The role of biomass in China’s long-term mitigation toward the Paris climate goals

Xunzhang Pan, Wenyong Chen, Lining Wang, Lu Lin and Nan Li

1 Academy of Chinese Energy Strategy, China University of Petroleum-Beijing, Beijing, 102249, People’s Republic of China
2 Institute of Energy, Environment and Economy, Tsinghua University, Beijing 100084, People’s Republic of China
3 Economics & Technology Research Institute, CNPC, Beijing 100724, People’s Republic of China

E-mail: chenwy@tsinghua.edu.cn and wanglining87@126.com

Keywords: biomass, China’s mitigation, Paris agreement, BECCS, climate change

Supplementary material for this article is available online

Abstract

Biomass is a crucial option of substituting fossil fuels to reduce emissions, and bioenergy with carbon capture and storage (BECCS) allows for obtaining net-negative emissions. We explore the role of biomass in China’s long-term mitigation toward the Paris climate goals in light of three narratives and five mitigation scenarios, modeling by a refined Global Change Assessment Model. While presenting a limited contribution to achieving China’s Nationally Determined Contribution (NDC), biomass plays an important role in China’s post-NDC mitigation toward the Paris climate goals. All the assessed scenarios call for extensive biomass use, accounting for 6.5%–28% of China’s 2100 primary energy in our three 2 °C scenarios and 15%–30% in our two 1.5 °C scenarios. The exact biomass deployment trajectories tend to depend greatly on how China envisions national mitigation paces and BECCS strategies. For either 2 °C or 1.5 °C, a smaller negative-emission narrative, which means a more rapid immediate decarbonization of the energy system toward mid-century, depends on larger bioenergy in medium-to-long-term. Delaying short- and medium-term ambition delays bioenergy applications but requires far more in the second half of the century to create greater negative emissions via BECCS. Moving from 2 °C toward 1.5 °C features higher and earlier bioenergy deployments and meaningfully increasing BECCS volumes and biofuel shares in China’s energy system. Consequently, the Chinese stockholders might be ready to make a decision on to what degree biomass and BECCS enter the sphere of China’s energy and climate policies, which will greatly influence not only national biomass roadmap but also mid-century mitigation targets.

1. Introduction

The Paris Agreement set the long-term climate goals as ‘holding 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 United Nations Framework Convention on Climate Change 2015). The international community has actively explored how the world might transform toward the goals using integrated assessment models (IAMs). Nearly all resulting global emissions pathways rely on different levels of negative emissions technologies (NETs) and in particular bioenergy with carbon capture and storage (BECCS) to achieve near-zero and even net-negative emissions in the second half of the century (Clarke et al 2014, Rogelj et al 2018b). Biomass and BECCS tend to play an essential role in assessing the possibilities and options of decarbonizing energy systems. In a global perspective, international IAM comparisons have repeatedly reached a common conclusion that large-scale biomass is vital to low-carbon energy transition and climate management (Fridahl et al 2018). By comparing results across 11 models, Bauer et al (2018) present that about 80–250 (90–280) and 140–420 (230–440) EJyr⁻¹ of global total biomass is used by 2050 and 2100, respectively for meeting 2 °C (1.5 °C). According to the Fifth
Assessment (AR5) of the Intergovernmental Panel on Climate Change (IPCC) (Clarke et al. 2014, Rose et al. 2014), bioenergy (modern biomass) is projected to account for 3%−37% (23%−50%) of global 2050 (2100) primary energy in 2 °C-consistent scenarios. In the recently published IPCC Special Report on Global Warming of 1.5 °C (SR15) (Rogelj et al. 2018b), the 2050 share ascends to 10%−54% in 1.5 °C-consistent scenarios, and even about 15 GtCO2 yr⁻¹ is projected to be removed by BECCS globally by 2100. Implementing BECCS and several other NETs, such as afforestation and reforestation, direct arı capture, enhanced weathering, ocean fertilization, biochar, soil carbon sequestration (Fuss et al. 2016, Frank et al. 2017, Werner et al. 2018), generally accommodates higher mid-century emissions (drastic near-term reductions are very expensive), but increases the uncertainties and risks of the success of the Paris climate goals in the later century. As invited in the Paris Agreement, China and all other countries, starting from the current Nationally Determined Contribution (NDC), will gradually consider mid-century and long-term low-carbon development strategies. In this process, understanding the role of biomass is significant.

