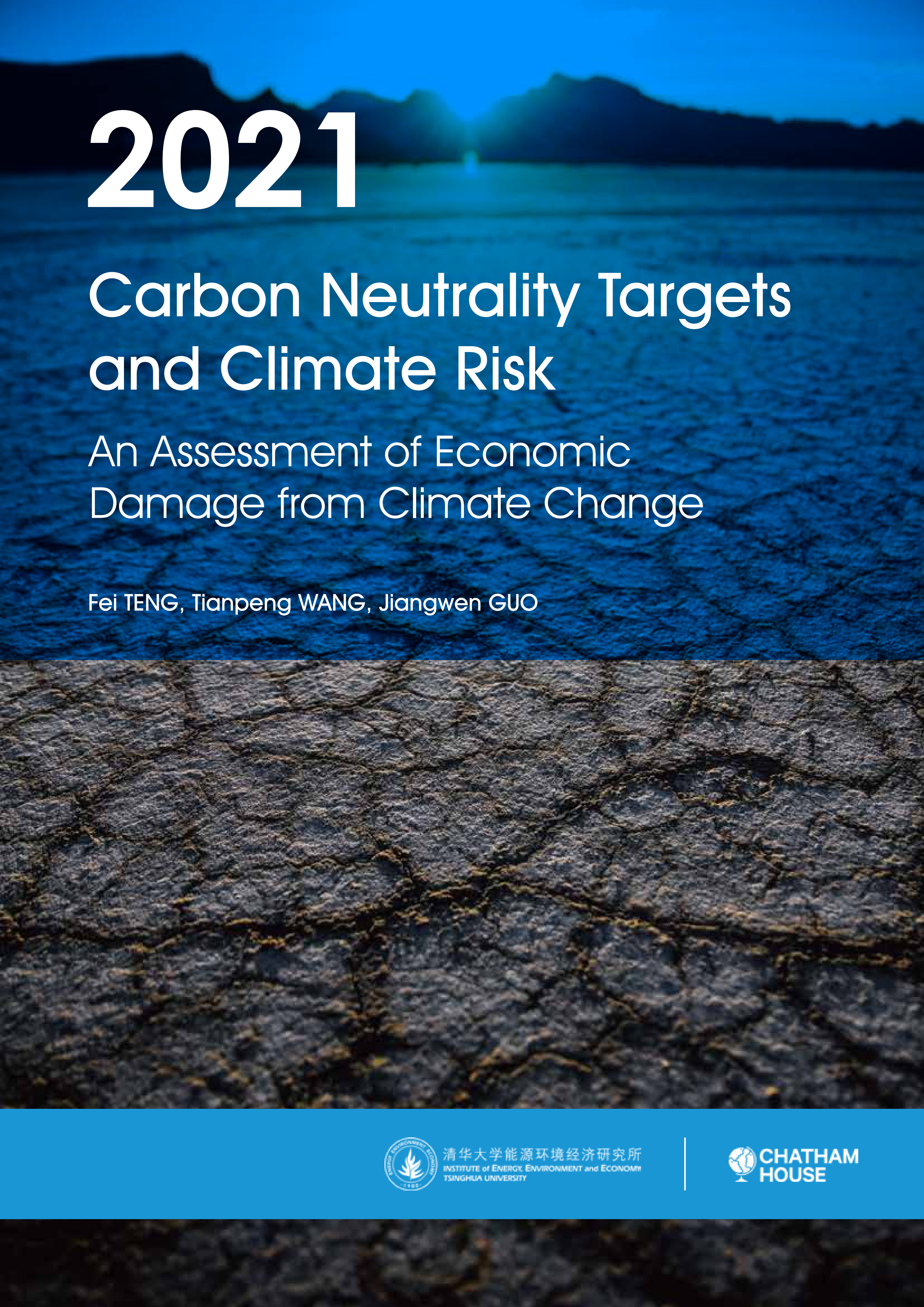

2021

Carbon Neutrality Targets and Climate Risk

An Assessment of Economic Damage from Climate Change

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EXECUTIVE SUMMARY

Climate change has caused visible economic impacts and losses. China's exposure to the adverse effects of climate change is higher than the global average, and climate risks and climate security are getting increasingly prominent. Scientific evidence shows that climate change has already caused significant impacts on global natural ecosystems and socio-economic systems. Without effective governance, the impacts and losses of global climate change will further intensify in the future, and the natural ecosystem and socio-economic systems on which human beings depend will also face serious threats. Climate warming in China is significantly higher than the global average. Since the middle of last century, the annual average temperature in China has risen at a rate of 0.27°C per decade, higher than the global average for the same period. As a result of climate change, heat-related extreme events in China has increased significantly, precipitation days decreased, but rainstorm days increased, and regional and periodic droughts intensified. The average annual direct economic loss due to frequent climate disasters amounts to more than $50 billion, or about 0.4% of GDP. In the future, with growing economic aggregates and deepened global economic integration, the risks caused by climate change to China's economic security will intensify.

Climate change may generate climate losses through extreme weather events, slow onset events, tipping points and its cascading events, climate risks may be significantly underestimated while existing climate disaster loss statistics only partially include direct losses from extreme weather events. In recent years, the adverse effects of climate change have become increasingly evident. According to WMO, the past 5 decades has witnessed more than 11,000 climate disasters, leading to more than 2 million deaths and economic losses up to $3.64 trillion. However, the existing climate disaster loss statistics only focus on direct climate losses caused by extreme weather events, while slow-onset event losses and indirect losses are excluded. In the future, as climate change approaches or exceeds critical thresholds, catastrophic losses may be triggered, and cascading risks may arise through complex socio-economic networks that lead to multiple risks exceeding the tipping points at the same time. Slow onset events, tipping points and its cascading risks are yet to be well understood. However, in China's case, working hours lost due to heat-related events from climate change alone is equivalent to 40% of the impact of the COVID-19 epidemic, and therefore potential climate risks may be much greater than the direct economic loss statistics of climate disasters.

Achieving the carbon neutrality target would enable China to avoid about 80% of accumulative climate change losses and reduce climate losses by about $134 trillion over the period 2020-2100. Future climate losses are closely related to global warming and increase nonlinearly with temperature rise. Under the NDC scenario, global temperature rise will reach 3.5°C in 2100, climate change losses account for 5.6% of China's GDP, and accumulative climate change losses amount to $189 trillion. In the contrast, under the carbon neutrality scenario, global temperature rise can be limited to about 1.5°C in 2100, and China's climate change losses can be contained to less than 1% of GDP, reducing accumulative climate change losses to $55 trillion or by $134 trillion. More than 85% of climate losses to occur in 2050-2100, delay in action therefore means transferring significant climate risks to next generations and embedding underlying dangers for socio-economic sustainability in the long run.

Uncertainties in the assessment on economic losses from climate change are not an excuse for inaction, rather it imply the possibility of broader climate risks. Therefore, achieving the carbon neutrality target is a necessity to effectively govern climate risks. Climate change is a complex physical process, and the assessment on climate losses involves equally complex socio-economic systems, as well as complex interactions between the climate system and the socio-economic systems. Although studies on climate loss mechanisms and functions have greatly advanced the understanding of climate risks in the past few decades, it is still far from adequate. However, uncertainties in climate change and its losses, are not an excuse for inaction. The scope of climate change losses may be much greater than what we have predicted due to the impacts of slow onset events, tipping points and cascading risks. Thus, uncertainties in climate losses actually enhance, rather than weaken, the rationale for action. From a risk management perspective, China's carbon neutrality target is not only the sustainable transformation target of energy system and economic structure, but also the safest and most effective way to reduce economic losses from climate change.

Climate change is the most critical global environmental issue for the world today, while also the most challenging issue in risk governance. The risks of climate change mainly come from three sources [1]: 1) risks of setbacks in global low-carbon transition and continued increase in GHG emissions; 2) risks of direct impacts from climate change exceeding the "intolerable" threshold; 3) systemic risks arising from the superposition and amplification of disasters due to interactions between climate change risks and other risks.

Climate change further poses serious threats to the national security and worldwide economic prosperity due to its widespread effects and the vulnerability of human societies to these impacts. The teams of China-UK Climate Risk Assessment Cooperation have conducted joint study on climate change risks over the years. Building on previous studies, this report will quantitatively assess the economic losses from climate change in China and the avoidable economic losses towards achieving the carbon neutrality target.

I. CHINA'S CARBON NEUTRALITY TARGET AND PROGRESS

On September 22, 2020, Chinese President Xi Jinping announced the carbon neutrality target at the General Debate of the 75th session of the UN General Assembly [2]. According to this, China will enhance its NDC, adopt more aggressive policies and measures to address climate change, and strive to peak CO_2 emissions by 2030, and achieve "carbon neutrality" by 2060. The carbon neutrality target announced by China has attracted great attention internationally and provided a strong impetus to the global climate agenda, which has been stalled in the wake of the epidemic. President Xi Jinping further articulated China's emission mitigation goals at the Climate Ambition Summit in December 2020 [3]: in addition to the carbon peaking and carbon neutrality targets, by 2030, China's CO_2 emissions per unit of GDP will drop by more than 65% compared to 2005. This sets up more specific milestones and its requirements for achieving carbon neutrality. On March 11, 2021, adopted the "Outline of the 14th Five-Year Plan for National Economic and Social Development and the Long-Range Objectives Through the Year 2035 for the People's Republic of China (Draft)" (hereinafter referred to as the "Outline of the 14th Five-Year Plan") [4] was adopted at the Fourth Session of the 13th National People's Congress (NPC). In the Outline of the 14th Five-Year Plan, carbon peaking by 2030 is included in the long-term vision, and three binding targets directly related to climate change are included in the main objectives of economic and social development in the 14th FYP period: reducing energy consumption and CO_2 emissions per unit of GDP by 13.5% and 18%, respectively, and increasing the forest cover to 24.1%.

On the eve of COP26 in 2021, the CPC Central Committee and the State Council jointly issued the "Working Guidance For Carbon Dioxide Peaking And Carbon Neutrality In Full And Faithful Implementation Of The New Development Philosophy" (hereinafter referred to as "Working Guidance") [5]. The "Working Guidance" summarizes the main objectives of carbon neutrality and sets up three milestones for 2025, 2030 and 2060. Specifically, by 2025, energy consumption and CO_2 emissions per unit of GDP will have dropped by 13.5% and 18% respectively from the 2020 level, the share of non-fossil energy consumption will have accounted for about 20%, forest cover will have reached 24.1%, and forest stock will have risen to 18 billion m^3. By 2030, CO_2 emissions per unit of GDP will have dropped by more than 65% compared to 2005, the share of non-fossil energy consumption will have accounted for about 25%, with the total installed capacity of wind and solar power reach more than 1200 GW, forest cover will have reached about 25%, forest stock will have reached 19 billion m^3, and CO_2 emissions will reach peak and stabilization and then decline. By 2060, the share of non-fossil energy consumption will be over 80%, and carbon neutrality will be achieved. On October 28, 2021, China submitted two documents to the UNFCCC Secretariat, "China's Achievements, New Goals and New Measures for Nationally Determined Contributions" and "China's Mid-Century Long-Term Low Greenhouse Gas Emission Development Strategy", which have updated and strengthened the 2030 NDCs targets proposed in 2015, as required by the Paris Agreement and its decisions, and formally transformed domestic mandates into international

Table1 Summary of China's Climate Change Mitigation Targets and Their Achievements

	NAMA Targets by 2020	Achievements as of 2020	14th FYP Targets by 2025	2030NDC	Updated 2030NDC	2060 Targets
CO_2 emissions				Peak around 2030 and strive for early peak	Strive to peak by 2030	Carbon neutrality
Total installed capacity of wind and solar power		535 GW ***			More than 1200 GW	
CO_2 emission intensity per unit of GDP	40-45% decline from 2005 levels	48.1% decline from 2005 levels	18% decline from 2020 levels (equivalent to 57.4% decline from 2005 levels)	60%-65% decline from 2005 levels	More than 65% decline from 2005 levels	
Share of non-fossil energy in energy consumption	15%	15.9%	Around 20%	Around 20%	Around 25%	More than 80%
Forest cover	Increased by 40 million ha. on 2005 basis**	23.04% (equivalent to an increase of 46 million ha.)	24.1%		Around 25%*	
Forest stock	Increased by 1.3 billion m^3 on 2005 basis**	17.56 billion m^3 (equivalent to an increase of 5.1 billion m^3)	18 billion m^3	Increased by 4.5 billion m^3 on 2005 basis	Increased by 6 billion m^3 on 2005 basis 19 billion m^3*	

Notes: * Binding targets included in the Outline of the 14th Five-Year Plan, but not included in the updated NDC submitted by China.

