1 $\mu g/m^3$ by 2030 respectively. But the 35 $\mu g/m^3$ target remains a challenge for 3.6% of cities in China and 9.6% of cities in the Jing-Jin-Ji Region and its periphery areas. By 2050, $PM_{2.5}$ pollution in China under the reinforced policy scenario is markedly alleviated compared to the policy scenario, with that in China as a whole, Jing-Jin-Ji Region and its periphery areas, Fenhe-Weihe Plain and the Yangtze River Delta falling to 10.1, 19.3, 11.4 and 9.3 $\mu g/m^3$, with some regions achieving 15 $\mu g/m^3$ in principle. However, 10% of Chinese cities and over 65% of cities in Jing-Jin-Ji Region and its periphery areas fall short of the 15 $\mu g/m^3$ Class one standard, presenting a health hazard that shouldn't be neglected.

In the 2 °C scenario, $PM_{2.5}$ concentration in China, Jing-Jin-Ji Region and its periphery areas, Fenhe-Weihe Plain and Yangtze River Delta is reduced to 16.2, 28.0, 8.2, and 16.0 $\mu g/m^3$ by 2030. All regions meet 25 $\mu g/m^3$ except for Jing-Jin-Ji Region. By 2050, concentration further declines to 8.3, 14.1, 9.6, and 7.5 $\mu g/m^3$, with no region in China classified as $PM_{2.5}$ high pollution zone, with majority of the regions realizing the 15 $\mu g/m^3$ standard. Though the 10 $\mu g/m^3$ goal is achievable in 81.7% of Chinese cities, but only 28.0% of cities in Jing-Jin-Ji Region meet this standard. In comparison, under the 1.5 °C scenario, all Chinese cities meet the 15 μg/m^3 target, with 88.8% reaching the 10 μg/m^3 target. But over 40% of cities in Jing-Jin-Ji Region and its periphery areas still fall short under this target.

In summary, achieving the deep decarbonization target under the 2 °C or even 1.5 °C significantly improves the environment quality. Even under the policy scenario, China's air quality sees considerable reduction in SO_2, NOx, $PM_{2.5}$ concentration, but it remains a challenge to meet the target of 35 μg/m^3 by 2030 and 15 μg/m^3 by 2050 in key regions. The 2 °C scenario goes a step further to realize the 35 μg/m^3 by 2030 and 15 μg/m^3 by 2050. And 1.5 °C scenario trumps the previous two scenarios to bring about fulfillment of 10 μg/m^3 target by 2050. In other words, deep decarbonization goal will drive substantial improvement of the environment and secure the success of building a "beautiful China".

Figure 5.7 shows the number of premature deaths from $PM_{2.5}$ exposures by 2030 and 2050 under various scenarios. Deep decarbonization will speed up the $PM_{2.5}$ reduction while ensuring better public health. In 2015, 1.379 million people died prematurely due to $PM_{2.5}$ exposures in China [4]. In the policy scenario, with continuous high $PM_{2.5}$ levels and the aging society, the number of premature deaths is 1.629 million and 2.424 million by 2030 and 2050 respectively, up 18.2% and 75.8% from the 1.379 million in 2015. In the reinforced policy scenario, the number is brought down to 1.541 million by 2030, an 88,000 people reduction than that in the policy scenario, which highlights the contribution of emissions reduction on public health, and by 2050, the health benefits are magnified with 545,000 fewer deaths. Both policy scenario and reinforced policy scenario see increased premature deaths