Some studies (Chen 2016, Wang 2017, Qin et al. 2018) have recently evaluated China’s current biomass consumption and supply potential. In China, biomass consumed in modern ways (such as producing bio-power, biofuel and biogas) is still much less than in the traditional way (serving rural space heating and cooking). Bioenergy consumption is currently only around 1.2 EJ, whose share in total primary energy is extremely limited and less than 1% (Wang 2017). There indeed exist some policies (such as the 13th five-year plan for bioenergy development) in China on incentivising modern applications and punishing straw burning, however, the official future biomass roadmap remains unclear. Many previous papers (Zhou et al. 2013, Johansson et al. 2015, Chen et al. 2016, Lugovoy et al. 2018), often using a bottom-up modeling, have examined China’s energy system in different climate scenarios. If focusing on biomass, these papers emerge three important weaknesses: (1) they have mainly concentrated on presenting structural changes in the whole energy system but not discussed sufficiently on bioenergy; (2) almost all have been implemented toward mid-century. However, large-scale biomass and in particular BECCS would likely enter systems beyond 2050 (Clarke et al. 2014, Rogelj et al. 2018b). Short- and medium-term analyses might thus to a large extent underrate the biomass role, leading to myopia and mismatching policies; (3) their climate scenarios have considered at most the 2 °C goal and paid no attention to 1.5 °C.

Since the IPCC AR5, a fast increasing attention in the intentional community is being paid to biomass and BECCS. Many papers have clarified their significance globally in realizing climate goals. However, what they explicitly indicate for specific countries and especially for China has not been sufficiently presented in literature. To fill the gap, this study will focus exclusively on China and try to explore what the role of biomass might be in China’s long-term mitigation toward the Paris climate goals by 2100, by assuming three narratives and five scenarios and modeling with an IAM framework—the Global Change Assessment Model (GCAM). The long timeframe results might offer a more complete picture for understanding potential roles of biomass, and shed some light on how the government might formulate its long-term biomass strategies in supporting a well-below 2 °C and even 1.5 °C future.

2. Methods

2.1. Modeling framework

GCAM (Shukla and Chaturvedi, 2012, McJeon et al. 2014), which simulates long-term changes in global energy-economy-land-climate systems and tracks emissions for multiple greenhouse gases (including both CO₂ and non-CO₂) and pollutants, is adopted as the modeling framework in this study (also see section SI in supplement information, available online at stacks.iop.org/ERL/13/124028/mmedia). As a bottom-up partial equilibrium model, GCAM incorporates relatively detailed representations of the energy system (the core of the model) covering resource production, energy conversion, energy distribution and end-use. The 4.0 version of GCAM divides the world into 32 geographical regions (China is an individual region) and calculates dynamic-recursively from 2010 (base year) toward 2100 at a 5 year step. The end-use energy service demands highly drive the dynamics and developments of the future energy system. To better reflect circumstances and energy service demands and identify mitigation options for China, we have further refined China’s three end-use sectors (industry, building and transportation) on top of the standard GCAM4.0 (the refined version is also called as GCAM-TU and detailed in Yin et al. 2015, Wang et al. 2016, Chen et al. 2018, Pan et al. 2018). Overall, industry is disaggregated into eleven subsectors (steel-iron, cement, aluminum and nonferrous metals, chemicals, manufacturing, construction, mining, paper and wood, nonmetallic minerals, food process, agriculture); building is disaggregated into four climate zones (severe cold, old, hot summer cold winter, hot summer warm winter) and five services (heating, cooling, lighting, hot water and cooking, household appliances); transportation is disaggregated into five passenger (intercity, urban, rural, business, international air) and four freight (general, rural, international ship, international air) subsectors and further into specific modes and technologies. GCAM considers both fossil and non-fossil resources. Biomass, a non-fossil resource, emerges in many fields in GCAM as either feedstock or fuel...
(table 1), and we will consider full availability of bioenergy technologies including BECCS in this study. The biomass-related technologies and fuels will compete with a rich set of technologies and fuels (both mature and under research, development and demonstration) related with other energy to provide energy carries and services in different sectors, through a logit sharing pattern. For instance, conventional and combined-cycle biomass (with/without CCS) compete with other nearly 20 technologies to generate electricity. As a global model, China’s biomass feedstock is supplied in GCAM through both domestic production (municipal waste, agriculture and forestry residues, and dedicated energy crops) and international import. Estimates of future domestic production in GCAM depend largely on economic level, bioenergy price and land profitability. In the model, there is no limitation of biomass feedstock availability and trade. More materials and assumptions on biomass in GCAM are provided in section S2 in supplement information.

