Implications of near-term mitigation on China's long-term energy transitions for aligning with the Paris goals

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ABSTRACT

In the international community, there are many appeals to ratcheting up the current nationally determined contributions (NDCs), in order to narrow the 2030 global emissions gap with the Paris goals. Near-term mitigation has a direct impact on the required efforts beyond 2030 to control warming within 2°C or 1.5°C successfully. In this study, implications of near-term mitigation on China's long-term energy transitions until 2100 for aligning with the Paris goals, are quantified using a refined Global Change Assessment Model (GCAM) with six mitigation scenarios. Results show that intensifying near-term mitigation will alleviate China's transitional challenges during 2030–2050 and long-term reliance on carbon dioxide removal technologies (CDR). Each five-year earlier peaking of CO_2 allows almost a five-year later carbon neutrality of China's energy system. To align with 2°C (1.5°C), peaking in 2025 instead of 2030 reduces the requirement of CDR over the century by 17% (13%). Intensifying near-term mitigation also tends to have economic benefits to China's Paris-aligned energy transitions. Under 2°C (1.5°C), peaking in 2025 instead of 2030, with larger near-term mitigation costs by 1.3 (1.6) times, has the potential to reduce China's aggregate mitigation costs throughout the century by 4% (6%). Although in what way China's NDC is to be updated is determined by decision-makers, transitional and economic benefits suggest China to try its best to pursue more ambitious near-term mitigation in accordance with its latest national circumstances and development needs.

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1. Introduction

In the Paris Agreement, the Parities to the United Nations Framework Convention on Climate Change (UNFCCC) collectively decide to "hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (UNFCCC, 2015). Responding to the achievement of such global goals, 184 Parties have submitted the nationally determined contributions (NDCs) to the UNFCCC secretariat during the last several years, in which their concrete near-term mitigation objectives until 2030 are determined. Previous studies (e.g., Fawcett et al., 2015; Robiou du Pont et al., 2017; Rogelj et al., 2016; UNEP, 2019) have assessed these national near-term objectives and declared that the global aggregate NDCs in 2030 fall short to meet cost-effective emissions levels consistent with well-below 2°C simulated by integrated assessment models (IAMs). Countries are therefore called for, by both the international climate change

negotiations and the literature, to ratchet up the current NDCs, in order to narrow and possibly close the 2030 global emissions gap.

Besides the NDC, the realization of the Paris goals by 2100, which are associated with very limited carbon budgets over the century (Clarke et al., 2014; Rogelj et al., 2018), also relies on the post-NDC, long-term mitigation (Rose et al., 2017). As the successor of the NDCs, to what degree the long-term mitigation is required will be closely related with how much mitigation has been achieved by 2030. At the global scope, several studies (e.g., Holz et al., 2018; Strefler et al., 2018) have recently discussed the potential influences of implementing more ambitious assumed near-term mitigation on long-term transitions to keep the Paris goals within reach. They concluded that intensifying mitigation before 2030 could help reduce long-term challenges and risks. To stay below 1.5°C, if global CO_2 emissions are further reduced by 30% from the NDC levels in 2030, the global requirement of carbon dioxide removal (CDR) technologies (represented often by bioenergy with carbon capture and storage (BECCS) in most models) in the second half of the century could be halved (Strefler et al., 2018).

China is the biggest CO_2 emitter and energy consumer in the world at present. China's NDC, which was submitted in 2015, pledged a

package of mitigation objectives and actions toward 2030. The main elements were determined as "to achieve the peaking of carbon dioxide emissions around 2030 and making best efforts to peak early; to lower carbon dioxide emissions per unit of GDP by 60% to 65% from the 2005 level; to increase the share of non-fossil fuels in primary energy consumption to around 20%" (NDRC, 2015). For China, 90% of emissions (excluding land use, land use change and forestry (LULUCF)) came from the energy system (UNFCCC, 2019). Energy system transition will be the primary means by which China reduces its emissions and contributes to the overarching global goals. The recent studies (e.g., Duan et al., 2018; Gallagher et al., 2019; Jiang et al., 2018, 2018a; Lugovoy et al., 2018; Mi et al., 2017; Wang and Chen, 2018; Zhou et al., 2019) are concentrated on assessing China's NDC CO_2 trajectories until 2030 or 2°C-aligned energy system changes until 2050 by using a bottom-up modeling. They showed that China, with additional efforts, could be able to overachieve its NDC targets including to achieve an earlier CO_2 peaking.

Well-below 2°C or 1.5°C is a goal by 2100. To align with the Paris goals, different near-term mitigation will have different implications on China's long-term energy transitions until 2100, and intensifying near-term mitigation will intuitively lower China's transitional challenges beyond 2030. With the global 'stocktake' adopted in the Paris Agreement (stated as "undertake its first global stocktake in 2023 and every five years thereafter"), national near-term mitigation objectives are being re-considered and might be updated in the coming years. The next-step choices China makes will have a long-lasting influence on the world's possibility to hold warming still within 2°C or 1.5°C by the end of the century. Although how China will ratchet up the NDC is ultimately determined by decision-makers, informing the degree to which China's near-term mitigation will impact its long-term transitional and economic challenges is useful to support the decisions. Most existing studies have only focused on investigating the achievement of the NDC itself. An important literature gap exists in assessing near-term mitigation implications on China's long-term transitions especially under 1.5°C.

To fill in the literature gap, this study will apply an IAM – a refined Global Change Assessment Model (GCAM), which is a participant of the China Energy Modeling Forum (CEMF) for this Special Issue "The Economic Feasibility and Trade-offs in Achieving China's Low-Carbon Transformation" – to derive key implications of China's near-term mitigation before 2030 on its long-term energy transitions until 2100, in aligning with well-below 2°C and 1.5°C. By doing so, we hope to identify and provide some quantitative information to support China's NDC reconsideration and low-carbon transformation. The study could also provide a reference to other developing countries when considering the update of their NDCs and the alignment between near-term mitigation and long-term transitions. The remainder of this paper is organized as follows. Section 2 describes the methods and scenarios. Section 3 presents the results of China's energy transitions under different near-term mitigation scenarios. Section 4 provides the main conclusions.