** According to the data of the 6th National Forest Resources Inventory, the forest area and stock in China registered 175 million ha. (with a forest cover of about 18.2%) and 12.456 billion m^3, respectively in 2005.

*** Including grid-connected wind power and grid-connected photovoltaic.

Figures in brackets are based on authors' calculations rather than official reporting data.

commitments. China submited its national climate change targets to the UNFCCC Secretariat following Nationally Appropriate Mitigation Actions (NAMAs) in 2009 and 2030 NDC targets in 2015. Table 1 summarizes China's climate change target submissions since 2009 and their achievements.

As the world's largest developing country, China's per capita energy consumption is much lower than that of developed countries. China's decision on the targets of achieving carbon peaking by 2030 and carbon neutrality by 2060 at a stage of "double rise" in terms of carbon emissions and energy consumption, has demonstrated its strong sense taking up the due responsibilities as a major country for the double challenges posed by the climate crisis and post-epidemic recovery. From carbon peaking to carbon neutrality and net zero emissions, it takes about 60 years for the EU and 45 years for the United States, while China is striving to achieve the targets within 30 years. There are enormous challenges in China's path towards carbon neutrality. To meet this daunting challenge, Chinese government has made adequate preparations in terms of systems and mechanisms in the past year.

In May 2021, China set up the Leading Group on Carbon Peaking and Carbon Neutrality. The Leading Group is China's deliberative and coordination mechanism specifically for dealing with interdepartmental or comprehensive affairs of carbon peaking and carbon neutrality. As early as 2007, China established the National Leading Group on Climate Change, Energy Conservation and Emission Reduction under the State Council as the deliberative and coordination body for climate change. The newly established Leading Group on Carbon Peaking and Carbon Neutrality and the existing Leading Group on Climate Change, Energy Conservation and Emission Reduction, together constitute China's top-level institutional design to address climate change. Since the 1st Plenary Meeting of the Leading Group on Carbon Peaking and Carbon Neutrality in May 2021, all levels government authorities in China have focused on developing the timetables and roadmaps for carbon peaking and carbon neutrality, and prepared action plans for carbon peaking by 2030, as well as implementation plans by sectors and industries, forming the "1+N" policy system. The "1" under the "1+N" policy system refers to the "Working Guidance" issued on October 24, 2021, which has specified three milestones for 2025, 2030 and 2060, and will play a programmatic role in guiding and coordinating related work. On October 26, the State Council issued the "Action Plan for Carbon Dioxide Peaking Before 2030" (hereinafter referred to as "Action Plan") [6], which, as the first document in the "N" series policies, will play a general and overarching role for the more than 30 "N" series policies planned for the future. The Action Plan focuses on how to achieve carbon peaking by 2030, and makes general arrangements for promoting carbon peaking in two phases, i.e. 2025 and 2030. The Action Plan elaborates the specific work and issues for achieving carbon peaking, and proposes "ten actions to achieve carbon peaking", specifically including green and low-carbon energy transition; energy saving, carbon emission mitigation and efficiency improvement; peaking carbon dioxide emissions in industry sector; peaking carbon dioxide emissions in urban-rural development area; promoting green and low-carbon transportation; promoting circular economy in carbon mitigation purpose; advancing green and low-carbon technology innovation; consolidating and enhancing carbon sink; green and low-carbon society; and promoting all regions to peak carbon dioxide emissions hierarchically and orderly.

The two key documents of the "1+N" policy system for carbon peaking and carbon neutrality and NDCs targets were released and updated on the eve of COP26, demonstrating China's ambition to promote domestic and international climate governance. The carbon peaking and carbon neutrality targets will not only effectively promote energy structuring and adapt to the inherent requirements for high-quality sustainable socio-economic development in the new era, but also represent China's solemn commitment to actively participate in and lead global climate governance, contributing China's efforts and wisdom to global response to climate change and SDGs.

Achieving carbon neutrality will require strenuous efforts to achieve dramatic transformation of energy and economic systems, with far-reaching implications for China's development path in the near to medium and long term. These implications are two-way, complex and dynamic: the early retirement of high-carbon infrastructure and the introduction of carbon constraints will undoubtedly affect factor prices and have an impact on China's short-term growth; but through a systematic transition to carbon neutrality, China's economy will become more resilient and boost greater potential for the development in the medium to long term. Most existing literatures take GDP as an indicator to evaluate the macro impact of emission mitigation on economic development. In general, most studies based on CGE models with GDP as an endogenous variable suggest that emission mitigation will have a negative impact on GDP. This is mainly attributed to the interactions of the following two mechanisms [7]: 1) as emission mitigation introducing emission constraints and carbon price, the price of carbon-intensive products and services will consequently rise, which in turn raises the factor costs for business and the costs of final services for households; 2) emission mitigation requires additional new investments which will crowd out investments or consumption in other sectors. However, studies based on Keynesian models [8] also show that increased public investment in emission mitigation actions actually raises GDP. The main limitation of existing studies is that most assessment models capture the direct link between emission mitigation and GDP, but typically fail to capture the indirect link, such as the economic benefits from improved air quality, and the economic benefits from avoided climate losses, which is of particular interest in this report. A systematic assessment on these benefits facilitates a more comprehensive understanding of the importance and urgency of carbon neutrality from both cost and benefit perspective.

As the Stern Report [9] released 15 years ago indicates, the costs of inaction to climate change are likely to be far greater than that of emission mitigation. While the term "business-as-usual" (BaU) is used to describe the baseline scenario of not tackling climate change, it should be aware that the climate system will not actually operate as business-as-usual. Under the BaU scenario, the climate system and its risks will change dramatically and irreversibly. This report will focus on assessing China's climate losses under different future scenarios, as well as climate losses that could be avoided through China's carbon neutrality target. This report concludes that by working together with the rest world to achieve carbon neutrality, China can largely avoid the negative impacts of climate change, and mitigate the economic losses and impacts brought by climate change in terms of increased energy consumption, declined crop yield, lower productivity and higher sea level rise. In other words, these avoided climate losses should be considered as economic benefits from emission mitigation actions. These huge potential economic benefits are an important reason for China to take aggressive actions to reduce emissions and achieve carbon neutrality.

II. DIRECT ECONOMIC LOSSES FROM CLIMATE DISASTERS IN CHINA

Research in climate science has confirmed that GHG emissions lead to higher GHG concentrations in the atmosphere, resulting in higher climate forcing [10] and higher average surface temperatures. Changes in the Earth's energy budget significantly affect the global water cycle and precipitation patterns, leading to increased frequency and intensity of extreme weather events, such as heavy precipitation, floods, droughts and heat waves. A WMO study [11] shows that the intensity and frequency of extreme weather is globally on the rise due to the impacts of climate change. In the past 5 decades, the number of weather-related disasters has increased fivefold. Although the number of deaths from weather-related disasters has decreased approximately threefold due to improvements in early warning systems and disaster management, more than 11,000 climate disasters occurred in the past 5 decades, resulting in more than 2 million deaths and economic losses up to $3.64 trillion. Droughts, storms, floods and extreme temperatures are the top culprits. Under future climate change conditions, the frequency and intensity of these extreme weather events will further intensify. The recently released IPCC Sixth Assessment Working Group I Report suggests that changes in the climate system are directly linked to global warming in the future. The frequency and intensity of extreme events will intensify in the future, including heat waves, heavy precipitation, droughts, tropical cyclones, and further reductions in Arctic sea ice, snow cover, and permafrost. Meanwhile, studies on climate change in China indicate that the temperature rise in China is significantly higher than the global average. Since 1960, the average temperature in China has risen at a rate of 0.27°C per decade, higher than the global level during the same period [12]. An analysis in China shows that annual direct economic losses from weather-related disasters have exceeded $50 billion over the past decade, representing about 0.4% of China's annual GDP (Fig. 1). Along with increasing severity of climate change , the intensity, frequency and impact of weather-related disasters will further intensify, posing systemic risks to the long-term stable economic development in China.

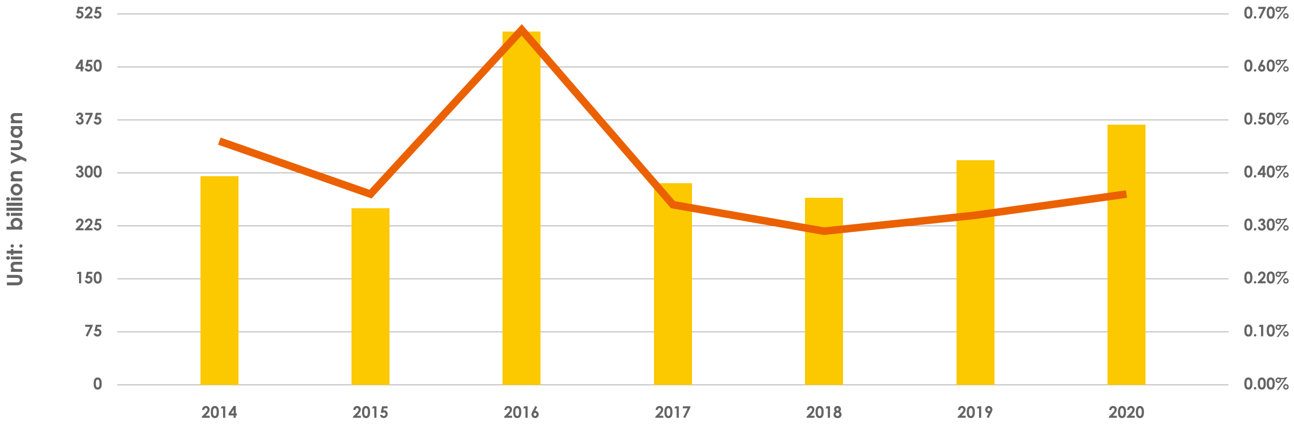


Fig.1 Climate Disasters-related Direct Losses and GDP % in China (2014-2020)

Note: Data on climate disasters-related direct losses are from the China Climate Bulletin, and GDP % is estimated by authors.

However, the above statistics on climate disasters cannot depict the full picture of climate change losses. This is due to several reasons: first, climate hazards are recorded based on extreme weather events that are considered as "disasters", such as floods, droughts, and wildfires, while slow onset events such as sea level rise and biodiversity loss are not taken into account; second, climate disasters usually only count direct property losses and human losses, and exclude secondary economic impacts, such as income and livelihood losses due to the cessation of industrial and commercial activities in the affected areas as a result of flooding. These direct and indirect economic losses from slow onset climate events may far exceed the direct losses in current climate disaster statistics. For example, a study in the Lancet [13] estimates that global working hours lost in 2019 due to heat events (i.e., 300 billion hours), is half of that caused by COVID-19 (Fig.2). In 2019, heat events caused approximately 28.3 billion working hours lost in China, 40% of that resulting from COVID-19. Therefore, the impact of climate change is estimated to be equivalent to being hit by COVID-19 every 2-3 years from the perspective of working hours lost alone. In the next section, this report will analyse the key impacts that climate change is likely to have on the Chinese economy in the future.