2.2. Scenarios and assumptions

China’s mitigation shall keep in step with global mitigation toward the Paris climate goals and the NDC is the first step. In this study, we focus on CO₂ mitigation in the energy system (fossil fuels and industrial processes). China’s emissions trajectories by 2030, resulting from implementing the current NDC, are assumed to follow Pan et al (2017) and updated with recent emissions data (CAIT Climate Analysis Indicators Tool 2018). With the assumption, China’s emissions reach 10.6 GtCO₂ by 2030 and approximately 205 GtCO₂ during 2011–2030. We adopt the global carbon budgets for the energy system by 2100 specified by the representative concentration pathway 2.6 (Van Vuuren et al 2011) and the average 1.5 °C pathway in Rogelj et al (2015) to characterize a well-below 2 °C and 1.5 °C future, respectively (figure 1(a)). Both the two global pathways have adopted BECCS to achieve net-negative emissions in the second half of the century. How many carbon budgets China’s energy system might share, under the two selected pathways, are determined applying a ‘carbon budgets’ methodology (BASIC experts 2011) (note that other allocations are also possible, but implications on decarbonizing the energy system are expected to be largely similar because their allocated budgets are simply all very small when compared with China’s current emissions and projected trends (Pan et al 2017)). Historical CO₂ emissions are counted from 1850, and then China’s energy system carbon budgets remaining beyond 2030 are calculated as about 115 GtCO₂ and 10 GtCO₂ for 2 °C and 1.5 °C, respectively.

To translate the calculated post-NDC budgets into emissions trajectories that China might follow from the NDC toward the Paris climate goals, this study largely follows Pan et al (2018) which revise the analytic capped-emissions trajectory model proposed in Rau-pach et al (2014) to accommodate negative emissions. The acceptable sizes of negative emissions and associated technologies (in particular BECCS) have been a social debate and not determined (the Chinese government has not yet promulgated any specific policy on BECCS). To better understand the biomass role, this study considers three narratives: zero-emission, negative-emission and deep-negative-emission (table 2). These narratives, to some extent, might be understood as the representations of three different underlying attitudes of the Chinese government to applying BECCS and other NETs in the future (for instance, zero-emission might in part imply conservatism, deep-negative-emission radicalism, and

---

| Sector                  | Biomass applications and technologies                                      |
|-------------------------|------------------------------------------------------------------------------|
| Electricity production  | Conventional biomass with/without CCS, biomass combined cycle with/without CCS |
| Refining                | Bioethanol with/without CCS, biodiesel with/without CCS                      |
| Other transformations   | Hydrogen production with/without CCS, gas processing and district heat generation |
| End-use sectors         | Fuels in industry (with/without CCS) and building (also including the traditional use in rural areas) |

---

**Table 1.** Modeling biomass applications in the energy system in GCAM.
negative-emission middle-of-the-road). Accordingly, five mitigation scenarios (figure 1(b)), three for 2 °C and two for 1.5 °C, are developed for China’s long-term energy system decarbonization. While using specific global emissions pathways and allocations, the created mitigation scenarios appear to cover a wide range of underlying transformation trajectories for China. For instance, the year of reaching net-zero carbon emissions ranges approximately between 2050 and 2070, and the 2050 emissions between −0.2 and 4.7 GtCO₂. The five scenarios will be imposed as China’s carbon caps of the energy system, respectively in GCAM (the rest world is assumed to share the remaining global budgets). To try to control inter-sectoral carbon leakage, the energy-sector carbon prices resulting from implementing these carbon caps will be also imposed to land-use CO₂ and non-CO₂ emissions. Socioeconomic assumptions toward 2100 largely follows Pan et al (2017) which consider China’s ‘New Normal’ and remain unchanged during modeling (also see section S3 in supplementary information).