2. Methods

2.1. Modeling framework

To implement the analysis, the paper applies GCAM (version 4.0) as the modeling framework. As an open-source model (http://www.globalchange.umd.edu/gcam/), GCAM is originally developed by the Joint Global Change Research Institute and has been widely invoked in international energy and climate assessments including the Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC). GCAM simulates dynamics of the global energy-economy-land-climate system until 2100 at a 5-year time step. It disaggregates the world into 32 geopolitical regions (and China is an individual region) which are linked through international trade.

GCAM is a bottom-up model with the ability to comprehensively simulate regional energy systems (covering energy supply, conversion,

distribution and demand) and to incorporate rich technologies and fuels (including CCS and BECCS). The model features a partially dynamic-recursive equilibrium where the demand and supply of primary energy, agricultural and forest commodities are balanced (market-clearing) globally at every simulated time period. The model also to a large degree features a cost-effectiveness where technologies, fuels, feedstock and modes compete for market shares through a logit function based on costs and preferences. The logit presents a discrete economic choice which avoids 'winner-take-all' (this is different from traditional choices which strictly minimize costs) with one typical implementation as Eq. (1),

$$s_i = \frac{b_i p_i^{r_i}}{\sum_i b_i p_i^{r_i}} \tag{1}$$

where s_i is the market share of candidate i whose service costs are p_i (comprised of energy costs and levelized non-energy costs), b_i is the associated share-weight which is used to calibrate historical data and represent future preferences, and r_i is the associated logit exponent which is also called as an elasticity. More information on GCAM structure, methodologies, technology assumptions and data sources have been presented by the GCAM team (e.g., McJeon et al., 2014; Muratori et al., 2017; Shukla and Chaturvedi, 2012; Yu et al., 2019) and the GCAM documentation (http://jgcri.github.io/gcam-doc/).

Energy service demands on the demand side are a primary driver of the energy system development. GCAM describes the demand side with three aggregate end-use sectors: industry, building and transportation. On top of the standard GCAM, the three end-use sectors (industry, building and transportation) of China have been refined as in the following:

- China's industrial structure is complicated. This sector is disaggregated and calibrated from an aggregate sector in the standard GCAM into eleven specific subsectors (iron-steel, aluminum-nonferrous metals, other nonmetallic minerals, paper pulp and wood, chemicals, food processing, other manufacturing, agriculture, construction, mining, and cement) with six intermediate energy services (boiler, process heat, machine drive, electrochemical process, other energy services, and feedstock) (Wang et al., 2016; Zhou et al., 2013).
- Regarding several climate conditions and differences between urban and rural areas, China's building sector is represented and calibrated using a combination of climate zones (severe cold, cold, hot summer-cold winter, and hot summer-warm winter) and districts (urban, rural and commercial) with five types of energy services (cooling, heating, lighting, water heating and cooking, and electric equipment) (Chen et al., 2019).
- According to transport areas, characters and purposes, China's transportation sector is downscaled and calibrated into five passenger (intercity transport, urban transport, rural transport and international aviation for private passengers; and business transport for government bodies and companies) and four freight subsectors (general domestic freight, rural three/four-wheeler freight, international ship freight, and international aviation freight) with specific types of modal services (Pan et al., 2018; Yin et al., 2015).

Energy service demands in the three disaggregated end-use sectors will be satisfied by multiple competing technologies and fuels through the logit-sharing pattern. In addition, a cascade of technologies have been also represented for power generation which is the primary energy conversion sector of China, including 10 types of fossil fuel technologies (coal, coal-CCS, integrated gasification combined cycle (IGCC), IGCC-CCS, gas, gas-CC, gas-CC-CCS, liquid, liquid-CC, and liquid-CC-CCS) and 15 types of non-fossil fuel technologies (nuclear-II, nuclear-III, hydro, wind, wind-storage, photovoltaic (PV), PV-storage, PV-rooftop, concentrated solar power (CSP), CSP-storage, biomass, biomass-CCS, biomass-CC, biomass-CC-CCS, and geothermal).

2.2. Key assumptions

Energy services demands relate closely with socioeconomic developments (how energy service demands are estimated is given in Appendix A). In this study, China's socioeconomic assumptions until 2100 are presented in Table 1, which take the latest socioeconomic trends such as 'new normal' economy and 'two-child' policy into account. With the assumptions, China's GDP increases by a factor of more than 3, 6 and 19 in 2030, 2050 and 2100, respectively from the 2010 level; China's population peaks in 2030 at 1.43 billion, then decreases to 1.33 billion in 2050 and further decreases to 1.08 billion in 2100; China's urbanization rate increases to 69.9%, 77.6% and 86.1% in 2030, 2050 and 2100, respectively.

Based on Wang et al. (2016) and Pan et al. (2017), the assumptions of other key parameters for China, such as demand-price elasticities and techno-economic parameters, are also updated to reflect the recent changes and polices in China. Some details of these parameters can be found in our recent papers (e.g., Pan et al., 2018, 2018a; Chen et al., 2019) (for the other 31 regions of the world, we maintain the default parameter assumptions in the standard GCAM). In our model, negative emissions of the energy system are achieved via BECCS which is the representation of CDR. CCS is assumed to start to enter the industry (synthetic fuel productions and industrial productions such as cement, steel and iron) and power sectors from 2020 and 2025 onward, respectively. Note that due to the characteristics of GCAM, all these parameters and assumptions are exogenous and will remain unchanged during modeling. Overall, our refinements and calibrations of GCAM for China are characterized by a more detailed sectoral disaggregation, more types of technologies and services, and a more localized parameterization. By doing so, we attempt to better reflect what is happening in China and better illustrate energy services and transitional options of China.