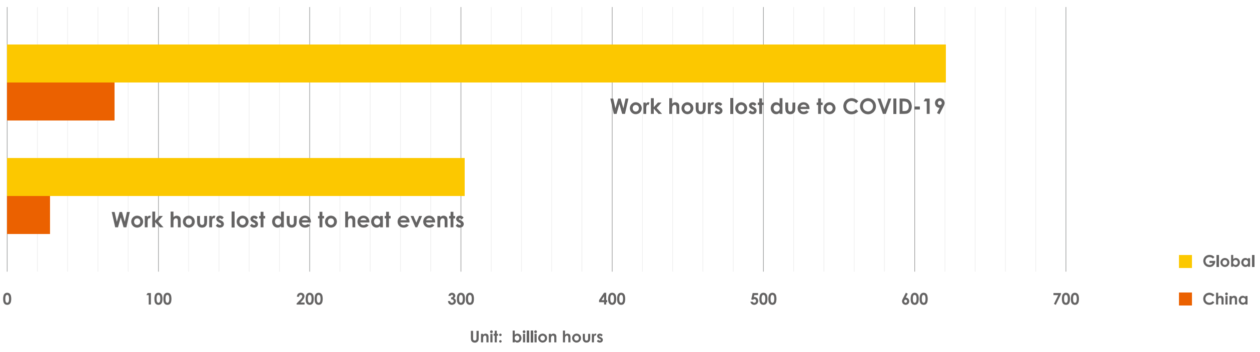


Fig.2 Comparison of Work Hours Lost due to Heat Events and COVID-19: China versus Global

III. FUTURE CLIMATE CHANGE LOSSES

Global climate change will alter global and regional climate characteristics, especially increasing the frequency and intensity of extreme weather events, such as increased extreme heat events, increased frequency of droughts and floods, and accelerated sea level rise. These changes in regional climate characteristics may alter ecosystems, thus causing other indirect effects such as biodiversity loss, increased risk of extinction, and degradation of forests and high-latitude tundra[14]. As ecosystems provide various services to human society, the impacts of climate change on ecosystems will also spill over to human socio-economic systems. For example, the loss of fish stocks in the ocean due to climate change will further reduce the productivity of fisheries and aquaculture[15]. In addition to these above, climate change will also have significant direct impacts on human society. As global warming intensifies, climate change may cause crop yield reductions, thus threatening food security. In the meantime, climate change will also lead to increased incidence of some diseases, increased demand for refrigeration, and inundation of coastal land and assets, all of which will impact the functioning of socio-economic systems[16,17]. The following sections will introduce different types of climate change impacts.

Impacts of climate change on energy systems

The impacts of climate change on energy systems involves different aspects, including the demand and supply of energy [18]. On the energy demand side, changes in average temperatures and its distribution due to climate change may alter energy use patterns and significantly affect heating and cooling demand. On the energy supply side, climate change may alter the cooling water temperature of thermal and nuclear power generating units, thus affecting the efficiency of the generating units. Renewable energy sources, including hydropower, solar power and wind power, will also be affected by changes in precipitation, temperature, wind speed and solar radiation as a result of climate change[19-21]. Also, climate change and extreme weather events may affect transmission and distribution infrastructure or transmission capacity, thus impairing energy system reliability [22].

In terms of energy demand, existing studies generally agree that climate change will lead to increased cooling demand and decreased heating demand in the future, but disagreement sitting on the extent of the impacts. Some studies argue that these two impacts can offset each other, and thus at the global level, the impacts of climate change on total energy demand can be negligible. For example, a recent study examined the relationship between temperature change and energy demand using econometric methods, and found that while countries in the tropics will experience a significant increase in power consumption due to climate change, it however will be offset by the reduced heating demand in countries in the temperate and boreal regions. Therefore, future climate change will have small impacts on total energy demand [23]. On the other side, there are also findings that climate change will cause rapid growth in energy demand if changes in energy demand in non-residential sectors and the amplification effect of air conditioning penetration are taken into account [18]. After simultaneously considering climate change-induced changes in energy demand in agricultural, industrial, commercial and residential sectors, findings indicate that global climate-influenced energy demand would increase by 25-58% around 2050 under the RCP8.5 scenario, while global energy demand would rise by 11-27% in 2050 under the RCP4.5 scenario[24]. While existing studies agree that reduced heating demand may offset increased cooling demand to varying degrees, almost all studies suggest that future global power demand will be driven by climate change[18] as heating is typically provided by oil or gas boilers while cooling relies primarily on electricity. Similar to the global situation, the conclusions of different studies on the extent to which China's energy demand is affected by climate change vary greatly. Several studies have concluded that domestic power demand would increase by 58.6% from 2021 to 2050 under the RCP4.5 scenario[25]. Other studies, on the other hand, have concluded climate change-induced changes in China's power consumption account for 1.0%, 3.53%, and 8.53% of 2017 power consumption by 2100 under the RCP2.6, 4.5, and 8.5 scenarios, respectively[26]. The differences between these studies reflect the fact that the extent of climate change impacts on energy demand is still controversial and the findings are highly uncertain.

From energy supply perspective, the impacts of climate change are mainly reflected in those on power generation efficiency and on renewable resources such as wind, solar and hydro power. Both thermal and nuclear power plants generate power by heating water into steam and driving turbines. A large amount of waste heat will be generated during the thermal cycle, which generally requires cooling water to conduct the heat. Existing studies have found that for every 1°C increase in cooling water temperature, the output power of thermal and nuclear power plants would decrease by 0.32% - 1%[27,28]. Climate change-induced changes in river runoff may also affect the use of cooling water, thus impairing the efficiency of power generation. In contrast to thermal and nuclear power, gas-fired power generation requires little cooling water and its output is mainly influenced by the dry bulb temperature of the ambient air. Increased ambient air temperature would decrease air density, resulting in reduced air mass flow through the gas turbines.

For renewable energy generation such as wind, solar and hydro power, climate change may alter wind speed, light, water distribution, etc., thus affecting renewable energy generating capacity. Early studies suggest that the available hydropower capacity in China would be reduced when considering climate change [30]. However, recent studies argue that due to the climate change, China's hydropower generating capacity would increase by 3.16 - 21.93% by 2100 compared to 2011 due to increased runoff [31]. Climate change may also alter the global distribution of temperature differences, thus affecting wind power generating capacity. Existing studies have found that in the context of global warming, with warming Arctic and land, decreased temperature difference between high and low latitudes in the northern hemisphere, and between land and sea, as well as weakened wind energy in the northern hemisphere, global wind energy resources are expected to shift southward [32]. Consequently, wind power resources will be reduced in most areas of China [33]. With regard to the impacts on PV power generation, studies have generally concluded that climate change has non-significant or small positive or negative impacts on regional solar power generation [18,33]. In addition, clouds and their distribution are also important factors affecting PV power generation. In addition to generation resources and efficiency, climate change will also affect energy supply by influencing energy transportation, especially the stable operation of transmission and distribution systems. In general, climate change has different impacts on both energy supply and demand, but has more prominent impacts on air conditioning power demand, which will not only cause additional growth in power demand, but also have significant impacts on future loads and peak loads of power systems.

Impacts of climate change on labour productivity

Increasing hot weather caused by climate change will make the working environment, especially the outdoor working environment, harsh, thus impairing labour productivity. As labour productivity directly links to economic output and national income, assessing the impacts of climate change on labour productivity is essential to quantifying climate losses. Many studies have shown that climate change-caused occupational heat exposure may have significant negative impacts on labour productivity globally, varying with temperature, humidity, and work intensity, etc. [35-38]. In order to quantify the impacts of these factors on labour productivity, existing studies usually consider Wet Bulb Globe Temperature (WBGT) as the main determinant of labour productivity, a parameter that combines various climatic conditions such as air temperature and humidity [38].

Existing studies indicate that labour productivity will decrease rapidly upon a certain threshold of WBGT is exceeded, and the sensitivity to WBGT varies with work intensity. It is generally accepted that industries with high outdoor exposure, such as agriculture and construction, are more vulnerable to the negative impacts of climate change, while work types such as indoor and outdoor shady operations are relatively less affected by heat exposure [38]. Dasgupta et al. found that global effective labour force indoors or outdoors in the shade would decrease by 18.3% under the 3.0°C scenario, with Africa being the most negatively affected with a 25.9% decrease in effective labour force. In the contrast, the negative impacts of climate change on labour productivity increase significantly under high exposure working conditions and the 3.0°C scenario, with the effective labour force in Africa expected to decrease by 32.8% on average [39]. Knittel et al. also found that by 2050, the average annual labour productivity of highly exposed jobs in Southeast Asia and the Middle East would decline by 31% under the RCP4.5 scenario and by 38% under the RCP8.5 scenario [40].

Reduced labour productivity will lead to declined economic output. After investigating the findings of different studies, one analysis suggested that global economic losses due to heat-related labour productivity changes would range from 0.31% (0.14-0.5%, RCP2.6 scenario) to 2.6% (1.4-4%, RCP8.5 scenario) of global GDP by 2100, after taking adaptation measures into account, with economic losses from reduced productivity occurring mainly in South and Southeast Asia, Sub-Saharan Africa, and Central America [36]. Climate losses will further increase if adaptation measures are not taken into account.

Impacts of climate change on agriculture

The impacts of climate change on the agricultural sector are profound and complex. Climate change may alter the climatic conditions required for crop growth, thus affecting the yields of major agroforestry crops [41,42]. Climate change-induced temperature changes are an important factor affecting agricultural output. Since different crops have optimal temperatures for the growth, climate change-induced temperature rise may increase crop yields if local temperature is lower than the optimal temperature. Conversely, if the current temperature is higher than the optimal temperature, then climate change may further result in decreased crop yields [42]. Similar to temperature, changes in precipitation conditions may also cause differential impacts on different crop types. In addition, extreme weather events such as floods and droughts may cause catastrophic effects on crop growth and thus significantly reduce agricultural output [43]. In addition to the negative impacts of climate change, laboratory studies have shown that elevated CO_2 concentrations accompanying climate change have a fertilizing effect on crop growth and thus may generate positive impacts on the agricultural sector [44]. However, recent studies suggest that the fertilizing effect of CO_2 would decline rapidly due to the limitation of other nutrients.

A large number of studies have been conducted to analyse the impacts of climate change on crop yields which can be generally classified into two categories. One is to functionally simulate the effects of climate and ecological factors such as temperature, precipitation, CO_2 concentration, and soil conditions on crop yields using process-based agricultural models. Currently, the Agricultural Model Intercomparison and Improvement Project (AgMIP) coordinates multiple process-based agricultural models to analyse the impacts of weather parameters on crop yields at the site level [45]. Process-based agricultural model simulations are with finer resolution and allow cross-model comparisons, but they have high requirements for both computational resources and expertise, and thus are difficult to apply. In addition to process-based agricultural models, statistical models are also important tools for studying how climate change affects agricultural output. Statistical models are mainly based on historical observations, and regression analysis is performed to estimate the effects of climate parameters such as temperature and precipitation on crop yields in a given country or region [46]. Compared to process-based agricultural models, statistical modelling is relatively simple, but limited data availability makes site-level analysis impossible. Moreover, as climate change is likely to cause future climate conditions beyond the range of historical observations, statistical models are relatively weak at predicting out-of-sample scenarios.

Almost all process-based agricultural modelling and statistical modelling studies suggest that climate change will seriously threaten future global agricultural yields. A recent study analysed the impacts of climate change on yields of major crops based on the latest version of agricultural process model, and found that global yields of corn, soybeans and rice under the SSP5-RCP85 scenario would all be negatively affected by climate change by the end of the century, with corn yields declining by about 24% [47]. Other studies using process models have also confirmed the negative impacts of climate change on agricultural yields. For example, a study based on five process models in AgMIP analysed the impacts of climate change on crop yields, and found that global average agricultural yields would be declined by 17% by 2050 under the RCP85 scenario [48]. Econometric-based statistical models yield consistent results, and analysis of panel datasets of global gridded annual crop yields based on dynamic econometric models suggests that climate change may reduce global crop yields by 3-12% by mid-century and by 11-25% by the end of the century [49].

Impacts of climate change on sea level rise

Climate change will lead to sea level rise and significantly affect socio-ecological systems in coastal areas and island nations. According to IPCC AR6, global mean sea level (GMSL) has risen at an unprecedented rate by about 20 cm since 1901 [50]. Due to high uncertainties in the prediction of sea level rise, some studies have also made predictions of future GMSL rise based on expert survey data, and the findings show that GMSL is likely to rise by 0.30-0.65 m by 2100 and 0.54-2.15 m by 2300 under the RCP 2.6 scenario; while likely to rise by 0.63-1.32 m by 2100 and 1.67-5.61 m by 2300 [51] under the RCP 8.5 scenario. The impacts of sea level rise are mainly reflected in the harm caused to coastal areas, including inundation and flooding at low latitudes, wetland erosion, ecosystem destruction, inundation damages to industrial and agricultural land and fixed assets, and migration of population from coastal areas to inland.