### 3. Results

#### 3.1. Biomass consumption

Consistent with improved urbanization and income, traditional biomass use in China’s rural area (figure 2(a)), as a desired outcome, swiftly decreases (currently over 20% below the 2010 level (Wang 2017)). According to our least-cost modeling, the limited bioenergy consumption is likely to continue toward 2030 (figures 2(b), (c)), indicating China’s NDC mitigation would rely mainly on other options such as sharply cutting coal and promoting non-biomass renewables. However, bioenergy will start to play an increasing role in China’s energy supply in the post-NDC period. Among the five scenarios, 2C00 and in particular 1.5C20 calls for much faster mitigation from 2030 toward mid-century. Besides displacing freely-emitting fossil energy by other non-fossil alternatives, meeting the two scenarios observably ramps bioenergy up during 2040–2050. By 2050, bioenergy consumption arrives at 21 EJyr⁻¹ in 2C00 and even 26 EJyr⁻¹ in 1.5C20, providing 10% and 13% of China’s total primary energy, respectively; and the majority of bioenergy is consumed in refineries (figure 2(d)) to provide zero-carbon liquids to difficult-to-abate sectors such as transportation. The other three scenarios partly delay China’s mitigation from medium- to long-term, resulting in that bioenergy is not widely utilized until 2050. However, from 2050 onwards, bioenergy expands at an aggressive speed, especially when China chooses to follow deep-negative-emission. By 2100, China’s bioenergy consumption in deep-negative-emission (55 EJyr⁻¹ for 2 °C and 59 EJyr⁻¹ for 1.5 °C) almost doubles the negative-emission level (31 EJyr⁻¹ for 2 °C and 28 EJyr⁻¹ for 1.5 °C) and quintuples the zero-emission level (11 EJyr⁻¹ for 2 °C).

Comparing these narratives and scenarios highlights three major implications: (1) biomass plays an important role and is used robustly in large amounts in China’s post-NDC mitigation when aiming at the Paris climate goals. The share in total primary energy reaches as high as 6.5%–30% in our five scenarios by the century end; (2) while overall significant, the exact biomass deployment trajectories are determined by how China arranges its mitigation pace beyond 2030. For either 2 °C or 1.5 °C, a more ambitious 2030–2050 transformation after the NDC depends on larger medium-to-long-term bioenergy (mainly used in refining); delaying the ambition delays bioenergy deployments but consumes far more (mainly used in refining and electricity generating) in the second half of the century to facilitate larger negative emissions; (3) moving from 2 °C to 1.5 °C is characterized by an increasing reliance on biomass, both in a given year and earlier in time. China’s cumulative bioenergy (excluding traditional biomass) consumed during 2011–20100 is about 1720–2165 EJ in the two 1.5 °C scenarios and 995–1580 EJ in the three 2 °C scenarios.

#### 3.2. BECCS

Previous papers have shown various options to transform to low-carbon pathways; however, to create negative emissions, BECCS has been widely assumed to be the predominant technology (Clarke et al 2014). Imposing very low carbon budgets for 1.5 °C would need BECCS to offset 600–1300 GtCO₂ globally over the 21st century, and excluding BECCS or limiting bioenergy use is most likely to make the stringent goal infeasible (Bauer et al 2018). In the first half of the century, according to cost-effective competitions, only a very small fraction of electricity is biopower in China (figures 3(a), (b)). By 2050, it is projected that China’s biopower is less than 300 TWh and accounts for less than 2% of total outputs in all five presented scenarios; but despite small volumes, BECCS represents 92%–

---

Table 2. Narratives and scenarios assumed for China contributing to the Paris climate goals.

