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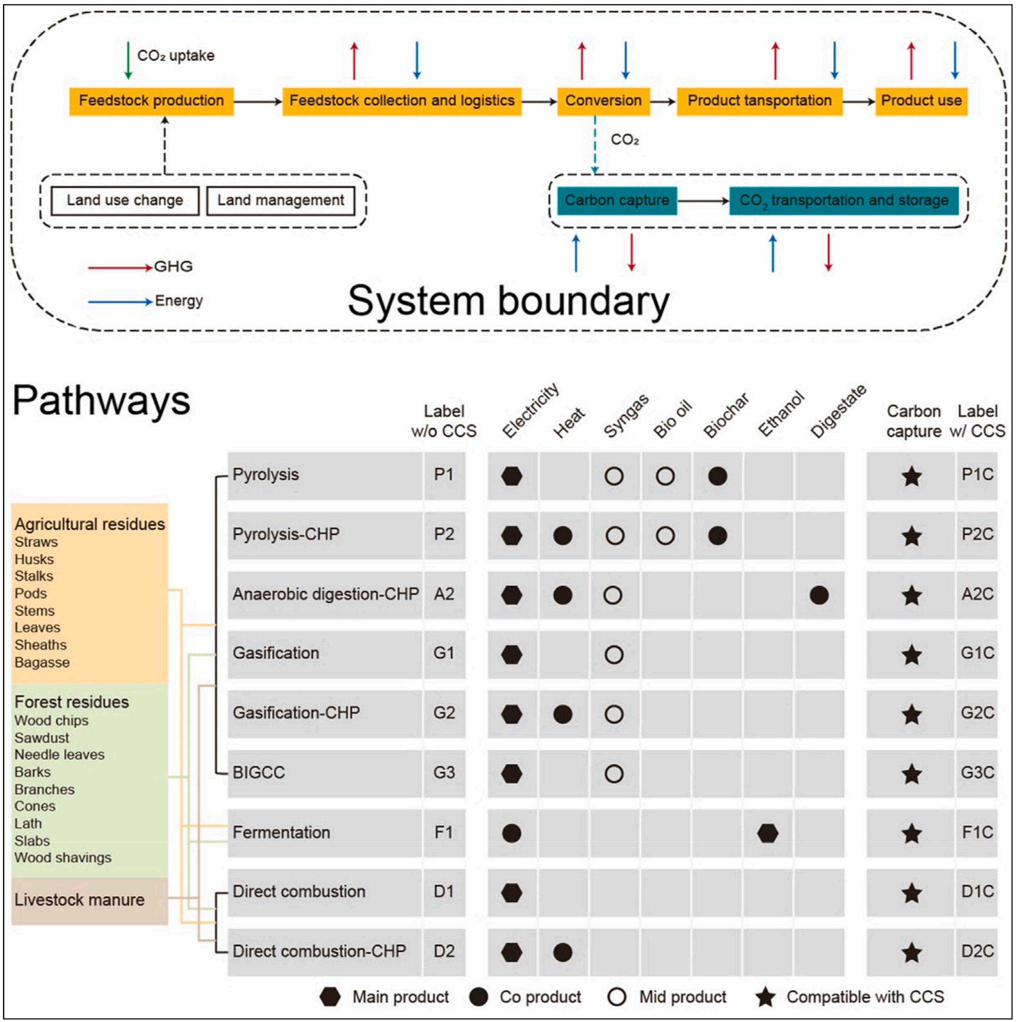
Sustainable bioenergy contributes to cost-effective climate change mitigation in China