To assess the vulnerability of coastal areas to sea level rise, many factors shall be taken into account, including identifying the populations affected by sea level rise, assessing the losses of land, wetlands, and assets due to sea level rise, and analysing potential adaptation and protection costs (e.g., construction of dikes). Global or national level sea level rise impact assessments rely on large amounts of high-precision geographic information data and socio-economic data for modelling. These models can assess the biophysical and socioeconomic consequences of sea level rise and socioeconomic development along various coastline segments, including coastal erosion, coastal flooding, and wetland changes, etc.

From a socioeconomic point of view, sea level rise may cause huge economic losses in the future. An analysis using the DIVA model showed that sea level rise would cause significant economic impacts. Compared to the 1.5°C target, global economic losses under the 2.0°C scenario would increase by about $1.4 trillion per year. Under the RCP 8.5 scenario, global annual flooding losses may account for 2.8% of global GDP in 2100 [54]. Without adaptation measures, 0.2-4.6% of the world's inhabited areas are projected to be inundated by 2100 in the event of a GMSL rise of 25-123 cm, representing an annual loss of 0.3-9.3% of global GDP [55]. If dikes were used to protect the coast, the annual investment and maintenance cost in 2100 would be $12-$71 billion, far less than the economic losses without adaptation.

Impacts of climate change on human health

Climate change will affect human health in many ways. Changes in climate factors may cause increased morbidity and mortality of some diseases. Some health threats that have not occurred previously may emerge in some regions as a result of climate change, as temperature changes alter the distribution of infectious vectors. The main climate impacts on human health in existing studies include extreme heat-related deaths, extreme event disasters, increased incidence of infectious diseases, and malnutrition caused by food shortages [56-59].

Extreme weather events pose a major threat to human health. Increased extreme heat will result in increased heat-related illness or deaths due to cardiovascular and respiratory complications, kidney failure, electrolyte imbalance, fatal miscarriage and premature birth, etc. [60]. An analysis using empirical data from 43 countries showed that 37.0% of warm season heat-related deaths during 1991-2018 were attributable to climate change triggered by anthropogenic emissions [61]. A global survey of nearly 15,000 extreme weather events over a 20-year period from 1993 to 2012 found that these events caused more than 530,000 deaths, and the resulting economic losses exceed $2.5 trillion [58].

Many regional and local studies have found that rising temperatures contribute to the spread of many infectious diseases among people. An analysis of monthly malaria cases in the Colombia and Ethiopian Highlands showed a shift in the distribution of malaria to higher altitudes in warmer years [62]. Moreover, declined crops yield as a result of climate change may further contribute to problems such as malnutrition. Under the high emission scenario, food shortages would intensify, resulting in more severe malnutrition and even famine [57]. Finally, the impacts of climate change on health are also closely related to economic income, community environment, and government management. In general, residents in low-income countries are more vulnerable to climate change-induced health threats due to poor health services and weak government governance [63].

Other impacts of climate change

In addition to the areas mentioned above, climate change may also affect tourism, biodiversity and many other aspects. Climate change will alter tourism resources in different regions by shaping ecological environment and thus affect tourism revenues. An analysis of how tourism is affected by climate change in different regions of the world, using the Hamburg Tourism Model, showed that tourism revenues in current warmer countries would decrease significantly due to climate change, while those in colder countries would increase [64]. In addition to tourism resources, the impacts of climate change on biodiversity are significant. A study using annual temperature and precipitation data from 1850 to 2100 to predict the exposure times of more than 30,000 marine and terrestrial species under potentially hazardous climate conditions finds that under the 2°C scenario, less than 2% of the world's biological clusters would experience abrupt exposure events involving more than 20% of their constituent species; however, the risk of exposure will accelerate with global warming, with 15% of the world's biological clusters at risk under the 4°C scenario [65]. Moreover, the impacts of climate change on the distribution of water resources, passive population migration, and the destruction of historical sites cannot be ignored.

IV. LINKING CLIMATE CHANGE TO ECONOMIC LOSSES

In order to estimate the climate losses in China under different future climate change scenarios, it is needed at the first instance to convert the changes in climate variables into effects on economic variables which is called as constructing the climate damage functions. Then the economic variables affected by climate variables are inputted into economic models to simulate the systemic economic impacts and losses resulting from climate change.

The climate damage function is an important tool for quantifying climate losses, which establishes a functional relationship between climate variables and economic variables. The climate damage functions can be divided into direct damage functions and indirect damage functions. The two damage functions both take climate response parameters as independent variables, such as temperature and precipitation change [74], but the dependent variables differ. The direct damage functions converts climate response parameters directly into GDP losses or welfare losses [74,75] and it is commonly used in integrated assessment models. Unlike the direct damage functions, the indirect damage functions convert climate response parameters into changes in economic factors or variables [76], for example, loss of land and capital due to sea level rise, or reduced labour productivity due to extreme heat. Such damage functions are unable to directly provide quantitative results of climate losses, but can be applied in models like computable general equilibrium models to assess the economic impacts of climate change in different sectors, and further examine the interactions of climate impacts among different sectors.

To assess the impacts of carbon neutrality target on climate losses in key sectors in China, an assessment framework coupling energy economic model and earth system model is constructed in this study (Fig. 3). Under this framework, the climate damage functions is used to connect the climate system to socioeconomic systems [76-78]. In this case, the climate system outputs the main climate variables driven by GHG emissions, while the damage functions module can convert climate change into economic variables through a series of damage functions. The China-in-Global Energy Model (C-GEM) is a computable general equilibrium model, which can simulate the flow of goods and factors in the market and assess how changes in economic variables due to climate change affect the whole economic system.

For climate variables, we have employed the CanESM5 model and the IPSL-CM6A-LR model from CMIP6 to obtain global gridded temperature, precipitation, and humidity data under the RCP1.9, RCP4.5, and RCP7.0 scenarios. We need to process the climate variables derived through the climate damage assessment module. To this end, an extensive literature research was conducted and assessment methods for different types of climate impacts were established (see Appendix). The study has mainly examined economic impacts of climate change on energy systems, labour productivity, agricultural yields, and sea level rise. Agricultural losses are currently a major part of direct loss statistics of climate disasters, while energy systems, labour productivity and sea level rise are slow-onset events and are not included in the current climate disaster loss statistics. The health impacts of climate change was not included in this study due to unavailability of relevant comprehensive data on the one hand, and the analytical models currently applied are yet able to process the impacts of health on economic development on the other. However, existing studies have shown that the health impacts of climate change could be an important component of climate damage.

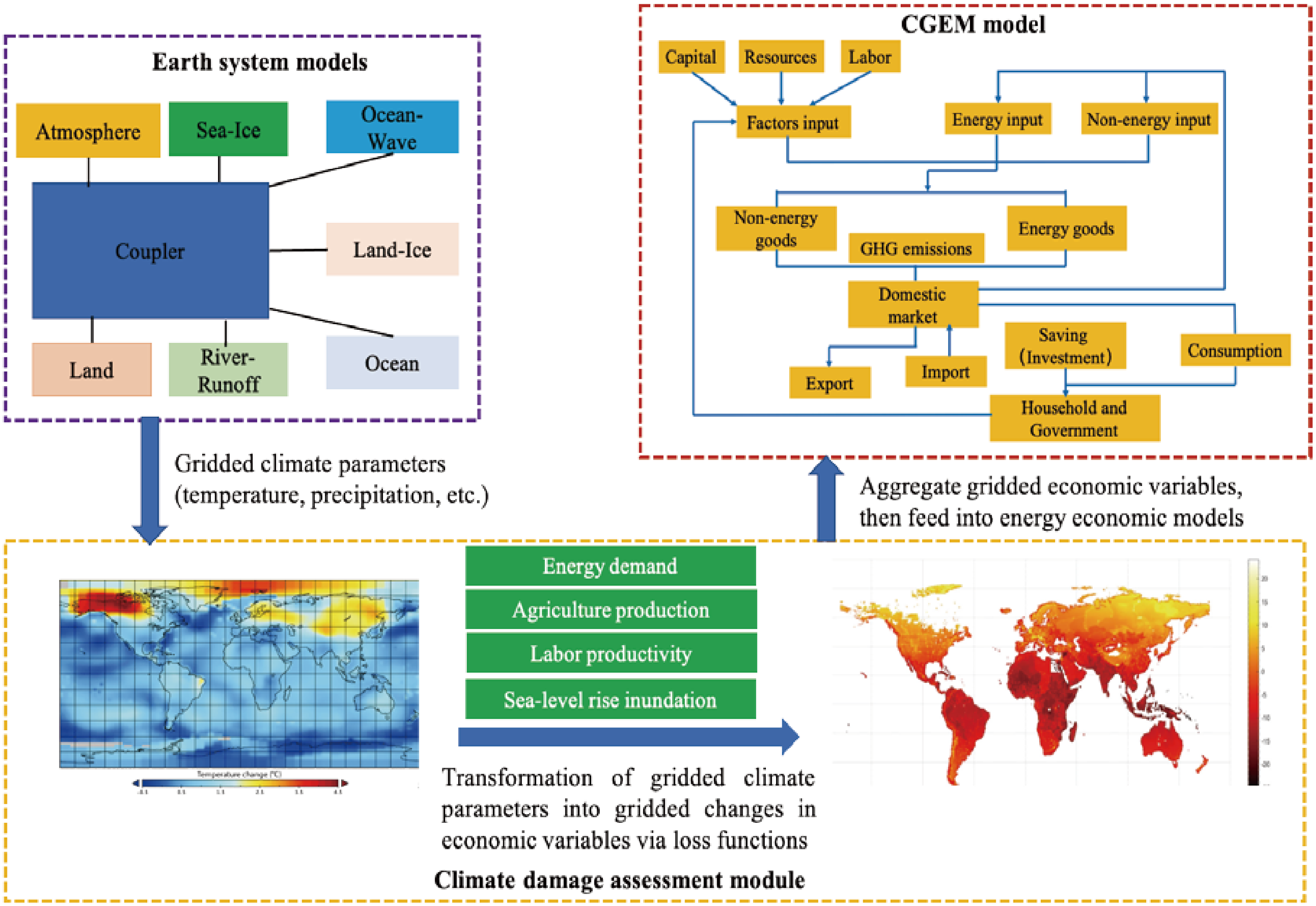


Fig.3 Assessment Framework Coupling Energy Economic Model and Earth System Model

V. FUTURE EMISSION PATHWAYS AND CLIMATE SCENARIOS

To assess the economic losses caused by climate change in China under different climate policy intensities, the baseline scenario, the NDC scenario, and the carbon neutrality scenario were developed respectively (Fig.4). Under the baseline scenario, countries around the world would "freeze" rather than enhance their existing climate mitigation policies. Under this scenario, total anthropogenic-related CO_2 emissions will increase from 36 Gt now to 75 Gt by the end of the century. We have adopted the RCP 7.0 pathway from the IPCC scenario dataset to represent the baseline scenario, which corresponds to a radiative forcing of 7.0 W/m^2 in 2100. The NDC scenario assumes that all countries or regions meet their NDC commitments by 2030. Beyond 2030, it is assumed that each country's carbon intensity will further decline at the rate required to achieve the NDC targets, with a lower bound of 2% set for all countries or regions beyond 2030. Compared to the baseline scenario, total CO_2 emissions under the NDC scenario would first stabilize at current levels and begin to decline rapidly around 2060. Total global CO_2 emissions under the NDC scenario would register about 15 Gt by 2100, less than half of current levels. The study has adopted the RCP 4.5 pathway from the IPCC scenario dataset to represent the NDC scenario, where the radiative forcing is about 4.5 W/m^2.