2.3. Mitigation scenario settings

At the global scope, a range of carbon budgets aligning with the Paris goals have been reported by IAM emissions scenarios (e.g., Clarke et al., 2009; Blanford et al., 2014; van Vuuren et al., 2016). These scenarios have been summarized in the fifth Assessment Report (Clarke et al., 2014) and the Special Report on Global Warming of 1.5°C (Rogelj et al., 2018) of the IPCC. Among these scenarios, as a numerical illustration, this paper uses the Representative Concentration Pathway 2.6 (van Vuuren et al., 2011) and the average pathway of the 1.5°C scenarios in Rogelj et al. (2015) as representatives of well-below 2°C (>66% chance) and 1.5°C (>50% chance), respectively. Their global carbon budgets for the energy system (fossil and industrial CO_2; LULUCF CO_2 and non-CO2 are excluded in this study) during 2011–2100 are approximately 1000 and 500 $GtCO_2$, respectively. Under the two selected global budgets, an allocation based on 'carbon budget account' (BASIC experts, 2011), as indicated in Eq. (2) (where B indicates the global carbon budget during 2011–2100; b_i, pop_i and his_i indicate the carbon budget during 2011–2100, the population in the year 2010 and the historical cumulative CO_2 emissions during 1850–2010, respectively of country i),

$$b_i = \left(\sum_i his_i + B\right) \cdot pop_i / \sum_i pop_i - his_i \tag{2}$$

implies that China needs to at least control its 2011–2100 emissions within 320 $GtCO_2$ to stay well-below 2°C and within 215 $GtCO_2$ to stay below 1.5°C.

Following the implementation of the NDC, China's CO_2 trajectories before 2030 are assumed to be based on the projections in Pan et al. (2017) and updated with the up-to-date inventory data (UNFCCC, 2019) in this study. With the assumption, China's energy system emissions are projected to be 10.1, 10.4 and 10.6 $GtCO_2$ by 2020, 2025 and 2030, respectively. This implies almost a plateauing of China's energy system CO_2 emissions during 2020–2030 and is consistent with the

trends projected in the first study program of the CEMF (Lugovoy et al., 2018). The study uses the peaking year of CO_2 to represent China's near-term mitigation. Besides 2030, this study further assumes a peaking of 2025 and 2020 with rapid mitigation thereafter. Therefore, in our following analysis, six mitigation scenarios, three for 2°C (2C2030, 2C2025 and 2C2020) and three for 1.5°C (1.5C2030, 1.5C2025 and 1.5C2020), will be developed, simulated and assessed. Intuitively, an earlier peaking indicates more ambitious near-term mitigation. It is important to note that an earlier peaking such as 2025 or 2020 is our theoretical assumption and doesn't represent any attitude, commitment or communication of the government of China (in other words, we don't imply China must ratchet up its NDC in this manner), but reflects some recent analyses of China's CO_2 emissions to align with the Paris goals (e.g., Gallagher et al., 2019; Jiang et al., 2018, 2018a; Wang and Chen, 2018).

Meeting the Paris-aligned carbon budget over the century needs countries to quickly decline their CO_2 trajectories after reaching the peaking (Raupach et al., 2014). At present, China's post-NDC, long-term mitigation objectives, however, are not yet determined. In this case, in order to align near-term mitigation with long-term goals until 2100, this paper follows Pan et al. (2018) which upgraded the capped-emissions trajectory model proposed in Raupach et al. (2014) to disaggregate China's 2011–2100 carbon budget (320 $GtCO_2$ for 2°C and 215 $GtCO_2$ for 1.5°C in this study) into annually exemplary CO_2 trajectories that China could follow, as indicated with Eq. (3),

$$y_t = \left(y_{peak} - n_{max}\right)(1 + mt)e^{-mt} + n_{max} \tag{3}$$

where y_t denotes China's annual CO_2 emissions in year t after the peaking, y_{peak} denotes the CO_2 peaking level, and m is a mitigation parameter calibrated by matching China's cumulative emissions with its carbon budget. Particularly, n_{max} is introduced to represent the sustained annual net-negative CO_2 emissions level (Rogelj et al., 2019) that China could achieve in the future through deploying CDR (BECCS in our model) in the energy system. In this study, the value of n_{max} is assumed to be −20% of China's CO_2 emissions in 2010. This number is approximately equivalent to the average global CO_2 emissions in 2100 (as a fraction of the 2010 levels) of our two selected global scenarios. Compared with the negative emissions levels of the existing scenarios in the literature (Clarke et al., 2014; Rogelj et al., 2018), a -level of 20% is moderate and would avoid too extreme CDR.

In simulations, the CO_2 trajectories designed from this trajectory model will be coupled into our refined GCAM by assuming them to be China's carbon caps of the energy system. GCAM will search recursively for the price vector so that these carbon caps are met. To control inter-sectoral carbon leakage, the modeled energy system carbon prices will be imposed to LULUCF CO_2; and to try to control inter-regional carbon leakage, the other 31 regions of the world are assumed to jointly meet the remaining global carbon budget. Note that with these carbon caps, China still participates in international trade of primary energy and other commodities in simulations, but has to meet its CO_2 trajectories unilaterally without emissions allowance trade across regions.

3. Results

3.1. CO_2 trajectories

China's energy system CO_2 trajectories toward the end of the century, subject to our assumptions above, are presented and compared across the six mitigation scenarios in Fig. 1. Note that applying these scenarios as illustrative examples aims to identify key implications of near-term mitigation on China's long-term energy transitions, but doesn't aim to determine which near-term mitigation or CO_2 peaking year is optimal to China. The identified implications are expected to be referred as part of information by decision-makers to formulate the

Table 1
China's socioeconomic assumptions until 2100.