	Label w/o CCS	Electricity	Heat	Syngas	Bio oil	Biochar	Ethanol	Digestate	Carbon capture	Label w/ CCS
Pyrolysis	P1	⬢		○	○	●			★	P1C
Pyrolysis-CHP	P2	⬢	●	○	○	●			★	P2C
Anaerobic digestion-CHP	A2	⬢	●	○				●	★	A2C
Gasification	G1	⬢		○					★	G1C
Gasification-CHP	G2	⬢	●	○					★	G2C
BIGCC	G3	⬢		○					★	G3C
Fermentation	F1	●					⬢		★	F1C
Direct combustion	D1	⬢							★	D1C
Direct combustion-CHP	D2	⬢	●						★	D2C

⬢ Main product ● Co product ○ Mid product ★ Compatible with CCS

Yifan Xu, Pete Smith, Zhangcai Qin

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Highlights

Only a quarter of the theoretical biomass is available for sustainable bioenergy

Bioenergy could meet over half of national residential electricity demand

Emissions reduction from bioenergy is comparable to national terrestrial carbon sink

The abatement costs of bioenergy are relatively low

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Article

Sustainable bioenergy contributes to cost-effective climate change mitigation in China

Yifan Xu,[1] Pete Smith,[2] and Zhangcai Qin[1,3,*]

SUMMARY

Bioenergy development is critical for achieving carbon neutrality. Biomass residues from agriculture, forest, and livestock manure provide substantial bioenergy resources in China, but their availability, climate, and economic impacts have not been evaluated systematically. Here we assess biomass sustainability, bioenergy potential, greenhouse gas emissions (GHG) reduction, and cost-effectiveness using an integrated data-modeling approach. Nationally, only 27% of biomass can be used for sustainable bioenergy production, but can contribute to significant climate change mitigation with optimized regional utilization. The annual GHG reduction can reach 1.0 Gt CO_2e for bioenergy, or 1.4 Gt CO_2e for bioenergy with carbon capture and storage (BECCS), which is comparable to total terrestrial ecosystem carbon sinks in China. The abatement cost varies regionally but is lower than many other carbon removal technologies. Our findings reveal region-specific bioenergy pathways that contribute to carbon neutrality, and encourage future assessments to explore factors including technological advances and carbon markets.

INTRODUCTION

Bioenergy has been proposed as a viable solution to meet energy demand and mitigate climate change toward a carbon-neutral world.[1–3] Various biomass sources from agriculture, forest, animal waste, and energy crops offer abundant resources, and enable the utilization of bioenergy in diverse forms (e.g., liquid fuel, solid fuel, biogas) across almost every sector (e.g., transportation, electricity, and heat).[2,4] By replacing fossil-based fuels, bioenergy can significantly mitigate greenhouse gas (GHG) emissions that would otherwise be released due to the combustion of carbon stored underground for millions of years (i.e., coal, oil, and gas). Particularly, bioenergy holds significant potential for sectors posing challenges in decarbonization, notably industry and transportation.[5] Bioenergy with carbon capture and storage (BECCS) could enhance the potential of biomass to mitigate climate change.[6,7] Moreover, bioenergy presents opportunities to ameliorate air pollution and associated health risks arising from the open burning of agricultural residues.[8–10] Currently, bioenergy constitutes merely 8.6% of the global primary energy consumption, contrasting sharply with the dominance of fossil fuels at 80% (2019).[11] Nevertheless, it is estimated that about 17.8 Gt of biomass could be produced each year globally,[2] with sustainable supply prospects reaching 5.6 Gt.[12] By 2050, the available global biomass production could reach 4.9–40.1 Gt annually, potentially replacing 51–460 EJ of fossil-based energy, and reducing GHG emissions by 4.9–38.7 Gt CO_2e per year.[12,13] Factoring in bioenergy's deployment across various climate and long-term scenarios, anticipated demand could soar to 100–300 EJ annually by 2050, with biomass residues contributing approximately 55 EJ yearly.[3,5,13]