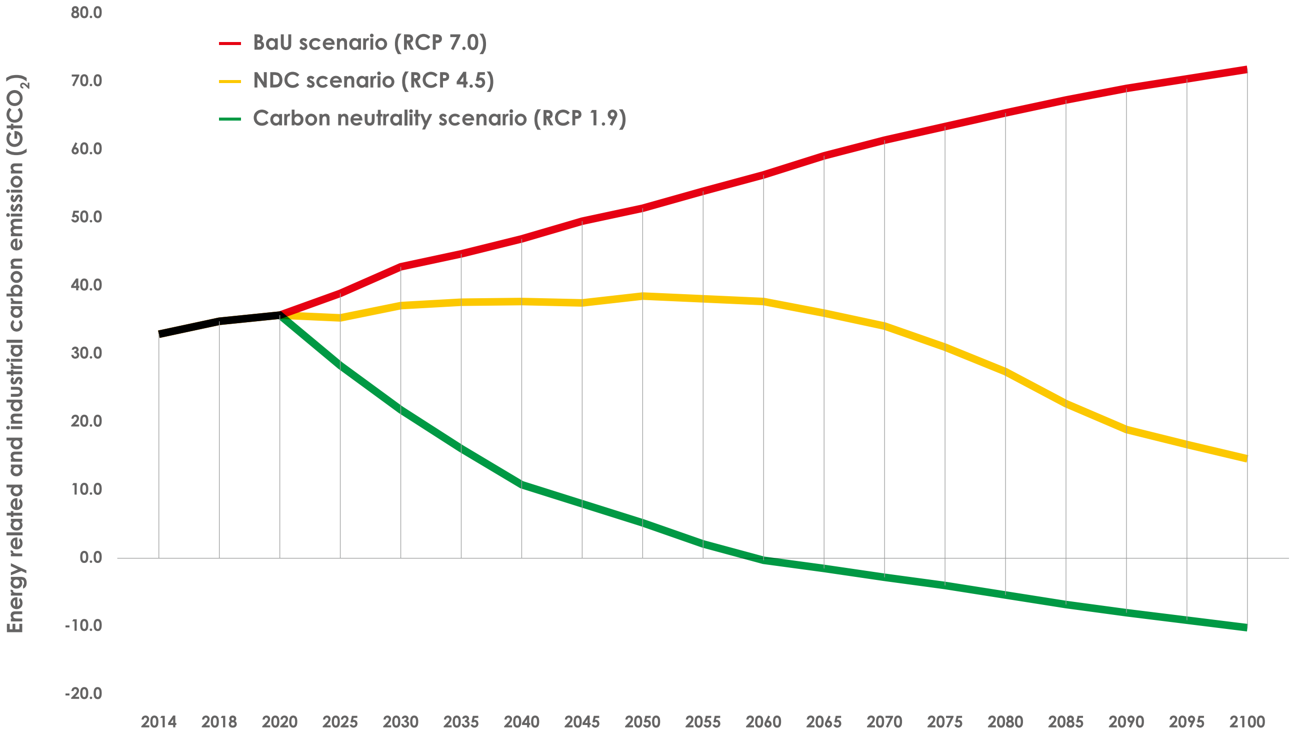


Fig.4 Global Emission Pathways under Different Scenarios ($GtCO_2$)

The carbon neutrality scenario refers to the GHG emission pathway that limits the global mean temperature rise level to about 1.5 °C by the end of the century. In order to achieve this target, global total CO_2 emission levels shall reach zero around 2060 and turn negative thereafter. Under the carbon neutrality scenario, global CO_2 emissions would register about -10 Gt by 2100, with a radiative forcing of 1.9 W/m^2. In this case, the realization of negative emissions relies on the deployment of technologies such as Biomass Energy with Carbon Capture and Storage (BECCS) and Direct Air Carbon Capture and Storage (DACCS).

GHG emission levels under different scenarios directly affect the magnitude of future global temperature rise. Fig. 5 represents the trends in global mean temperature rise assessed by the Earth System Model under the baseline scenario, NDC scenario, and carbon neutrality scenario. The simulation results show that the global mean temperature rise by 2050 under the three scenarios is relatively similar. The baseline scenario has seen the highest global temperature rise of about 2.6 °C by 2050, compared with 2.2 °C for the NDC scenario and 2.1 °C for the carbon neutrality scenario. Beyond 2050, the global mean temperature rise under the three scenarios starts to vary greatly, with the global mean temperature rise under both the baseline and NDC scenarios showing an increasing trend, while that under the carbon neutrality scenario starting to decline. By 2100, the global mean temperature rise under the baseline scenario, NDC scenario and carbon neutrality scenario registers 5.2 °C, 3.5 °C and 1.6 °C, respectively.

There are geographical differences in the degree of global warming caused by climate change. As shown in Fig. 5, the simulation results under the baseline scenario, NDC scenario and carbon neutrality scenario all show that the temperature rise in the northern hemisphere is higher than that in the southern hemisphere as a whole, while the highest temperature rise is found near the Arctic Circle, up to 10 °C or more under the baseline scenario. In addition, major economies such as China, the U.S., and Europe are experiencing higher temperature rise than the global average.

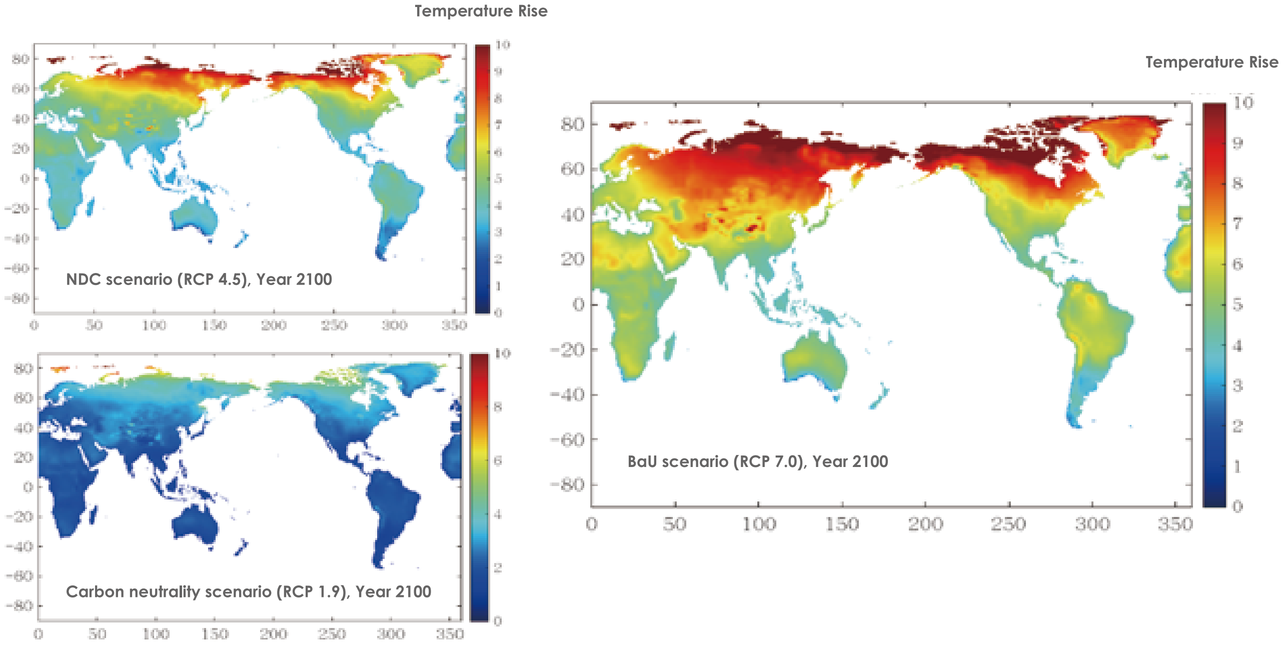


Fig.5 Global Temperature Rise Distribution in 2100 under Different Emission Scenarios

VI. IMPACTS OF CARBON NEUTRALITY TARGET ON CLIMATE LOSSES IN KEY SECTORS IN CHINA

In assessing the impacts of carbon neutrality target on climate losses in key sectors in China, we have mainly examined the impacts of climate change on energy demand, labour productivity, crop yields, and land inundation and property losses due to sea level rise. The following sections will analyse the assessment results by climate loss type.

Impacts of climate change on energy demand

Based on the damage functions construction method described earlier, the study conducted gridded analysis of the extent to which China's energy consumption being affected by climate change (Fig. 6). Under the high emission scenario (RCP7.0), China's energy demand would increase by more than 130% by 2100 due to climate change. By energy type, increasing cooling-related power consumption is the main reason for the expansion of energy demand, especially in the service and household sectors, which would see a significant increase in power consumption due to climate change. The rapid growth in energy demand, especially for power, is mainly attributed to rapidly increasing hot days (greater than 27.5 °C) under the high emission scenario. According to the simulation results of the earth system model, the number of hot days would increase by 50 to 100 days in most areas of China by the end of this century compared to the base year, and even increase by more than 150 days in some areas, greatly increasing the demand for air conditioning and cooling in these areas. Compared to the high emission scenario, China's energy demand would increase by about 90% by the end of the century

under the medium emission scenario (RCP4.5), which is still a high growth rate. Under the carbon neutrality scenario, with global mean temperature rise limited to about 1.5 °C, the number of hot days would be much fewer compared to the high and medium emission scenarios. Cooling-related power demand growth is not significant. The growth rate of China's total energy demand resulting from climate change is maintained at around 20%, well below the high and medium emission scenarios.

The extent to which China's energy demand being affected by climate change is characterized by regional heterogeneity. South and East China will be most affected by climate change, and energy demand in these regions would increase by about twofold by the end of this century due to climate change under the high emission scenario. They are closely followed by Northeast China and parts of Northwest China. Energy demand in Southwest China and parts of North China are relatively less negatively impacted by climate change, with energy demand growth in these regions generally below 50% by the end of the century. In addition, there are areas where energy demand is trending downward as lower heating demand offsets higher cooling demand, especially under the carbon neutrality scenario.