| Narrative            | Scenario                                      | Notation               |
|----------------------|-----------------------------------------------|------------------------|
| Zero-emission        | China’s CO₂ emissions gradually decrease to net-zero | 2C00                   |
| Negative-emission    | China’s CO₂ emissions gradually decrease to net-negative, and the maximal net-negative emissions per year are assumed to be 20% of China’s 2010 emissions levels | 2C20 1.5C20            |
| Deep-negative-emission| China’s CO₂ emissions gradually decrease to net-negative, and the maximal net-negative emissions per year are assumed to be as large as 50% of China’s 2010 emissions levels | 2C50 1.5C50            |
100% of biopower. China’s 2050 electricity is generated to a great extent from non-biomass renewables, nuclear and fossil-CCS technologies. Following zero-emission and negative-emission narratives, BECCS-sourced electricity shows slightly increases from 2050 onwards, and China’s 2100 electricity supply is dominated by wind, solar and nuclear. However, in achieving deep-negative-emission in 2C50 and in particular in 1.5C50, BECCS gradually becomes competitive in power sector after 2050. The 2100 electricity sourced from BECCS approximately elevates to 2000 TWh in 2C50 and 3250 TWh in 1.5C50, accounting for nearly 10% and 16% of total outputs, respectively.
Besides in electricity, BECCS is also assumed in liquid refining, hydrogen production and industrial activities in our modeling (their removal fractions might be different, see figure S3 in supplement information). In fact, in all five scenarios, more biomass is overall consumed in China in non-electric applications than in electricity, and over a half of BECCS is applied in liquid and hydrogen production over the century. This is because the processes of biofuel and hydrogen production produce pure CO₂ streams which are relatively easier to capture, leading to smaller cost increments when applying CCS (Rogelj et al 2018a). A key feature of China contributing to the Paris climate goals is that BECCS plays an irreplaceable role and seems unavoidable in all assessed scenarios (even zero-emission narrative calls for BECCS), and any delayed mitigation evidently increases the need for BECCS (figure 3(c)). For 1.5°C, approximately 95 GtCO₂ in 1.5C20 and even 138 GtCO₂ in 1.5C50 is offset from China’s energy system via BECCS during the century, contributing 43% and 56% of China’s total captured CO₂ emissions, respectively. The numbers are equivalent to nearly 10 and 14 years of current annual emissions, respectively. For 2°C, cumulative volumes stored by BECCS are roughly 53–91 GtCO₂ and account for 26%–42% of total captured CO₂ depending on the selection of narratives. It is noted here that other conceivable NET options have not been explicitly represented in detail for China in our modeling. Therefore, the BECCS requirement reported here might be broadly understood as the requirement of the full NET portfolio, however, BECCS is believed to contribute the dominant part in the energy system (Rogelj et al 2018b). The IPCC SR15 indicates that the global BECCS is deployed at a scale of around 3–7 and 6–15 GtCO₂yr⁻¹ by 2050 and 2100, respectively. If looking at 2050 (2100), China’s emissions removed through BECCS are roughly 0.01–1.1 (0.7–3.6) and 0.02–1.4 (1.7–4.1) GtCO₂yr⁻¹ over our 2°C and 1.5°C scenarios, respectively. Due to tight carbon budgets, China’s bioenergy needs to rapidly combine with CCS over the next two to three decades beyond 2030 (figure 3(d)). In all assessed narratives and scenarios, bioenergy will be almost fully equipped with CCS by 2060 at the latest (the scenarios in the IPCC AR5 indicate that BECCS might even potentially represent 100% of bioenergy use by 2050).

According to the review on extensive NETs literature by Fuss et al (2018), the average unit cost of BECCS ranges from 15 to 400 US$/tCO₂ depending on sources. With the optimistic (pessimistic) cost, China possibly spends 0.8–1.3 (21–36) Trillion US$ on deploying BECCS in the three 2°C scenarios throughout the century, and 1.4–2.1 (38–55) Trillion US$ in the two 1.5°C scenarios; these payments are approximately 0.3%–0.5% (0.7%–1.2%) and 0.5%–0.7% (1.3%–2.9%) of China’s aggregate 2011–2100 GDP, respectively. To date, however, BECCS has received little investment and attention and not been demonstrated in China. Its development is greatly constrained by resource supply, capital, CCS technology, storage capacity, land availability and the lack of public and political supports (Gough et al 2011, Scott and Geden 2018), which have not yet been resolved. Regarding the essential role based on the modeling outcomes, we therefore suggest the Chinese government to deliberate timely and carefully on whether and how to foster BECCS in practice. The finalized BECCS strategies will directly affect not only biomass roadmap but also how much China might need to mitigate when considering mid-century and long-term low-carbon development strategies. If trying to minimize BECCS, policies and investments on enabling factors, such as shifting consumption pattern, lowering energy demand, raising energy efficiency and promoting renewable energy (Van Vuuren et al 2017, 2018), need to be reinforced and implemented in the coming years at an unprecedented pace so that very low mid-century carbon emissions become achievable in China. Otherwise, the government has to make thorough domestic preparations and pursue international supports for moving economic, infrastructural and sociopolitical barriers to bear large-scale NETs later in the century.