Yet estimates of the biomass production potential provide limited insight into the level of the practical deployment of bioenergy.[2] Additional constraints restrict the availability of biomass for bioenergy production.[2,12] Technical challenges in harvesting and collecting residues (e.g., crop stubble, and forest litter) restrict the collectible biomass to a relatively small portion of the total.[14] Furthermore, considerations for environmental sustainability, biodiversity, livelihoods, and intertemporal carbon balances should be in place to protect and preserve natural ecosystems (e.g., primary forests). The availability of resources including land, water, and nutrients determines the maximum biomass production. Bioenergy production should avoid competing use of resources with food, fiber, and other essential uses, especially for purpose-grown energy crops.[5,6,15,16] Excluding current uses including energy (i.e., current traditional and modern bioenergy), fertilizer, and returns to cropland, and losses during harvest, transportation, and delivery, may further limit the available biomass for additional energy production. Depending on assumptions for alternative use, estimates of biomass available for energy production vary greatly.[2,14] In contrast to food crops, fiber plants, and purpose-grown energy crops, residues and wastes from agriculture, forest, and livestock sectors can be deemed sustainable, by providing a fairly large quantity of biomass residues without significant demand for extra land, water, and nutrient resources, and avoiding competing use with other dedicated purposes (e.g., feed, and return to soil) if best management can be practiced.[14–17] In a populous country

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such as China, where land is predominantly reserved for food and fiber, biomass residues from these resources could dominate bioenergy feedstock.[18] However, given the vastness of China, and the spatial variability of these biomass residues,[14,19] the potential for energy production and climate change mitigation is largely uncertain, especially if carbon capture and storage (CCS) and associated costs are taken into consideration.[19,20]

While numerous studies have explored biomass availability, bioenergy production, and greenhouse gas (GHG) emissions using various methodologies,[14,18,19] a consistent and comprehensive assessment from multiple perspectives (e.g., biomass, energy, emissions, and cost) is much needed in China but still unavailable so far.[14,21,22] Currently, individual studies predominantly emphasize biomass resources, reporting annual biomass residues in China ranging from 775 to 1680 million metric tons (Mt), with estimates varying significantly due to differences in biomass definition, data sources, and system boundaries.[18,19,21,23,24] Similarly, estimates of potential bioenergy production, emissions reduction, and cost/benefit also exhibit substantial disparities across separate reports, primarily attributable to variations in source data,[18,19,21] modeling approaches,[23,25] system boundary, and data-model consistency.[19,26] A nationwide, comprehensive evaluation of bioenergy presents a formidable challenge yet remains urgently necessary as China progresses toward carbon neutrality, armed with ambitious emissions reduction targets.[14]

Here, we develop an integrated data-modeling approach based on well-defined biomass residues datasets, aiming to offer consistent, accurate, and systematic assessments of national and regional bioenergy potential, climate impacts, and cost. Specifically, we quantify the optimal utilization of biomass residues in China (e.g., to maximize emissions reduction or minimize cost) to replace fossil fuels in 2020, by evaluating the availability of regional feedstock, gross and net energy output, emissions reduction, and the associated cost for achieving the level of mitigation. The amount of biomass, including theoretical, collectible, and sustainable, is quantified for agricultural residues, forest residues, and animal manure specific to province-level regions (31 with available data). The intensity (i.e., per ton of biomass residues) as well as the total amount of energy production, emissions reduction, and the abatement cost are estimated by various bioenergy conversion pathways, for scenarios without (i.e., BE) and with CCS (BECCS) (nine pathways each). We further evaluate the optimal provincial-level utilization of biomass residues to ascertain the maximum national climate change mitigation potential and associated costs. Our findings indicate that only a very limited fraction of biomass residues (27%) could be sustainably used for bioenergy without competing with other applications, a notably lower proportion than previously reported.[18,19] Nevertheless, these limited biomass residues can still substantially reduce greenhouse gas emissions under cost-effective scenarios.