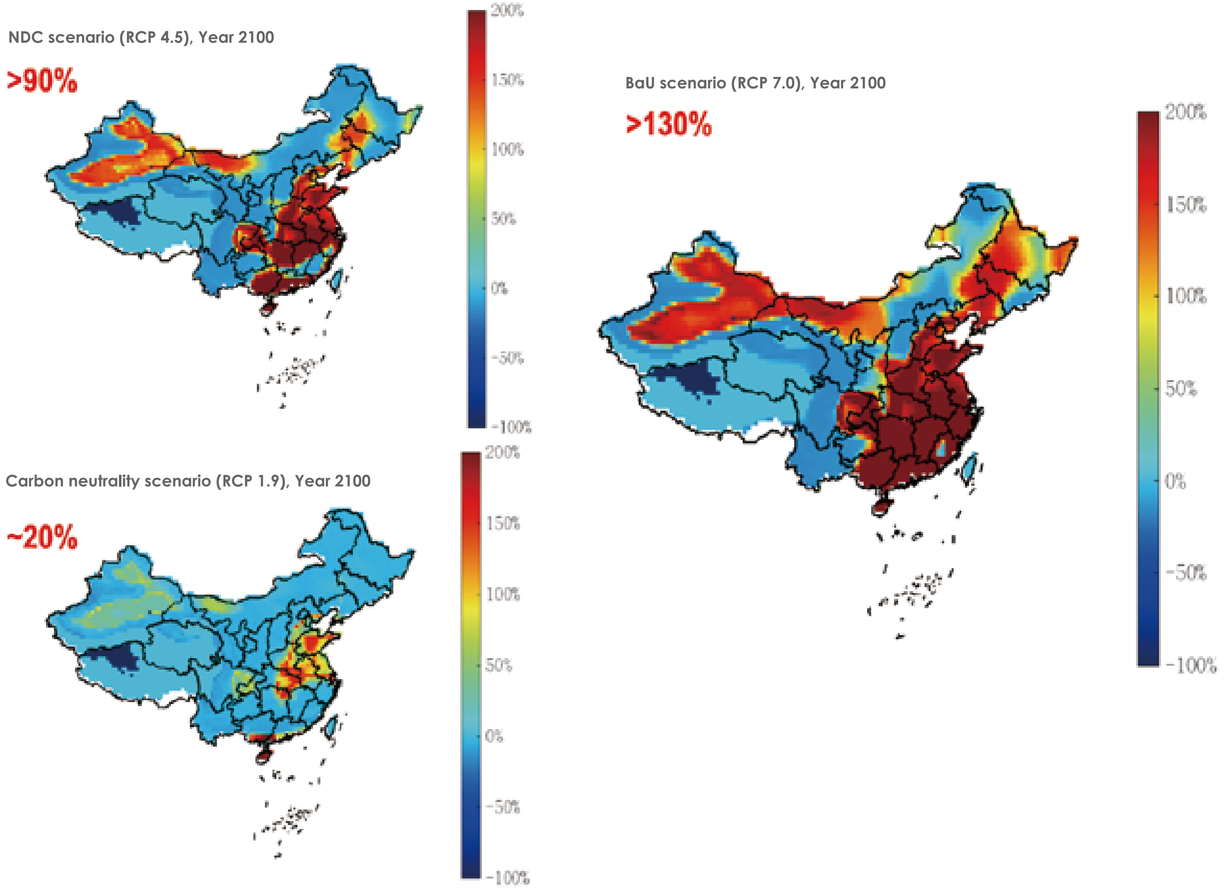
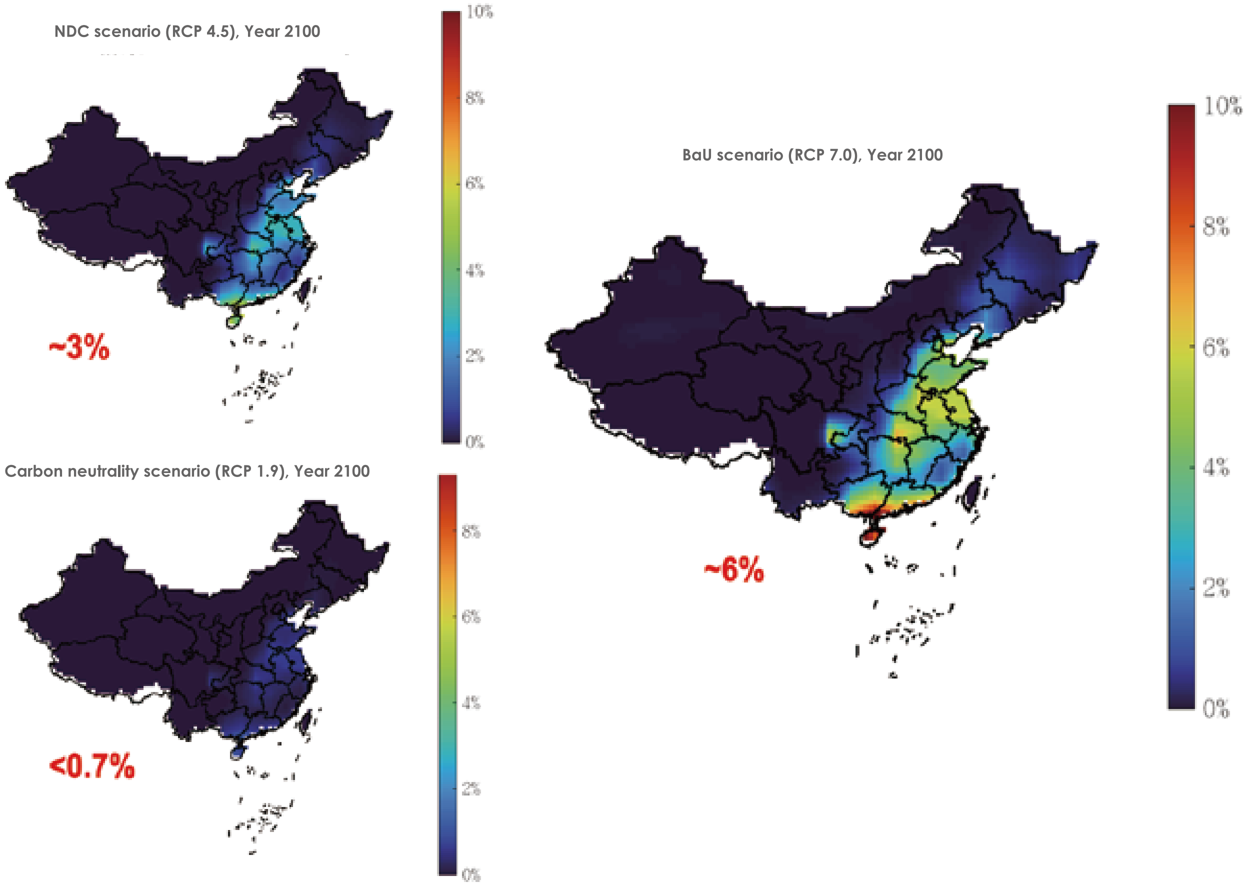


Fig.6 Rate of Change of Total Energy Consumption in China under Different Emission Scenarios (%)

Impacts of climate change on labour productivity

Based on the gridded temperature and humidity data output from the earth system model in CMIP6, we have predicted the future trend of labour productivity in China under different emission scenarios (Fig. 7). Under the high emission scenario, labour productivity declines are most pronounced in East and South China, which could reach 10% in some areas. Because of high population density and economic output in East and South China, significant declines in labour productivity in these regions would have a significant negative impact on China’s overall economy. Labour productivity in the rest of China is relatively less negatively impacted by climate change, with decline rates generally below 3%.

Upon population weighting, the overall labour productivity in China under the high emission scenario declines by about 6% by the end of the century. In contrast, labour productivity declines by less than 4% in all regions of China under the medium emission scenario, and overall labour productivity declines by about 3%, only half of that under the high emission scenario. Under the carbon neutrality scenario, China's labour productivity is relatively less negatively affected by climate change, with overall labour productivity declining by less than 0.7% by the end of the century, well below that under the high and medium emission scenarios. Therefore, a vast majority of climate losses caused by declined labour productivity could be avoided under the carbon neutrality scenario.



NDC scenario (RCP 4.5), Year 2100

~3%

Carbon neutrality scenario (RCP 1.9), Year 2100

<0.7%

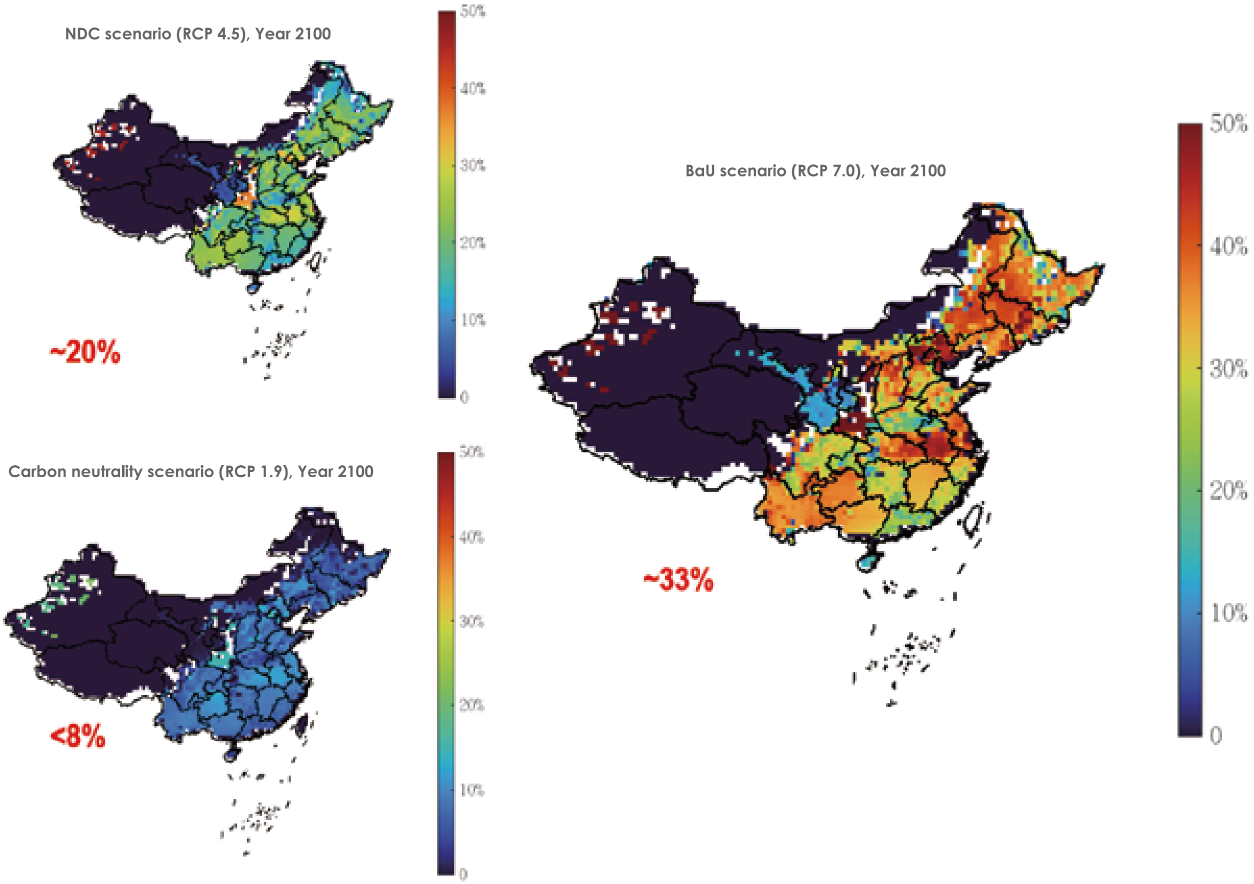
BaU scenario (RCP 7.0), Year 2100

~6%

Fig.7 Rate of Labour Productivity Decline in China under Different Emission Scenarios (%)

Impacts of climate change on agricultural output

In analysing the impacts of climate change on crop yields, we have mainly considered four major crops, i.e. wheat, rice, corn, and soybeans, and distinguished between irrigated and non-irrigated areas. The study has simulated the impacts of climate change on different crops separately using Persephone (see Appendix) and obtained via aggregation the total crop yield change rate (Fig.8). Under the high emission scenario, China's major crop yield declines by about 33%, which could pose a serious threat to future food security. To be specific, the magnitude of grain losses in the eastern region far exceeds that in the western region, covering the major grain-producing areas of Northeast, North and Central China. The negative impacts of climate change on China's grain yield decline from 33% under the high emission scenario to 20% under the medium emission scenario, but the threat to major grain-producing areas remains significant. Finally, climate change contributes only about 8% to China's grain yield declines under the carbon neutrality scenario, much lower than that under the high emission scenario.


NDC scenario (RCP 4.5), Year 2100

BaU scenario (RCP 7.0), Year 2100

Carbon neutrality scenario (RCP 1.9), Year 2100

Fig.8 Rate of Crop Yield Decline in China under Different Emission Scenarios (%)

Impacts of climate change on sea level rise

According to the simulation results of the climate loss assessment module, China's asset losses due to sea-level rise would exceed $6 trillion (constant price in 2011) by the end of this century under the high emission scenario, 19% and 50% higher than that under the NDC and carbon neutrality scenarios, respectively (Fig. 9). With regard to land inundation losses, China will lose a small proportion of its land to rising sea levels, registering only about 0.26% under the high emission scenario. However, considering that the economic level, population density and asset size in coastal areas are much higher than those of inland areas, the economic loss from land inundation is much greater than the loss of the land itself.