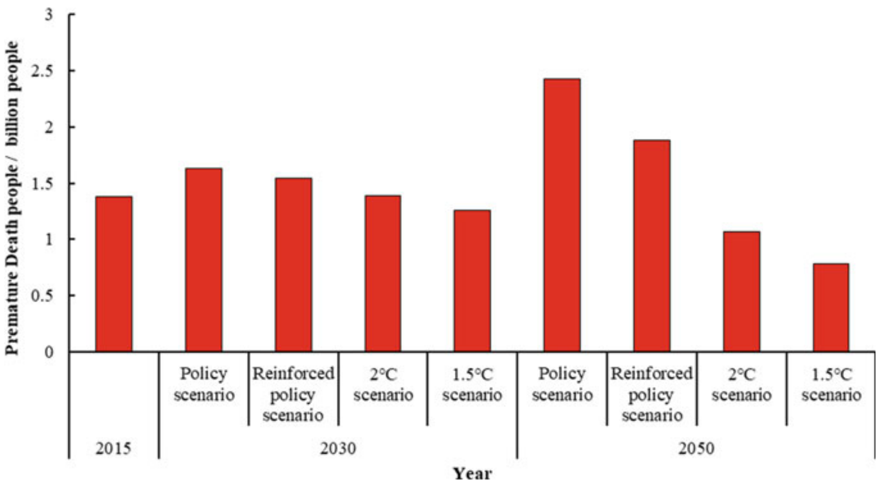

Fig. 5.7 Number of premature deaths from $PM_{2.5}$ exposure by 2030 and 2050 under various scenarios

by 2030 and 2050, suggesting that the health benefits of improved air quality under such scenarios are insufficient to offset the health losses from the ageing population.

Under the 2 °C and 1.5 °C scenarios, the number of premature deaths from $PM_{2.5}$ exposures by 2030 is 1.387 million and 1.26 million respectively, an 8,000 people increase and a 118,000 decrease compared to that of in 2015 respectively, equivalent to a 14.8% and 22.6% reduction than that of in the policy scenario. The number of such deaths falls to 1.065 million and 782,000 by 2050, a 23.2% and 37.9% reduction compared with 2030. Concludingthat with the profound transformation of energy mix and tightening of control measures, the health benefits brought by air quality improvement can offset most of the health losses from population ageing and changes in demographic distribution.

5.4 Policy Suggestions

1. Implement coordinated measures for win–win outcome in economic development, environmental protection, and carbon emissions reduction

China actively now pursues a new development philosophy under the new normal of its economy, working to achieve innovative, coordinated, green, open and shared development by fostering new growth drivers through innovation, while shifting its growth model through green development. Green development, in essence, seeks to boost the harmonious coexistence between human and nature while pursuing green and low-carbon development, thereby promoting the coordinated and sustainable development of economy, society, resources, and environment. This echoes the path of climate-friendly low-carbon economic development advocated in the Paris Agreement. China's enormous strides in energy conservation, carbon reduction, and economic transformation are also attributed to the combined efforts in addressing climate change and promoting domestic sustainable development. China has become a major contributor and leader in driving energy transition and low-carbon economic transformation in the world.

The key to green and low-carbon development lies in promoting the reform of the energy system and transformation of economic development model. With the ongoing industrialization and urbanization in China, the economic takeoff is hampered by resource and environmental constraints. It's important to facilitate revolution in energy production and consumption, save energy, enhance energy efficiency, cap fossil fuel consumption, and vigorously develop new and renewable energy, promote the low-carbonization of the energy mix in a bid to curb conventional pollutants and CO_2 emissions. Domestic efforts in conserving environment and building ecological civilization are consistent with the goals and measures of addressing climate change and protecting ecological safety of the earth, and extensive synergies can be harnessed in this regard. It's essential to devise holistic plans for coordinated progress, aim for sustainable domestic development, and ramp up goal-driven initiatives for long-term low-carbon development and emission reduction. Currently, given the enhanced prevention and treatment of environment pollution, tightened emission standards, and control measures of conventional pollutants in the use of coal, petroleum, and other fossil fuels, more focus should be placed on cutting and replacing coal and oil in the end-use consumption, increasing the share of electricity in this mix, pacing up the development of renewable energy, and increasing the share of renewable power generation in primary energy consumption in an effort to set the stage for faster growth of renewables amid a slowdown in total energy demand. The substitution of non-fossil power generation for coal and oil in the end consumption could enable the dual effect of environment improvement as well as CO_2 emission reduction.