RESULTS

Rich biomass residues with limited availability

Theoretically, about 2200 million metric tons (Mt) of dry biomass residues (36 EJ) can be annually generated from existing sources, comprising agricultural residues (41%), forest residues (35%), and livestock manure (24%) (Figure 1). Agricultural residues primarily consist of crop straw, with secondary residues (e.g., rice husks, and corn cobs) accounting for only 12% of total agricultural residues (2020). Residues from corn, wheat, and rice collectively contribute the most to agricultural residue production, totaling 660 Mt annually (75%, 2020). In the forestry sector, in addition to approximately 16% of secondary biomass residues from commercial harvest and processing (e.g., timber, firewood, and bamboo), substantial quantities of tree trunks and debris may persist due to forest management practices such as thinning, tending, pruning, stubble rejuvenation, and clear-cutting. Livestock manure, originating from animal excretion, stands as one of the primary biomass residue sources. Nationally, beef cattle, sheep, and pig emerge as the top three contributors, collectively accounting for 66% of the total solid manure production of 521 Mt (Figure 1).

Regarding the spatial distribution of total biomass residues in 2020 (Figure 1), Inner Mongolia, Guangxi, Xinjiang, Sichuan, and Henan emerge as the top five contributors, collectively representing 32% of the total production. Inner Mongolia and Guangxi are predominantly characterized by forest residues, whereas Xinjiang and Henan exhibit a higher prevalence of agricultural residues. In the case of Sichuan, the theoretical resources of the three types of residues are roughly equivalent. Nationally, Heilongjiang, Henan, and Shandong, endowed with abundant agricultural residues, possess biomass residue resource potential exceeding 60 Mt of dry matter annually. Due to the extensive forest area and substantial stock volumes, Inner Mongolia, Guangxi, and Yunnan can generate over 60 Mt of forest residues every year. The majority of agricultural residues concentrate in the eastern region, a pattern closely linked to crop cultivation conditions and population density. Forest residues and livestock manure predominantly exist in the central and western regions. Theoretical biomass residues' production estimated here is in line with prior studies (Figure S1), however, the portion that can be sustainably used for energy in China has rarely been investigated.

We demonstrate that only about one-quarter (i.e., 27%) of the theoretically available biomass residues can be feasibly collected for further utilization. The limitation primarily stems from factors including harvest challenges, returns for environmental sustainability, existing uses, and potential losses (Figure 1G). Nationwide, approximately 14% of agricultural residues (i.e., stubble), 46% of forest residues (e.g., litter and residues from remote locations), and 39% of manure (mainly from household farming) remain uncollectible due to environmental, technical, or economic constraints. In the process of collection, storage, and transportation, a total of 74 Mt of biomass residues are lost. Out of the 1400 Mt (26 EJ) of collectible biomass residues, roughly 25% is returned to cropland mainly to maintain soil quality and productivity (e.g., crop residues, livestock manure), and another 31% is allocated for various applications, such as raw materials, fertilizer, energy, and other purposes. Consequently, only 28%, 18%, and 38% of the theoretical biomass residues from agricultural, forest, and animal waste sources, respectively, remain sustainably available, resulting in a total of 578 Mt (10 EJ) of sustainable biomass residues potentially collectible for free (i.e., bioenergy). The estimated production of sustainable biomass residues is lower than previously reported on national biomass residue production.[14,19]