Parameter	2010	2020	2030	2040	2050	2100
Population (billion)	1.35	1.41	1.43	1.40	1.33	1.08
GDP (billion $_{2010}$)	6100	12,170	19,820	28,500	38,865	116,840
Urbanization (%)	50.3	61.6	69.9	74.9	77.6	86.1

Note: Sourced from the second study program of the CEMF, provided by the State Information Center of China in 2019.
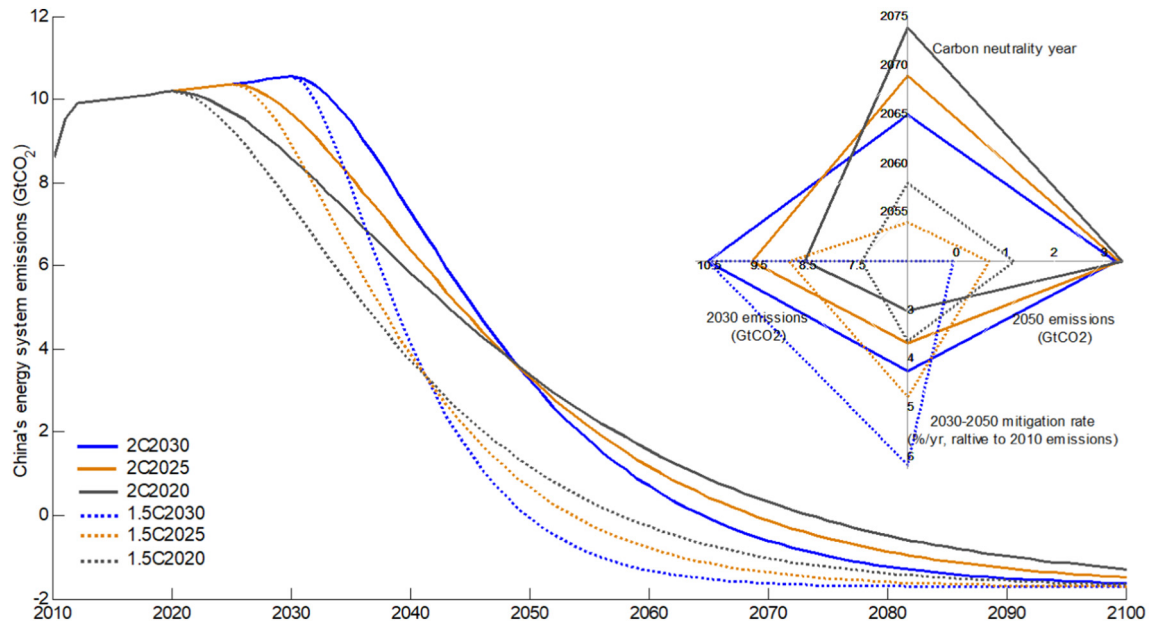

Fig. 1. China's CO_2 mitigation trajectories until 2100 under different peaking scenarios. Note: For the three scenarios under the same climate goal, despite different CO_2 peaking years, their carbon budgets throughout the century is strictly the same.

most suitable transitional trajectories for China. Logically, the 1.5°C scenarios require China to achieve more aggressive mitigation than the 2°C scenarios. Under 2°C (1.5°C), China's 2030 emissions decrease to 9.6 (8.9) and 8.6 (7.4) $GtCO_2$ when the peaking is achieved earlier in 2025 and 2020, respectively. These emissions are approximately 10% (15%) and 20% (30%) lower than the current NDC levels, respectively. As expected, more ambitious mitigation by 2030 alleviates China's medium-to-long-term mitigation paces to align with its carbon budget. China's average mitigation rate during 2030–2050, as a fraction of 2010 emissions, decreases from 4.2%/yr in 2C2030 (6.2%/yr in 1.5C2030) to 3.7%/yr in 2C2025 (4.8%/yr in 1.5C2025) and further to 3.0%/yr in 2C2020 (3.6%/yr in 1.5C2020). Importantly, near-term mitigation has an important implication on the timing of carbon neutrality of China's energy system, which has not been systematically assessed in the prior literature. According to the trajectory model, the current NDC requires achieving the carbon neutrality of China's energy system in 2065 under 2°C and in 2050 under 1.5°C. Our scenarios feature that each five-year earlier peaking of CO_2 could allow almost a five-year later carbon neutrality.

3.2. Energy system transitions

Given a long-term climate goal, our simulations, which seek largely cost-effective options to match the CO_2 mitigation trajectories in Fig. 1, present that near-term mitigation tends to have comparatively small impacts on China's total energy consumption and power generation (Table 2). Across our three 2°C scenarios, in 2050, China's primary and final energy consumption are estimated to be about 170 and 98 EJ, respectively, and power generation presents a swift growth to

Table 2
China's primary, final energy consumption and power generation under different scenarios.

Scenario	Primary energy (EJ)			Power Generation (PWh)			Final energy (EJ)		
	2030	2050	2100	2030	2050	2100	2030	2050	2100
2C3030	160	170	157	9.0	15.9	18.8	103	98	80
2C2025	159	172	155	9.2	15.9	18.8	100	98	80
2C2020	158	173	154	9.5	15.8	18.8	97	98	80
15C2030	160	173	148	9.0	17.4	19.2	103	86	78
15C2025	158	170	148	9.5	17.4	19.2	98	86	78
15C2020	157	169	148	9.9	17.4	19.2	96	86	78

Note: Non-fossil energy is accounted for using coal equivalent calculation.

reach nearly 16 PWh. Compared with 2°C, the 1.5°C scenarios will further reduce China's energy service demands (induced by higher carbon prices) and accelerate end-use electrification. However, the changes of China's total energy consumption and electricity production across our three 1.5°C scenarios are also shown to be small.