2. Optimizing energy mix is major task and long-term goal for achieving low-emission development

Under the policy scenario, non-fossil energy makes up 22.4% in 2030, further rises to 36.3% in 2050 in the energy mix; coal consumption reaches peak around 2030, and its proportion reduces to 34.9% by 2050. Under the reinforced policy scenario, energy mix is improved in comparison to the policy scenario, with coal and oil dropping by 1.6 and 1.7 percent respectively, and natural gas and non-fossil increasing by 1.5 and 1.8 percent by 2030 respectively. Coal consumption meets its peak around 2020 at 2.84 billion tce, and its proportion drops to 25.3% in the energy consumption mix by 2050. In the same year, non-fossil energy in primary energy consumption increases to 51.5% as a dominant energy source. Under the 2 °C scenario, power generation from coal, natural gas, and biomass with CCS would have evolved around 2040, with non-fossil energy and fossil energy with CCS (carbon-free energy in short) taking over the energy mix. Non-fossil energy as a percentage of primary energy consumption is 28.6% in 2030 before jumping to 73.2% in 2050. Under the 1.5 °C scenario, power generation from coal, natural gas and biomass with CCS would have been developed around 2035, with non-fossil energy in primary energy consumption standing at 38.7% in 2030 before hitting 86.1% in 2050.

As things stand, the installation of coal-fired power units would reach approximately 1.1 billion kilowatts at the end of the 13th Five-Year Plan period, with adequate capacity to support future growth of electricity demand. But in the long run, such capacity will inevitably diminish, and extra caution should be exercised for new installations. In principle, no new coal power units should be added to avoid waste. Furthermore, a shift in coal power usage should be considered for the full use of existing units. Major steps should be taken to make existing coal power plants more flexible prior to 2030, and these plants should gradually undertake more peak-shaving task than the provision of base load. Under the 2 °C and 1.5 °C scenarios, some coal power units need to retire before the end of their service life, which causes tremendous waste of social resources and investment. Therefore, an orderly withdrawal mechanism for existing coal power units should be created for the appropriate management of retiring units.

3. Industrial structure upgrade and technological innovation underpin and safeguard the energy revolution

On its way to a wholistic modernization, China can't afford to replicate the path and model of developed countries, new modes of production and new drivers of modernization should be fostered. The traditional pattern of China's economic development resulted in inefficient resource allocation with mounting economic risks.

The adjustment and upgrading of industrial structure can dramatically mitigate the economic impact from the low-carbon transformation. Therefore, accelerating the transformation of the development pattern is a crucial step along the way to achieving China's economic modernization. Meanwhile, the global energy transformation will prompt major changes in the mode of economic and social development worldwide, thus affecting the dynamics of international economic and technological competition. One important trigger and strategic goal of major countries in mitigating climate change is to increase its competitiveness in advanced energy technologies. Only with more breakthroughs and massive application of key low-carbon technologies for technological and institutional innovations can low emission pathway be made much more accessible.

To start, multiple technological means should be adopted to ensure a high uptake of renewable energy. As more wind and solar power is fed into the grid, grid itself is increasingly challenged by the balance of power, diverse operation pattern, scarce flexible resources, and complicated stability mechanism. The mounting challenges of grid operation calls for various technical solutions to ensure the smooth continuous operation of the grid. More peak-frequency modulation and reserve capacity are often used in case intermittent renewable energy comprises less than 50% of power production, which entails a sound portfolio of technologies, which in turn hinges on the structure of power sources and grid as well as the maturity and economy of various technologies. If intermittent renewable energy reaches over 50%, virtual synchronization and seasonal energy storage technologies should be adopted for the renewable power generators. These two technologies are still under development or demonstration, thus more R&D and investment are crucial to enhance their maturity and cost reduction through a mixture of technology, policy, and market means in order to prepare for their massive application.

Secondly, efforts should be made to actively promote the R&D and application of energy storage technology, strengthen the construction of trans-regional power exchange channels, and press ahead with power market reform. As the grid operates with more intermittent renewable energy, power systems need to provide better flexibility to meet hourly peak demand. Prior to 2030, peak regulation through flexibility upgrading and grid interconnection could well accommodate the integration of intermittent renewables. After 2030, with carbon emissions accelerating, the share of renewables further increased, and the installed capacity of flexibility-supporting coal power on the decline, new energy storage units need to be built for intermittent renewables, especially in Inner Mongolia, Xinjiang, Shandong, and northwest China. Therefore, proactive steps should be taken to develop, demonstrate and apply energy storage technology, create green financing tools to provide funding for building massive cross-regional power exchange channels. Deep decarbonization of the power industry in the future, from the policy standpoint, rests on the improvement of power market mechanism. This provides the rationale for continued reform of the power market and the use of market means for minimum total social cost.