3.3. Biofuel
Biofuel is identified as a valuable bridging option to decarbonize downstream such as transportation where a large-scale electrification is comparatively hard and emissions cannot be compensated through BECCS any longer. China’s liquid system is currently predominated by petroleum, which is projected to maintain toward at least 2040 in our scenarios. After 2040, a clear shift away from fossil-liquid toward biofuel first boosts in 1.5C20 and 2C00 (figure 4(a)). In 2C00 and 15C20, China produces 7.4 and 10.5 EJ of biofuel, respectively by 2050, providing 25% and 49% of total liquids. These numbers are around or a bit above the upper-end of China’s 2050 biofuel production ranges resulting from domestic resource and technology projections in previous papers (Zhao et al 2015). Consistent with the dynamics of biomass consumption, a greater negative-emission narrative maintains a higher share of oil-refined liquid in medium-term but entails more biofuel to replace later on. Compared against 2°C scenarios, the 1.5°C scenarios shrink China’s liquid production and particularly increase the dependence of liquid supply on biofuel, produced in higher shares and earlier in time (figure 4(b)). Fossil-liquid tends to phase out by 2065 (2080) in 1.5C50 (1.5C20) and by almost 2080 in 2C50, but still provides 11% (72%) of China’s total liquids in 2C20 (2C00) by 2100. In international IAM comparisons, phasing-out fossil-liquid seems imperative to achieve 1.5°C (Rogelj et al 2018a). However, regarding the concrete circumstance and the
determining role of petroleum at present, substituting entirely by biofuel will be extremely not easy in China based on our current foresight. Accordingly, more targeted measures aimed at promoting bioethanol and biodiesel technologies and applications are urgently expected to facilitate a high biofuel penetration in China’s liquid market.

3.4. Comparison between consumption and production

Above-mentioned results have focused on a consumption perspective. Dong et al (2018) recently project China’s bioenergy production to be roughly around 20 and 40 EJyr$^{-1}$ by 2050 and 2100, respectively under global socioeconomic and emissions scenarios. Our production projections from GCAM, 16–18 (21–22) and 32–33 (39–40) EJyr$^{-1}$ by 2050 and 2100, respectively in the 2°C (1.5°C) scenarios, are largely consistent with them. Meeting the Paris climate goals likely means, for China, either a very fast immediate decarbonization toward mid-century or a high risk associated with large-scale BECCS beyond 2050. Interestingly, in both cases, China’s bioenergy production reported by our scenarios tends to fall short of consumption in either medium- or long-term (GCAM fills the gap between production and consumption with import). Around 20% of China’s consumed biomass feedstock in 2050 is shown to rely on import (mainly from Africa, other Asian countries and some OECD countries) in both 2C00 and 15C20. In particular, in deep-negative-emissions narrative, where bioenergy is projected to contribute nearly 30% of China’s primary energy by 2100, over a third of the consumed bioenergy will need be obtained from international trade by 2100, which in practice might raise major concerns and challenges on resource supply for China further into the 21st century (our modeling and assumptions are comparatively idealized and allow globally comprehensive supply and trade of biomass feedstock), due to trade barriers, geophysical limitations and surrounding constraints (Muri 2018). Large-scale bioenergy also has pronounced impacts on economic costs, food security and biodiversity (Fuss et al 2016, Sanchez and Kammen 2016, Strapasson et al 2017). Further detailed research, identifying China’s long-term biomass supply potential and the tradeoff between supply and side-effect, would be essential in the future. Meanwhile, a policy package coordinating climate goal and food security is also desired for the purpose of sustainable development.