Due to the resource endowment, while actions have been taken in recent years, China's energy system is still carbon-intensive at present. Coal still accounted for 59% of China's primary energy in 2018, while non-fossil energy only accounted for 14%. To align with the Paris goals, all our scenarios feature a predominant role of non-fossil energy in China's energy transitions and require achieving substantially challenging objectives in long-term, as presented in Fig. 2. By 2050, the non-fossil share of China's primary energy consumption requires exceeding 55% (67%) to align with 2°C (1.5°C), and the coal share requires a dramatic decrease to less than 15% (10%); the electricity supply
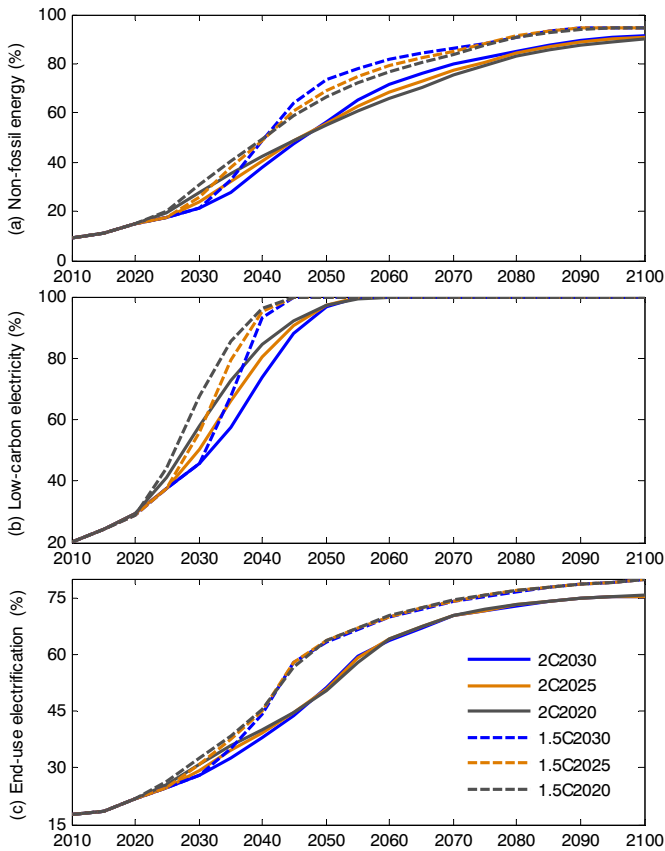
Fig. 2. China's energy transitions in the 21st century toward the Paris goals. Note: In (a), non-fossil energy is accounted for using coal equivalent calculation. In (b), low-carbon electricity includes generations from renewable, nuclear and fossil-CCS. The three subplots use the same legend as presented in (c).

system requires almost complete decarbonization in all scenarios; the share of electricity in China's final energy consumption, with the increasing electrification in the building, industry and transportation sectors, requires reaching 51% (64%) in 2°C (1.5°C) scenarios. In the second half of the century, with technology progress and more stringent mitigation, fossil options will be continuously substituted by non-fossil alternatives. By 2100, all three 2°C (1.5°C) scenarios show that non-fossil energy and electricity provide 90% (95%) and 75% (80%) of China's primary and final energy consumption, respectively. Our simulation of the current NDC indicates non-fossil energy contributes 21% of China's 2030 primary energy supply, which meets the NDC target.

The associated low-carbon electricity share (including renewable, nuclear and fossil-CCS generations here) and end-use electrification rate are projected to be 46% and 28%, respectively in 2030. Compared with the current NDC, intensifying the mitigation before 2030 will to some degree temper the challenge of China to achieve these transitional objectives in the post-NDC period especially between 2030 and 2050. For instance, different peaking years of CO_2, while barely affect total energy consumption, present implications on the pace at which China needs to develop non-fossil energy to substitute fossil energy. To follow 2°C (1.5°C) mitigation trajectories, during 2030–2050, the current NDC requires an average increase of the non-fossil share in China's primary energy supply by 1.8%/yr (2.6%/yr), which could be lowered by 0.2%/yr (0.4%/yr) with each five-year earlier CO_2 peaking.

Enabling more ambitious 2030 mitigation in China than the NDC depends primarily on a scaling-up of non-fossil energy development to replace coal in the coming decade. In 2030, the share of non-fossil increases to 24% in 2C2025 (26% in 1.5C2025) and 28% in 2C2020 (30% in 1.5C2020) (30% is a very optimistic estimation of China's 2030 non-fossil share by Climate Action Tracker (CAT, 2019)). In contrast, the share of coal in 2030 reduces from 47% associated with the NDC to 43% in 2C2025 (40% in 1.5C2025) and further to 39% in 2C2020 (33% in 1.5C2020). The scaling-up of non-fossil energy will be in parallel with a rapid ramping-up of low-carbon electricity production and end-use electrification. For instance, a peaking of CO_2 in 2C2025 (1.5C2025) implies low-carbon generations promoted to 51% (56%) of China's electricity supply in 2030. Encouragingly, facilitating factors are happening in China in the recent years. The costs of solar and wind energy have declined rapidly; the government is issuing some useful plans and measures such as the industrial structure upgrade, the national emissions trading scheme, the renewable portfolio standard, and the more stringent building codes and transport emissions standards. In 2017, China's renewable energy investments reached 126.6 billion dollars and accounted for 45% of the global total renewable energy investments (Frankfurt School-UNEP Centre/BNEF, 2018). However, making a high penetration of non-fossil energy viable in China in near-term still poses critical challenges to some fundamental supporting factors, such as large-scale energy storage, advanced power transmission and distribution network, smart grid, and phasing-out of the existing conventional coal power plants. Beyond current policies, these factors call for significantly more measures, projects and investments in China immediately.