Lastly, step up the R&D and industrialization of advanced energy technologies. Alongside renewable energy technologies such as solar and wind, nuclear technology and hydrogen technology, energy storage, and smart grid technologies, China should place particular attention to CCS and advanced nuclear technology with more focus on R&D and demonstration. Studies have found that the power sector won't succeed in its migrating to the 1.5 °C carbon-free pathway without revolutionary technological breakthroughs. With this in mind, CCS should be deemed as a key technology with intensive R&D and demonstration to set the scene for large-scale application. In addition, with coal long taking the center stage in China's primary energy consumption—nearly 60% by 2020—and urgent global emission reduction targets and high carbon prices, apart from efforts in clean coal and its efficient utilization, CCS will be a major alternative technology by 2040. CCS may sequester hundreds of millions of tons to one billion tons of carbon, playing a pivotal role in emission reduction in the long run. Given the difficulty of replacing fossil fuels in chemical and cement industries, BECCS technology, as a relatively predictable negative emission technology right now, will be instrumental to achieving ultra-low emission targets in the future.

4. Market mechanism and leverage pricing signals to encourage low-carbon green development should be improved

Studies show that China's low-carbon energy transition must be accompanied by forceful policies and legislations, including laws and regulations, targeted policies for renewable energy development and natural gas utilization, market mechanisms like carbon trading, and institutional mechanism reform, etc. By translating all policies other than the targeted policies for renewable energy development and natural gas utilization into carbon price incentives, under the policy scenario, the marginal cost of CO_2 emissions reduction is approximately CNY100/ton in 2030, and CNY 265/ton in 2050. Under the reinforced policy scenario, the cost is around CNY106/ton in 2030 and CNY510/ton in 2050. As for the 2 °C and 1.5 °C scenarios, the cost in 2050 soars to CNY1,364 and CNY 5,701 /ton respectively.

Low-carbon development entails clear policy guidance and, more importantly, long-term market signals. It's essential to stay rooted in reality, deepen reform in energy prices, ensure equitable access to quality energy services for low-income families to boost harmonious social development, alongside efforts in curbing irrational consumption and promoting energy conservation. In particular, institutional reform of the energy market should be strengthened to restore the attributes of energy as a commodity so as to create a just, fair, and effective market structure and system.

Carbon market will be a major institutional safeguard for the early peak of CO_2 emissions in China, and part and parcel of ecological civilization in the country. Now, on top of the carbon trading pilots in five cities and two provinces, China has launched a single national carbon market, which will be continuously expanded and improved. Carbon market is a crucial policy tool that seeks to minimize the cost of emission reduction for the whole society and helps attain national target of emission reduction through government-led market mechanism. It quantifies the value of carbon emission quotas and environmental capacity as scarce public resources and production factors and internalizes the social cost of resource and environmental losses, thereby encouraging the conservation of fossil energy, the development of new and renewable energy, and the transformation of energy mix. The accounting, monitoring, reporting, and verification systems built for the unified national carbon market also constitute the main institutional guarantee for building a green, low carbon, and circular economic system in China. It's important to create holistic plans for the varied indicators and assessment of energy conservation and emissions reduction, for instance, to coordinate the implementation of energy use right of enterprises and emission allowance systems. Compared with the right to energy use, the emission allowance system stresses not only energy saving, but more importantly, the development of alternative energy sources by encouraging enterprises to tap into distributed renewables and focus on the curtailment of coal, oil and other fossil fuels, which is more aligned, in a comprehensive manner, with the vision of energy revolution featuring a clean, low-carbon, safe, and efficient system of energy supply and consumption.

References

1. Xinhua News Agency (2018) Opinions of the Central Committee of the Communist Party of China and the State Council on comprehensively strengthening ecological environmental protection and resolutely fighting the battle against pollution, 24 June 2018. http://www.gov.cn/zhengce/2018-06/24/content_5300953.htm
2. Ministry of Environmental Protection, Environmental Air Quality Standard (GB3095-2012). 2012
3. Institute of Climate Change and Sustainable Development, Tsinghua University (2019) Coordinated governance of environment and climate—successful cases in China and beyond. Tsinghua University, Beijing
4. Liu J, Han Y, Tang X et al (2016) Estimating adult mortality attributable to $PM_{2.5}$ exposure in China with assimilated $PM_{2.5}$ concentrations based on a ground monitoring network. Sci Total Environ 568:1253–1262