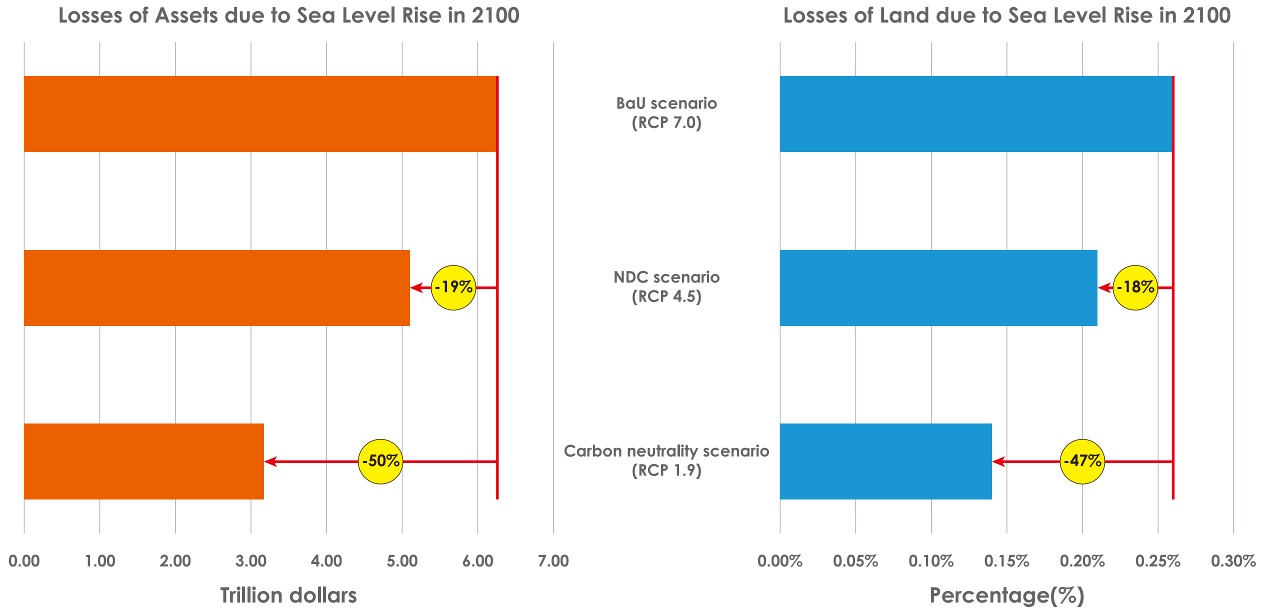


Fig.9 Losses of Assets and Land due to Sea Level Rise in 2100

VII. IMPACTS OF CARBON NEUTRALITY TARGET ON TOTAL ECONOMIC LOSSES

After simulating climate change impacts on future energy demand, crop yield, labour productivity, and land & assets in China using the climate loss assessment module, the study further simulated the total economic losses due to climate change under different emission scenarios using the C-GEM model. As a computable general equilibrium model, the C-GEM model can simulate the transmission of different types of losses caused by climate change between economic sectors. Due to the negative impacts of climate change on the economic system, economic output of China's major economic sectors will decline to varying degrees. Here the model-simulated GDP loss rate is applied as the main indicator of climate loss, and the specific results are shown in Fig. 10.

Under the baseline scenario, global GHG emission levels continue to grow rapidly, and economic losses caused by climate change in China as a share of GDP increase year by year, registering 1.6% in 2030, rising to 4.3% in 2050, and further reaching 8.9% in 2100, corresponding to an absolute economic loss of $ 0.34 trillion, $ 1.6 trillion, and $ 9.7 trillion, suggesting significant negative impacts on the economic system. The NDC scenario could mitigate the negative impacts of climate change on Chinese economy to some extent compared to the high emission scenario. In terms of GDP loss rates, climate losses incurred by 2024 under the NDC scenario are relatively close to those under the baseline scenario, but significantly lower thereafter. By 2100, China's GDP loss rate due to climate change under the NDC scenario is 5.6%, and the amount of GDP loss is reduced by about $3.7 trillion, or 38% compared to the baseline scenario. Under the carbon neutrality scenario, with global mean temperature rise limited to about 1.5 °C, the total economic loss from climate change in China is much lower than that under the baseline and NDC scenarios. By 2100, China's GDP loss rate due to climate change can be controlled at about 0.8%, and the amount of GDP loss is less than $0.8 trillion. Moreover, since global carbon emission levels under the carbon neutrality scenario turn negative after 2060 and corresponding global mean temperature rise starts to decrease, the scale of climate loss in China would also gradually decrease after peaking at a GDP loss rate of about 2% in 2060.

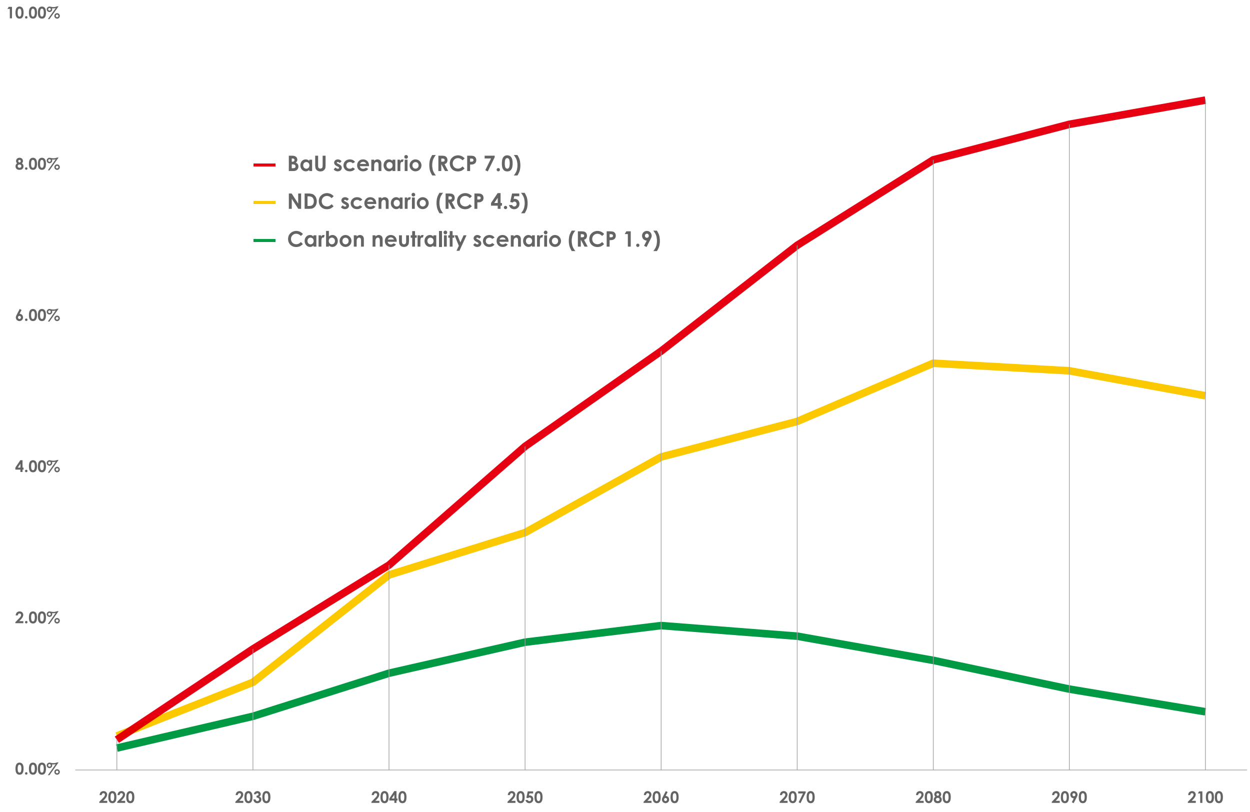


Fig.10 Climate Losses as a Share of China's GDP under Different Scenarios

Since climate change will have long-term impacts on economic systems, Fig. 11 further takes into account the climate change-caused accumulative GDP losses in China (without considering the discount rate). Under the baseline scenario, China's accumulative GDP losses over the period 2021-2050 register $18.5 trillion, slightly higher than the $16.9 trillion under the NDC scenario, and more than twice that under the carbon neutrality scenario. The reason why the NDC scenario is closer to the baseline scenario in terms of accumulative climate losses over the period 2021-2050 is that, main mitigation efforts would come to the fore after 2050, thus economic losses avoided from mitigation are not significant until 2050. Under the baseline scenario, China's accumulative climate losses over the period 2021-2100 register $289.9 trillion, about 53% higher than that under the NDC scenario, and the difference between the two is much larger than the accumulative results over the period 2021-2050. The same is true for the carbon neutrality scenario, where China's accumulative climate losses over the period 2021-2100 register $5.52 billion, a fifth of that under the baseline scenario. Thus, because of the lagging of the climate system, climate losses avoided by recent mitigation actions will only become apparent in the long run. To avoid huge future climate losses, mitigation actions must be deployed in the near to medium term. However, given the costs of mitigation actions shall be borne by the present generation, while the vast majority of avoided climate losses would be realized in the future, intergenerational equity in climate change is of great significance to climate governance. If policymakers focus only on near-term social development goals without factoring in the long-term development and risks to socio- economic systems, there would be less incentive to take enhanced mitigation actions, thus exposing mankind to irreversible climate risks in the future.

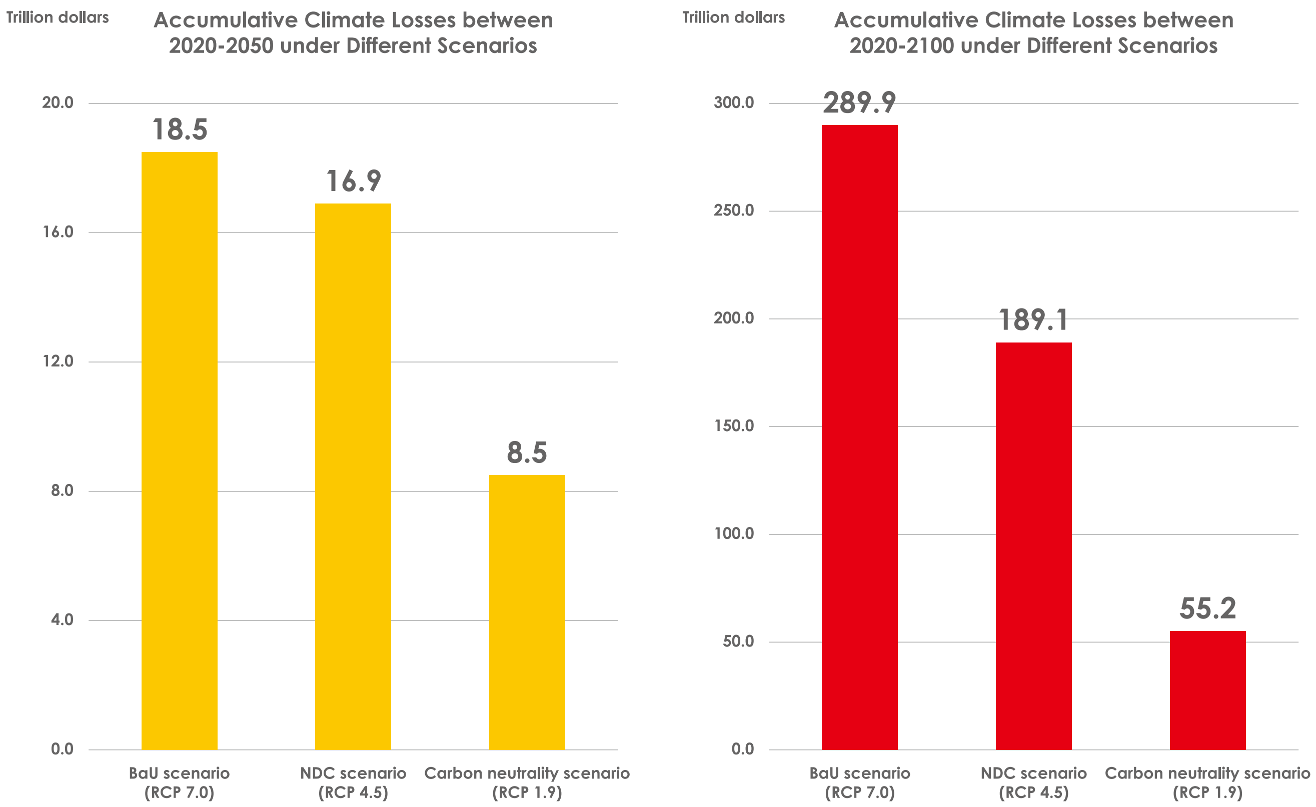


Fig.11 Accumulative Climate Losses in China between 2020-2050 and 2020-2100 under Different Scenarios

By achieving its carbon neutrality target, China could significantly reduce economic losses from climate change and avoid accumulative future climate risks. Note that since we take 2014 as the base year, the estimated climate losses are actually “additional” to those already incurred. As we see in Section 2, the impacts of climate change on socio-economic systems are already occurring as global temperature has already risen by 1.2 °C. These impacts already occurred should be superimposed on our results. In addition, our study doesn’t cover the impacts of climate change on human health due to model and data limitations, whereas existing studies suggest that climate change would significantly affect human health which could possibly dominate estimates of climate losses. Third, the study also excludes estimates of climate losses from climate change catastrophes or “tipping points”. Once these tipping points are reached (e.g., the cessation of the North Atlantic Gyre), small changes in the climate system may trigger large effects that can be catastrophic and irreversible. Fourth, a complex earth system model has been used to derive climate projections and drive economic analysis. The earth system model used does not cover the full range of CMIP6, and therefore does not fully account for the uncertainties of the climate system. Finally, other studies under this project have shown that the indirect risks of climate change are equally important as the systemic risks. Due to the complexity of socio-economic systems, climate change risks may transmit through chains of risks that is failed to perceive currently, and create significant systemic risks across sectors, countries, and systems. Moreover, the transmission mechanisms of systemic risks and risk governance measures are still known very little. Therefore, the assessment of climate change losses is largely indicative of only a lower bound on future climate losses.