3.3. Dependence on carbon removal

At the global scope, a range of papers (e.g., Clarke et al., 2014; Pan et al., 2018a; Rogelj et al., 2018) have highlighted that realizing Paris-
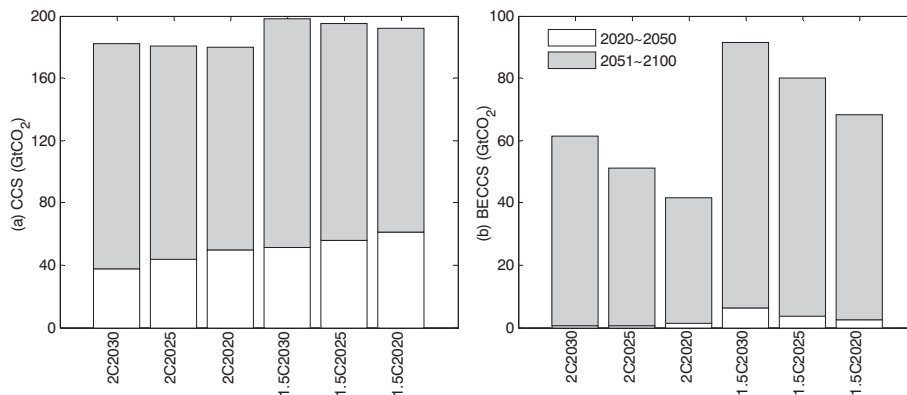

Fig. 3. The reliance of China's energy transitions on CCS and BECCS. Note: In (a), CCS includes fossil-CCS and BECCS. The two subplots use the same legend as presented in (b). Note that the precise numbers here relate with modeling assumptions including the use of a specific sustained annual net-negative CO_2 level.

aligned energy transitions relies on applying CCS and CDR to remove CO_2 emissions from the energy system. Besides a strong scaling-up of non-fossil energy, all our scenarios also feature an extensive and unavoidable requirement of CCS and CDR for China to realize its long-term energy transitions, as presented in Fig. 3. Although an earlier peaking of CO_2 slightly increases (decreases) the deployment of CCS in the first (second) half of the century, the total emissions stored by CCS are projected to be around 180 (195) $GtCO_2$ across all three 2°C (1.5°C) scenarios over the century, which are equivalent to 21 (23) years of China's 2010 CO_2 levels. Regarding the infrastructure life span, the existing coal power plants should be quickly equipped with CCS. In our scenarios, all conventional coal power plants without CCS are required to be fully phased out by 2055 to stay well-below 2°C and by 2045 to stay below 1.5°C.

According to Fig. 3b, BECCS is presented to enter China's energy system (largely in refining biofuel and producing bio-power) mainly after 2050 when its costs become economically competitive (due to high carbon prices associated with reaching very low and even negative emissions). With the completion of the NDC, 61 (91) $GtCO_2$ are estimated to be offset from China's energy system via BECCS over the century to align with 2°C (1.5°C). By assessing the potentials of saline aquifers, oil and gas reservoirs and coal seams, China's optimistic storage capacity is estimated to be possibly over 1500 $GtCO_2$ (Höller and Viebahn, 2016; Sun et al., 2018). Although this optimistic capacity sustains the CCS requirement here, a wide application of BECCS will be practically afflicted with risks. Besides technological and economic issues, it also raises public concerns on food security, biodiversity and other sustainable development goals (van Vuuren et al., 2017). We therefore suggest the government of China to make preparations in advance so that sociopolitical, technological and economic barriers of the CDR development could be gradually removed. To align with the Paris goals, our scenarios highlight that to what degree China deploys CDR is highly closely related with the near-term mitigation achieved by 2030. Intensifying near-term mitigation could significantly alleviate the risk of the long-term CDR deployment for China. Compared with the NDC, BECCS over the century is lowered by 17% in 2C2025 (13% in 1.5C2025) and even by 32% in 2C2020 (25% in 1.5C2020). Note that China's CO_2 emissions in 2050 of the 2°C scenarios in the study (Fig. 1) are at the lower end of the range of emissions in the prior 2°C scenarios of China (about 3.0–6.5 $GtCO_2$) (e.g., Chen et al., 2016; Jiang et al., 2018a; Li et al., 2019). Hence, the prior scenarios are likely to require China to deploy more CDR in the post-2050 period than projected here to support the final achievement of the Pairs goals.

3.4. Mitigation costs

The results above quantified some key transitional benefits of intensifying near-term mitigation (note that this is not equivalent to saying that China's current NDC is not ambitious; the discussions of the NDC fairness and adequacy are beyond the purpose of the paper) to China's Paris-aligned energy transitions beyond 2030. According to Fig. 4a, our scenarios further indicate that intensifying near-term mitigation also tends to have economic benefits to China's transitions throughout the century, especially when decision-makers discount future mitigation costs at no more than 6%/yr under 2°C (7%/yr under 1.5°C). Following the current NDC, China's aggregate mitigation costs between now and 2100, with a discount of 5%/yr (used in the IPCC reports to obtain net-present mitigation costs), are projected to be 3.23% of GDP in 2C2030 and 5.60% in 1.5C2030. Intensifying near-term mitigation reduces these costs to 3.10% in 2C2025 (5.28% in 1.5C2025) and 3.05% in 2C2020 (5.07% 1.5C2020). Note that the mitigation costs assessed here are direct investment, operation and maintenance costs on mitigation measures and estimated as the area under marginal abatement cost curves, which don't include mitigation benefit or co-benefit. Incorporating (co-)benefits such as improved air quality and public health would further hedge the mitigation costs resulting from mitigation in an early stage (Li et al., 2019). Overall, our scenarios highlight that intensifying near-tem mitigation is most likely to have not only transitional but also economic benefits to China's long-term energy transitions for aligning with the Paris goals. These benefits suggest China to try its best to pursue more ambitious near-term mitigation including an earlier CO_2 peaking, in accordance with its latest national circumstances and development needs.