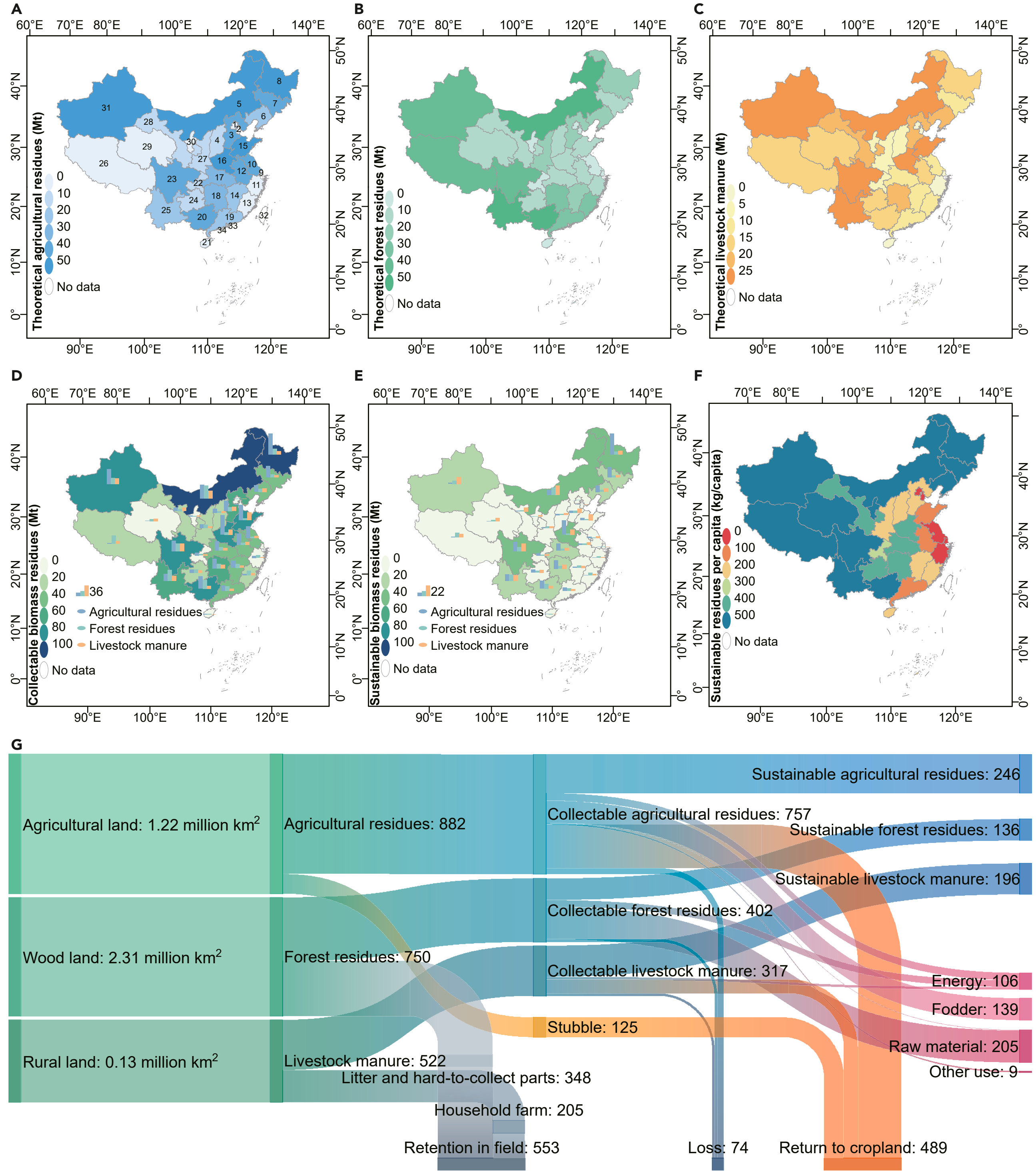