VIII. CONCLUSION

China is earnestly implementing its commitment to the "carbon peak and carbon neutrality" targets, and made preparations in institutional arrangements and strategic planning in the past year. However, China faces unprecedented difficulties in transition. The low-carbon transition in developed countries is dominated by the phase-out of existing high-carbon infrastructure, while most of those existing infrastructure has also reached the end of its technical life and entered a natural phase out phase. In contrast, developing countries, represented by China, not only need to achieve a low-carbon transition in their stock infrastructure, but also need to invest massively in new low-carbon infrastructure to meet newly raised energy demand, making the transition far more difficult than that in developed countries. The scale of low-carbon investments towards the carbon neutrality target is enormous, but the necessity is indisputable from a climate risk governnace point of view. The risks of climate change are threatening the outcomes of development, while the complexity and speed being rapidly increasing, and challenging the existing capacity of human societies to mitigate and manage climate risks. Low-carbon investments for carbon neutrality therefore not only represent investments in energy transition and sustainable development, but also a risk management strategy to mitigate climate risks.

The economic losses associated with climate change have already incurred, and are having devastating impacts on work and life. According to the current assessment of direct losses from climate disasters, direct economic losses from climate disasters account for approximately 0.4% of China's GDP in the last decade. However, this statistic excludes indirect losses from climate disasters or economic losses from slow-onset events such as temperature and sea level rise. With further increases in global mean temperature rise in the future, climate change-caused economic losses will also grow increasingly. These climate losses cover at least four aspects: 1) economic losses from extreme weather events,

the main part of concern in the current statistics, which will increase with the frequency and intensity of extreme weather events; 2) climate losses from a range of slow-onset events such as temperature and sea level rise, which are not fully accounted for at present, but will become more prominent over time; 3) potentially catastrophic losses due to breach of the "tipping points". While the scientific understanding of tipping points is inadequate, there is evidence that we are approaching a number of climate tipping points, some of which, once breached, could result in catastrophic consequences; 4) Due to the losses caused by climate cascades, the risk transmission chain and mechanism of these losses have not been fully defined, but existing studies have shown that these cascades may trigger large-scale economic and social risks and losses.

Combining the climate system predictions from the earth system model with damage assessment models and economic models, the study has predicted the climate change damage in China under different climate change scenarios. Four categories of economic losses were selected, including energy demand, agriculture, labour productivity, and land inundation and asset loss due to sea level rise, taking into account the current research progress on losses and the limitations of models and data. These four categories of economic losses include both losses from extreme weather events (e.g., the impacts of flooding on agriculture) and losses from slow onset events (e.g., land inundation due to sea level rise). The study suggests that achieving the carbon neutrality target could avoid about 80% of accumulative climate change losses during 2020-2100. Under the NDC scenario, global temperature will rise by 3.5 °C in 2100, climate change losses account for 5.6% of China' GDP, and accumulative climate change losses register $189 trillion. In contrast, under the carbon neutrality scenario, global temperature rise would be limited to about 1.5 °C in 2100, climate change losses account for less than 1% of China' GDP, and accumulative climate change losses could be reduced to $55 trillion. As the study doesn't cover all possible climate loss categories, actual climate change losses may be higher than the estimates. From a risk management perspective, we can never know the real risks, but that does not preclude the main conclusion: climate change is already taking a heavy toll on Chinese economy and will be even more severe in the future with climate change. From the perspective of risk governance and avoiding future climate losses, there is a strong case for achieving carbon neutrality as the primary strategy for climate risk governance so as to avoid transferring significant climate risks to future generations.

APPENDIX

For energy demand, the temperature rise effect caused by GHG emissions will increase the demand for some varieties of energy, such as power for air conditioning and cooling, and also reduce the demand for some other types of energy, such as coal and natural gas for heating. In order to quantify the relationship between residential energy demand and the degree of global warming, Enrica Cian et al. analysed the relationship between end-use demand for oil, gas, and power and temperature thresholds in tropical versus temperate regions using an econometric approach [24,79]. The results show that the climate change-induced temperature rise effect will significantly increase the end-use energy demand [24]. Referring to the findings of existing studies, the study concludes that the change in the number of days greater than 27.5 °C and less than 12.5 °C is the main climatic factor affecting changes in energy demand. The study has first calculated the change in the number of days greater than 27.5 °C and less than 12.5 °C for different grids under different scenarios based on the outputs of the earth system model in CMIP6. Then the study has converted the change in gridded temperature threshold into change in gridded energy demand based on the damage functions. In order to map gridded energy demand to regional divisions of the C-GEM model, the gridded data was aggregated. In the process, the climate loss assessment module simplifies the assumption on consistent per capita energy consumption across grids in different regions, and aggregates grids into regional data based on gridded population distribution. Based on the aggregation results, the transfer coefficient of the energy demand function in the C-GEM model will be adjusted accordingly to reflect the impacts of climate change on energy demand.

In assessing the impacts of climate change on labour productivity in China, a quantitative relationship was constructed between climate change and labour productivity by referring to Kjellstrom et al. and using WBGT as the main determinant of labour productivity [38,80]. Considering that different job types are negatively impacted by climate change to varying degrees, the economic sectors in the C-GEM model were divided into three categories: light intensity jobs (services), medium intensity jobs (industry) and heavy intensity jobs (agriculture and construction), which are exposed to the negative impacts of climate change in increasing order of magnitude. Similar to energy demand, in order to introduce labour productivity changes into the C-GEM model, we have aggregated gridded labour productivity decline data into parameters of the corresponding region in the C-GEM model based on gridded population distribution. After aggregating gridded labour productivity data, the study has simulated economic losses from declined labour productivity by adjusting the corresponding labour productivity supply parameters in the C-GEM model.

Climate change will affect grain yield by altering the climatic conditions required for crop growth. To quantify the impacts of climate change on grain yield, the study has approximated the outputs of multiple complex crop models for climate change impacts using the simulator Persephone and with reference to Snyder et al. [81]. Based on statistical analysis methods, Persephone fits the relationship between future climate parameters such as temperature, precipitation, CO_2 concentration from complex crop models and grain yield change data by regression analysis. Through regression modelling, Persephone can simulate global gridded crop yield changes under different future climate policy scenarios with fewer computational resources, facilitating its application in integrated assessment models. To analyse the impacts of grain yield changes on different economic sectors in the C-GEM model, the gridded crop yield changes were aggregated into regional-level crop yield changes. In the process, a base crop yield map for each grid was constructed by referring to global grain yield dataset [82]. By using the aggregated yield changes as an indicator of land productivity change to measure the negative impacts of climate change, the study has accordingly updated the land productivity parameters in the economic system in the C-GEM model.

The impact of rising sea levels on coastal areas is one of the major negative effects of climate change. The study has mainly considered the losses of land and assets in China due to sea level rise. To quantify land and asset losses, two open-source models have been incorporated, BRICK [83] and CIAM [84], in the climate loss assessment module, whose linking framework is shown in Fig. A1. As shown in Fig. A1, BRICK (Building blocks for Relevant Ice and Climate Knowledge) is a modular, semi-empirical modelling framework that simulates global temperature changes and sea level rise levels in different regions. In the default BRICK model configuration, global mean surface temperature and ocean heat absorption are mainly simulated by its sub-module DOECLIM. Changes in global mean surface temperature drive changes in GMSL, and the BRICK model can simulate the contribution of Greenland and Antarctic ice caps, thermal expansion, and glaciers and ice caps to GMSL. Finally, the BRICK model also includes a downscaling sub-module that can convert GMSL changes to regional-level mean sea level changes.

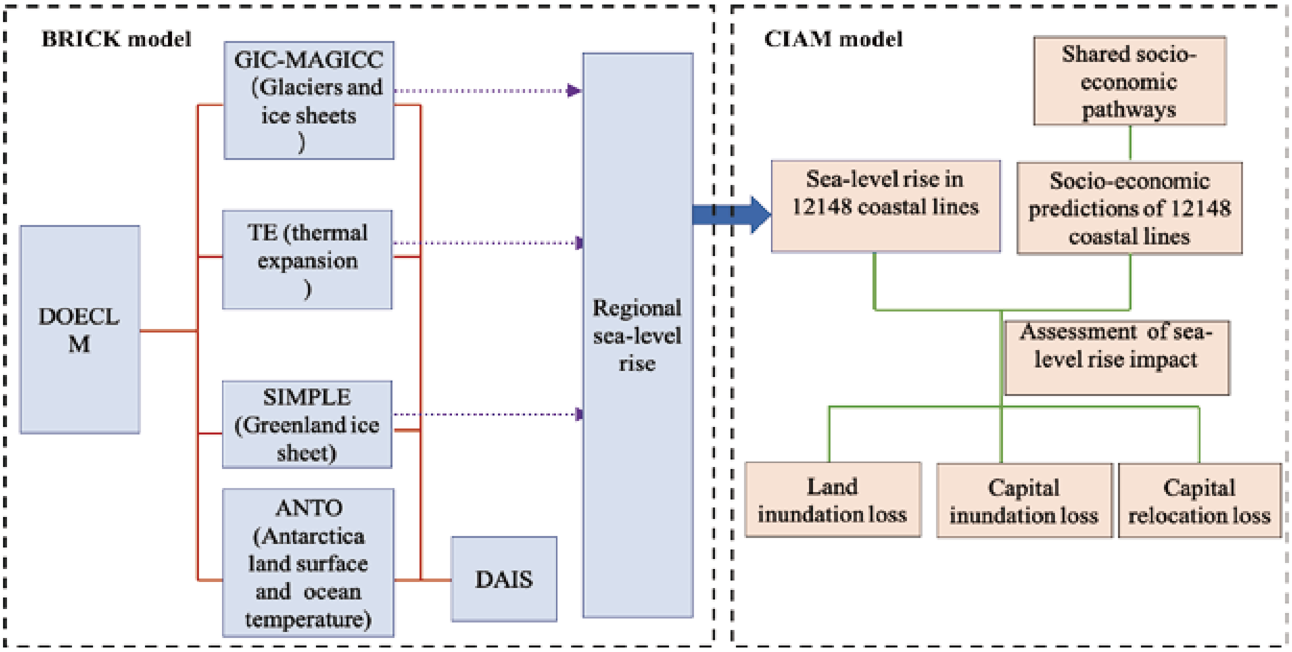


Fig. A1 BRICK-CIAM Model for Sea Level Rise Impact Assessment

After simulating the magnitude of regional mean sea level changes using the BRICK model, the study has simulated land and asset losses from sea level rise mainly using the CIAM model. The CIAM model (Coastal Impact and Adaptation Model) is a high spatial resolution assessment model that assesses the impacts of sea level rise on coastal areas by decomposing least-cost adaptation decisions to the local level [84], with underlying data from the DIVA model [85]. After simulating land and asset losses of each coastal section using the BRICK model and the CIAM model, the impacts of each coastal section and introduced the aggregated results have been aggregated into the C-GEM model. For land losses, after estimating the rate of land loss in different regions, the model investigates the change in economic outputs by adjusting the stock of land resources in the economic system of the C-GEM model. As the land factor is an important input to the agricultural sector in the C-GEM model, the agricultural sector is also the most affected sector. For asset losses due to sea level rise, the capital stock in the C-GEM model has been adjusted accordingly.

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The support from the UK-China cooperation project on climate change risk assessment funded by UK Foreign, Commonwealth & Development Office for the study is greatly appreciated.