However, enabling more ambitious mitigation than the NDC appears costly for this developing country in the coming decade (Fig. 4b). Implementing the current NDC indicates China's mitigation costs between now and 2030 are equivalent to 0.42% of GDP (discounted at 5%/yr). These costs increase by a factor of 1.3 in 2C2025 (1.6 in 1.5C2025) and even 1.9 in 2C2020 (3.2 in 1.5C2020). In 2030, the carbon prices associated with 2C2025 (1.5C2025) and 2C2020 (1.5C2020) are estimated to be 1.4 (1.8) and 1.9 (2.3) times as high as with 2C2030 (1.5C2030), respectively. Several general equilibrium exercises in the literature even estimated that an earlier peaking of CO_2 might lead to an over 2% loss of GDP in China before 2030 (Duan et al., 2018; Mi et al., 2017). As a developing country, in the following decade, China will still need substantial investments to accelerate economic growth, social development and poverty eradication. To enable more ambitious mitigation by 2030 in China, which will make valuable contributes to narrowing the 2030 global emissions gap, international supports (e.g., financial transfers from the Green Climate Fund) and cooperation (e.g., a regional emissions trading scheme, a sustainable development mechanism) are essential and expected immediately. In the framework of the Paris Agreement, we emphasize that the concept of ratcheting up the NDCs should broadly include mitigation, finance, technology and capacity-building supports rather than narrowly indicate mitigation.

4. Conclusions

To keep the door open for aligning with well-below 2°C or 1.5°C, the intergovernmental climate change negotiations are appealing to all governments to ratchet up the current NDCs. Informing the implications of near-term mitigation on long-term energy transitions is useful to support China's re-consideration of the NDC and preparation for a low-carbon transformation. The existing literature didn't assess these implications. This paper filled in the literature gap by using an integrated assessment model with six representative mitigation scenarios.

Key indicators of China's energy transitions under the six scenarios are summarized and compared in Table 3. The Paris goals require achieving substantially challenging objectives in China's long-term transitions. In 2050, for aligning with 2°C (1.5°C), non-fossil energy accounts for over 55% (67%) of China's primary energy consumption; electricity supply is almost fully decarbonized; end-use electrification rate reaches 51% (64%). Intensifying near-term mitigation to some degree attenuates the stringency of realizing these transitional objectives in the period of 2030–2050. Reaching an earlier CO_2 peaking with rapid mitigation thereafter allows a later carbon neutrality and reduces the reliance on CDR in China. Importantly, intensifying near-term mitigation also tends to reduce China's aggregate mitigation costs across the century. Therefore, China could consider reconciling mitigation and development by trying its best to pursue more ambitious near-term mitigation based on its national circumstances and development needs. Enhanced mitigation would not only provide long-term transitional and economic benefits to the country itself but also contribute to narrowing the 2030 global emissions gap.

In the coming decade, in order to enable more ambitious mitigation, China requires further boosting the penetration of non-fossil energy to replace coal. Accordingly, China could more aggressively reinforce policies, mechanisms and investments in renewables and their supporting technologies (e.g., large-scale energy storage, advanced power transmission and distribution network, and smart grid) during the 14th and 15th Five-Year Plan periods. Measures aimed at ramping up low-carbon electricity production and end-use electrification, such as
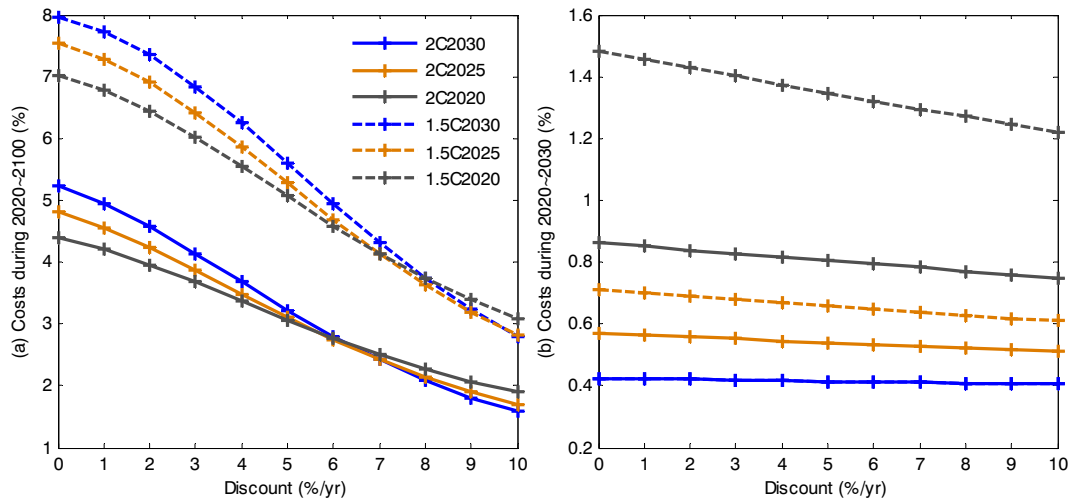
Fig. 4. China's mitigation costs as percentages of GDP under different assumed discounts. Note: In (b), during 2020– 2030, the mitigation costs of '2C2030' and '1.5C2030' are the same. The two subplots use the same legend as presented in (a).

Table 3
Comparisons of some key indicators of China's energy transitions under different peaking scenarios.