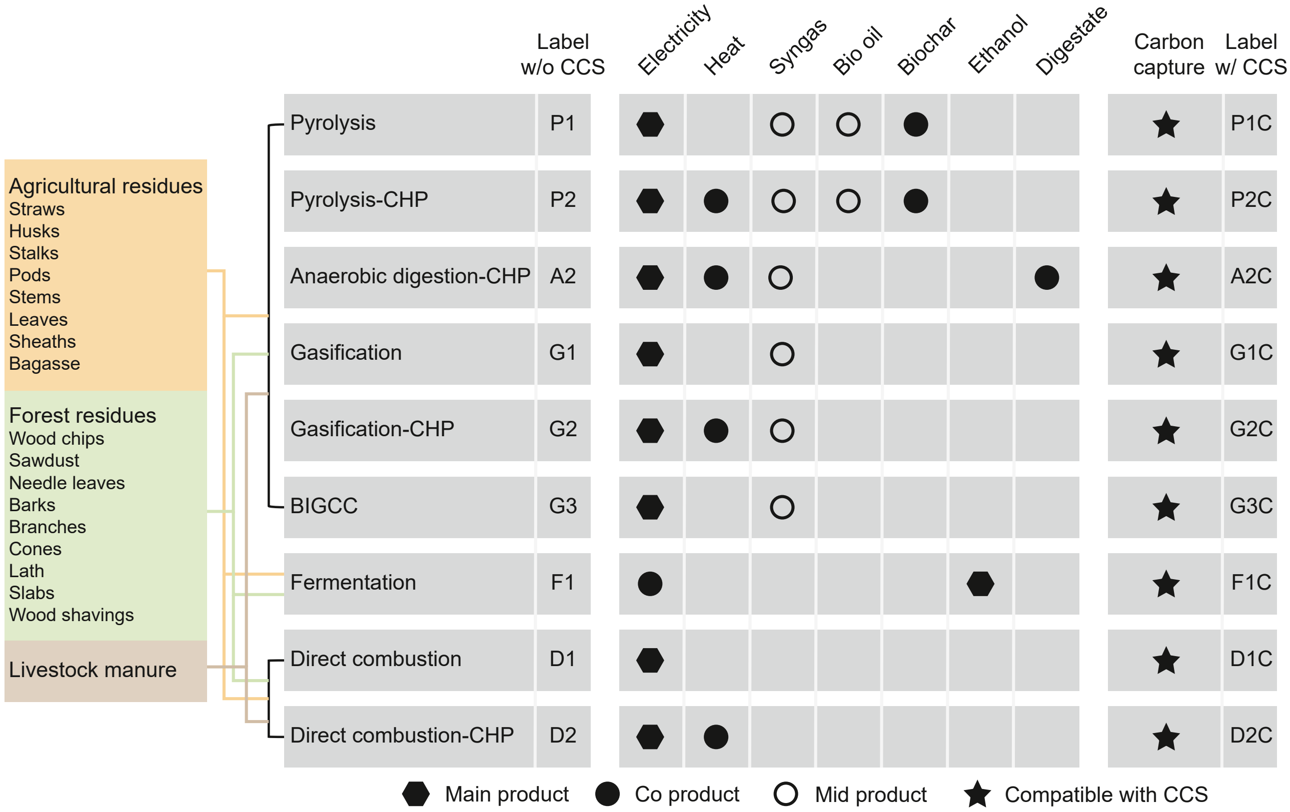