4. Conclusions

This study has examined the role of biomass in China’s long-term mitigation toward the Paris climate goals by 2100, by assuming three narratives and five scenarios and modeling with a refined GCAM4.0. While not providing all possibilities and answers (we have used a specific version of GCAM and a specific set of storylines, assumptions and parameters), the obtained results have verified the significance of biomass in China’s post-NDC mitigation, providing 6.5%–28% of total 2100 primary energy in the three 2°C scenarios and 15%–30% in the two 1.5°C scenarios. In any assessed scenario, bioenergy use is most likely to be extensive, but the explicit deployment trajectories rely on how the Chinese government considers the post-NDC mitigation pace and how much it wants to accept BECCS: a deeper 2030–2050 decarbonization of the energy system depends on larger medium-to-long-term bioenergy use; delaying the ambition, from short- and medium- to long-term, calls for more substantial bioenergy, BECCS and deployment costs in the second half of the century to make greater negative emissions viable. Moving from 2°C to 1.5°C features that bioenergy is applied in greater quantities and earlier in time, and both BECCS volumes and biofuel shares ramp meaningfully up in China’s energy system.

Although biomass is projected to come into large use only in the post-NDC period, actions and measures should be taken in advance. Our scenarios highlight a widespread development of and an inevitable reliance on BECCS and biofuel beyond 2030, as a key characteristic for China toward the Paris climate goals, which might become a transitional challenge and risk due to the large uncertainties on fundamental impact factors such as technology progress, feedstock supply and even social supports. Therefore, more
comprehensive policies, investments and efforts covering the whole biomass chain, as well as international supports, are expected in China to pave the way from now on. It is also noted that, at the global scope, there is at present a gap by 2030 between the globally aggregate NDCs and the cost-effective emissions levels matching the Paris climate goals (Rogelj et al 2016, United Nations Environment Programme (UNEP) 2017). Implementing more rapid profound near-term actions has the potential to relieve the dependence on NETs in long-term (Clarke et al 2014, Rogelj et al 2018b). If global 2030 emissions are assumed to be reduced by 30% from the current NDC levels, the required global carbon capture scales for meeting 1.5 °C might be possibly halved (Streffer et al 2018). To retain 2 °C and in particular 1.5 °C within reach at a higher possibility, China and all large emitters might hence consider to ratchet-up the NDC, which will help leave more flexibility for the second half of the century—not pinning the hope on deep-negative-emission as a silver bullet.

Acknowledgments

This study is supported by the National Natural Science Foundation of China (71690243, 71703167, 51861135102).

ORCID iDs

Xunzhang Pan https://orcid.org/0000-0001-7269-0475

References

BASIC experts 2011 Equitable access to sustainable development: contribution to the body of scientific knowledge The Expert Forum (Beijing, Brasilia, Cape Town and New Delhi)

Bauer N et al 2018 Global energy sector emission reductions and bioenergy use—overview of the bioenergy demand phase of the EMF-33 model comparison Clim. Change Accepted (https://doi.org/10.1007/s10584-018-2226-y)

CAIT (Climate Analysis Indicators Tool) 2018 CAIT Climate Data Explorer (Washington, DC: World Resources Institute)

Chen H et al 2018 Modeling on building sector’s carbon mitigation in China to achieve the 1.5 °C climate target Energy Efficiency Accepted (https://doi.org/10.1007/s12053-018-9687-8)

Chen W et al 2016 Towards low carbon development in China: a comparison of national and global models Clim. Change 136 95–108

Chen X 2016 Economic potential of biomass supply from crop residues in China Appl. Energy 166 141–9

Clarke L et al 2014 Assessing transformation pathways Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed O Edenhofer et al (Cambridge/New York: Cambridge University Press)

Dong N et al 2018 Land use projections in China under global socioeconomic and emission scenarios: utilizing a scenario-based land-use change assessment framework Glob. Environ. Change 50 164–77

Frank S et al 2017 Reducing greenhouse gas emissions in agriculture without compromising food security? Environ. Res. Lett 12,105004

Fridahl M et al 2018 Bioenergy with carbon capture and storage (BECCS): global potential, investment preferences, and deployment barriers Int. J. Energy Res. 42 135–65

Fuss S et al 2016 Research priorities for negative emissions Environ. Res. Lett. 11 115007

Fuss S, Lamb W F and Callaghan M W 2018 Negative emissions III. Costs, potentials and side effects Environ. Res. Lett. 13 063002