Indicator	2C2030	2C2025	2C2020	1.5C2030	1.5C2025	1.5C2020
Emissions (GtCO$_2$)	10.6/3.2/−1.6	9.6/3.3/−1.5	8.6/3.4/−1.3	10.6/−0.1/−1.7	8.9/0.7/−1.7	7.4/1.2/−1.7
Non-fossil share (%)	21/57/91	24/56/91	28/55/90	21/73/95	26/69/95	30/67/95
Coal share (%)	47/12/4	43/13/4	39/14/4	47/9/2	40/9/2	33/10/2
Low-carbon electricity share (%)	46/97/100	51/97/100	58/97/100	46/100/100	56/100/100	68/100/100
End-use electrification (%)	28/51/75	29/51/75	31/51/75	28/64/80	31/64/80	33/64/80
Carbon prices (US$$_{2010}$/tCO$_2$)	43/225/1373	61/217/1368	80/210/1367	43/689/2017	77/668/2017	100/648/2017
Carbon neutrality	2065	2070	2075	2050	2055	2060
Conventional coal power plants phase-out	2055	2055	2055	2045	2045	2045
CCS/BECCS (GtCO$_2$)	182/61	181/51	180/42	198/91	195/80	192/68
2020– 2030/2020– 2100 mitigation costs (%)	0.42/3.23	0.54/3.10	0.81/3.05	0.42/5.60	0.66/5.28	1.34/5.07

Note: For the first six indicators, the 2030/2050/2100 values are presented. 'CCS/BECCS' is for the years 2020–2100. '2020–2030/2020–2100 mitigation costs' here correspond to a discount of 5%/yr.

banning the construction of new coal power plants, fostering CCS in the existing power plants, promoting the replacement of coal by electricity in the industry sector, improving electric vehicles in the transportation sector, and popularizing green dwellings in the building sector, must be also accelerated. Implementing these policies and measures needs substantial costs in the years 2020–2030. Compared with the NDC, a ten-year earlier peaking of CO$_2$ with rapid mitigation thereafter might double China's mitigation costs in the coming decade under 2°C and even triple under 1.5°C. As a developing countries, besides domestic efforts, international finance supports and cooperation are of significant value in enabling more ambitious mitigation in China by 2030 without compromising its sustainable development. In addition, our scenarios highlighted that CCS and CDR would play a crucial role in China's long-term energy transitions. Although they have not received sufficient attention in China until now, CCS and CDR should be included in China's future energy development strategies and require targeted investments and cultivations.

Our study has limitations. First, the results are subject to specific global carbon budgets and the 'carbon budget account' allocation. Using other global carbon budgets and allocations will change China's budgets. However, under the Paris goals, the basic implications of different budgets on China's energy transitions are expected to be similar, because the allocated budgets are really stringent compared with China's emissions levels (Pan et al., 2017). Second, the results are also subject to specific assumptions of technologies. Including new promising options such as direct air CCS, more advanced hydrogen and nuclear technologies is expected to provide some flexibilities to China's long-term transitions. Finally, ratcheting up the NDC is a systematic decision which needs

comprehensive information to support. The study only provided supporting information from the perspective of energy transitions. Assessing how the achievement of near-term mitigation relates with other aspects, such as the economy, society, employment, and development environment (e.g., the 2019 novel coronavirus), is also important.

CRediT authorship contribution statement

Xunzhang Pan: Methodology, Investigation, Writing - original draft. **Wenying Chen:** Methodology, Validation, Writing - review & editing. **Sheng Zhou:** Investigation, Validation, Writing - review & editing. **Lining Wang:** Methodology, Investigation, Validation, Writing - review & editing. **Jiaquan Dai:** Validation, Writing - review & editing. **Qi Zhang:** Validation, Writing - review & editing. **Xinzhu Zheng:** Validation, Writing - review & editing. **Hailin Wang:** Validation, Writing - review & editing.

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Appendix A. Estimation of energy service demand in GCAM

In the modeling framework, end-use energy service demands in the future, as a primary driver of the energy system development, are

assumed to be driven by socioeconomic developments over time through income, price and preference. Overall, industrial service demands (D_t) are projected using Eq. (A-1), where p_t denotes the energy service price, g_t denotes per capita GDP, N_t denotes the total population, k denotes a calibration factor, and α and β denote elasticities. For the transportation sector, passenger transport service demands are also projected using Eq. (A-1), and freight service demands are projected using Eq. (A-2) where G denotes GDP. In the building sector, energy service demands are not projected using the elasticity, but are projected by considering the saturations of per capita floorspace and per unit floorspace service (Ecom et al., 2012; Shi et al., 2016). Per capita floorspace (s_t) is projected using Eq. (A-3), where s_s denotes the satiated level, s_m denotes the minimum level, and s_i denotes the saturation impedance of floorspace. Per unit floorspace energy service demands (d_t) are largely projected using Eq. (A-4), where d_s denotes the satiated level (for cooling and heating, d_s further considers other factors mainly including cooling and heating degree days, building shell efficiency, and internal gains (Yu et al., 2014)), and d_i denotes the saturation impedance of service. More detailed calculations can be found in our previous papers (e.g. Chen et al., 2019; Pan et al., 2018, 2020; Zhou et al., 2013).

$$D_t = kg_t^\alpha p_t^\beta N_t \qquad (A-1)$$

$$D_t = kG_t^\alpha p_t^\beta \qquad (A-2)$$

$$s_t = (s_s - s_m)\left(1 - 0.5^{g_t/s_i}\right) + s_m \qquad (A-3)$$

$$d_t = kd_s\left(1 - 0.5^{g_t/(d_i p_t)}\right) \qquad (A-4)$$

Appendix B. Supplementary data

The standard GCAM, the capped-emissions trajectory model and the data supporting the figures can be found online. Other data is available from the corresponding author upon reasonable request. Supplementary data to this article can be found online at doi:https://doi.org/10.1016/j.eneco.2020.104865.

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