Figure 1. Biomass residue production and its destination in China

The province-level production of biomass residues for (A) theoretical agricultural residues, (B) theoretical forest residues, (C) theoretical livestock manure, (D) total collectible residues, (E) total sustainable residues, and (F) total sustainable residue per capita. The material flow (G) shows the current production and utilization of biomass residues. NA, data not available. The values show dry matter mass in Mt (of 2020). The sustainable residues and manure could be further used for energy purposes. Provinces/regions: 1, Beijing; 2, Tianjin; 3, Hebei; 4, Shanxi; 5, Inner Mongolia; 6, Liaoning; 7, Jilin; 8, Heilongjiang; 9, Shanghai; 10, Jiangsu; 11, Zhejiang; 12, Anhui; 13, Fujian; 14, Jiangxi; 15, Shandong; 16, Henan; 17, Hubei; 18, Hunan; 19, Guangdong; 20, Guangxi; 21, Hainan; 22, Chongqing; 23, Sichuan; 24, Guizhou; 25, Yunnan; 26, Tibet; 27, Shaanxi; 28, Gansu; 29, Qinghai; 30, Ningxia; 31, Xinjiang; 32, Taiwan; 33, Hongkong; 34, Macao.



	Label w/o CCS	Electricity	Heat	Syngas	Bio oil	Biochar	Ethanol	Digestate	Carbon capture	Label w/ CCS
Pyrolysis	P1	⬢		○	○	●			★	P1C
Pyrolysis-CHP	P2	⬢	●	○	○	●			★	P2C
Anaerobic digestion-CHP	A2	⬢	●	○				●	★	A2C
Gasification	G1	⬢		○					★	G1C
Gasification-CHP	G2	⬢	●	○					★	G2C
BIGCC	G3	⬢		○					★	G3C
Fermentation	F1	●					⬢		★	F1C
Direct combustion	D1	⬢							★	D1C
Direct combustion-CHP	D2	⬢	●						★	D2C

⬢ Main product ● Co product ○ Mid product ★ Compatible with CCS

Figure 2. Conversion pathways for BE and BECCS

CCS, carbon capture and storage; CHP, combined heat and power; BIGCC, Biomass integrated gasification combined cycle.

Most biomass residues in China are concentrated in the Northeast, the North China Plain, and the South, characterized by extensive croplands and forests (Figure 1E). At the provincial level, Heilongjiang, Henan, and Jilin dominate in agricultural residue production, collectively contributing 93 Mt annually, while Guangxi, Yunnan, and Inner Mongolia account for 28% of total forest residues. Concerning animal manure, Sichuan, Inner Mongolia, and Xinjiang collectively contribute 25% of the total manure output due to their substantial livestock production. Several provinces in the far west (e.g., Tibet, Qinghai, Ningxia, and Shaanxi) produce comparatively limited biomass residues across all types. When considering availability per capita, the eastern region displays lower biomass residues compared to the western region. Provinces with high population densities, such as Shanghai, Beijing, Tianjin, Zhejiang, and Jiangsu, exhibit relatively modest biomass residues per capita (<100 kg per capita) (Figure 1F). Notably, Tibet stands out due to its vast area and sparse population, resulting in significant biomass residues per capita. Inner Mongolia, Heilongjiang, and Sichuan possess both substantial total biomass residues and impressive biomass residues per capita. Thus, from this perspective, these three provinces emerge as pivotal regions for the development of bioenergy.

Considerable uncertainty exists in assessing the theoretical resource quantities of biomass residues (Tables S5–S7). Nationally, uncertainties for agricultural residues, forest residues, and livestock manure stand at 11%, 22%, and 11%, respectively (Figure S2). The primary source of uncertainty arises from the estimation of forestry residues, largely influenced by China's current forestry policy and industry status. The absence of standardized and consistent definitions for forest residues, coupled with inaccurate calculations in estimating residues, contributes significantly to this uncertainty.[27] Uncertainties in the theoretical amounts of livestock manure vary greatly among provinces. This primarily results from significant variations in the coefficients of livestock and poultry excretion between provinces. The excretion coefficient of pigs in western provinces (e.g., Guizhou, Shaanxi, and Tibet) exhibits uncertainties nearing 50%. In some southwestern regions (e.g., Guizhou, and Yunnan), the uncertainties in cattle's excretion coefficient exceed 30%, while in Jiangxi, the uncertainty of the excretion coefficient of chickens reaches a staggering 98% (Table S7). Furthermore, the assessment of the collectability of forest residue and the portion that poses collection challenges carries substantial uncertainty with current data (Figure S2).