Johansson D et al 2015 Multi-model comparison of the economic and energy implications for China and India in an international climate regime Mitigation Adaptation Strateg. Glob. Change 20 1335–59

Gough C et al 2011 Biomass energy with carbon capture and storage (BECCS or Bio—CCS) Greenhouse Gases 1 324–34

Lugovoy O et al 2018 Multi-model comparison of CO2 emissions peaking in China: lessons from CEMF01 study Adv. Clim. Change Res. 9 1–15

McJeon H et al 2014 Limited impact on decadal-scale climate change from increased use of natural gas Nature 514 482–5

Muri H 2018 The role of large-scale BECCS in the pursuit of the 1.5 °C target: an Earth system model perspective Environ. Res. Lett. 13 044010

Pan X et al 2017 China’s energy system transformation toward the 2 °C goal: implications of different effort-sharing principles Energy Policy 103 116–26

Pan X et al 2018 Decarbonization of China’s transportation sector: in light of national mitigation toward the Paris Agreement goals Energy 155 853–64

Qin Z et al 2018 Bioenergy and biofuels in China: toward bioenergy resource potentials and their impacts on the environment Renew. Sustain. Energy Rev. 82 2387–400

Raupach M R et al 2014 Sharing a quota on cumulative carbon emissions Nat. Clim. Change 4 873–9

Rogelj J et al 2015 Energy system transformations for limiting end-of-century warming to below 1.5 °C Nat. Clim. Change 5 519–27

Rogelj J et al 2016 Paris Agreement climate proposals need a boost to keep warming well below 2 °C Nature 534 631–9

Rogelj J et al 2018a Scenarios towards limiting global mean temperature increase below 1.5 °C Nat. Clim. Change 8 325–32

Rogelj J et al 2018b Mitigation pathways compatible with 1.5 °C in the context of sustainable development The Special Report on Global Warming of 1.5 °C of the Intergovernmental Panel on Climate Change

Rose S K et al 2014 Bioenergy in energy transformation and climate management Clim. Change 123 477–93

Sanchez D and Kammen D M 2016 A commercialization strategy for carbon-negative energy Nat. Energy 1 15002

Scott V and Geden O 2018 The challenge of carbon dioxide removal to keep warming well below 1.5 °C Nat. Clim. Change 8 354–63

Shukla P R and Chaturvedi V 2012 Low carbon and clean energy Economic aspects Adv. Clim. Change Res. 4 166–93

Strapasson A et al 2017 On the global limits of bioenergy and land use for climate change mitigation GCB Bioenergy 9 1721–35

Streffer et al 2018 Between Scylla and Charybdis: delayed mitigation narrows the passage between large-scale CDR and high costs Environ. Res. Lett. 13 044015

UNEP (United Nations Environment Programme) 2017 The Emissions Gap Report (Nairobi, United Nations Environment Programme)

UNFCCC (United Nations Framework Convention on Climate Change) 2015 Adoption of the Paris Agreement (1/CP.21) (Paris: United Nations Framework Convention on Climate Change) vol 21932 http://unfccc.int/resource/docs/2015/cop21/eng/t090101.pdf

Van Vuuren D P et al 2011 RCP2.6: exploring the possibility to keep global mean temperature increase below 2 °C Clim. Change 109 95–116
Van Vuuren D P et al 2017 Open discussions of negative emissions is urgently needed Nat. Energy 2 902–4
Van Vuuren D P et al 2018 Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies Nat. Clim. Change 8 391–7
Wang L et al 2016 Win–win strategies to promote air pollutant control policies and non-fossil energy target regulation in China Appl. Energy 163 244–53
Wang Q 2017 2017 Energy Data (Beijing: The Energy Foundation) (in Chinese)
Werner C et al 2018 Biogeochemical potential of biomass pyrolysis systems for limiting global warming to 1.5 °C Environ. Res. Lett. 13 044036
Yin X et al 2015 China’s transportation energy consumption and CO₂ emissions from a global perspective Energy Policy 82 233–48
Zhao L et al 2015 Long-term projections of liquid biofuels in China: uncertainties and potential benefits Energy 83 37–54
Zhou N et al 2013 China’s energy and emissions outlook to 2050: perspectives from bottom-up energy end-use model Energy Policy 53 51–62