Sustainable energy production

The potential energy generated from sustainable biomass residues varies depending on the type of residue and the chosen bioenergy conversion pathways. Here we include 18 conversion pathways that are either already widely or potentially applicable in China, i.e., nine pairs of pathways for BE and BECCS (Figure 2).[28–35] Given China's ambitious electrification plans for the transportation sector (e.g., full electrification of public sector vehicles by 2035),[36] and the imperative to reduce reliance on coal-based, emission-intensive power,[37] our study primarily

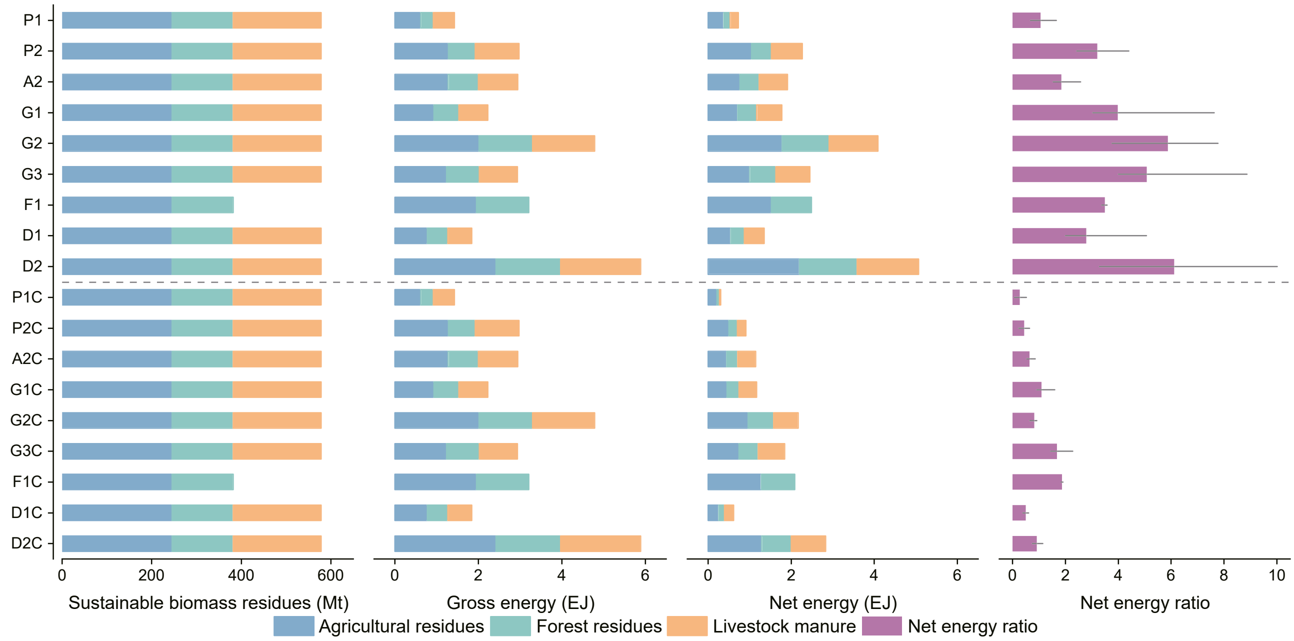


Figure 3. National bioenergy production by pathway

The net energy accounts for energy consumption during biomass residues collection and transportation, bioenergy generation, product transportation, and CO_2 transportation and storage. The error bars indicate the differences in net energy ratio using different biomass residues (i.e., agricultural residues, forest residues, and livestock manure) as feedstock.

focuses on biomass-to-bioenergy conversion technologies aimed at electricity generation, with the sole exception of ethanol as an alternative vehicle fuel (Figure 2). Various biomass residue utilization pathways are comprehensively investigated based on China's bioenergy strategies and the availability of conversion technologies to provide a thorough comparison of emission reduction potentials. Among these options, agricultural and forest residues can be utilized in all pathways, whereas manure cannot be used for ethanol production via fermentation (i.e., F1, F1C). Considering the large lignin content of the forest residue and the high moisture content of the manure, we have taken into account the specific volatile solids (VS) content and digestibility of the forest residues in the anaerobic digestion pathway. For the thermochemical process, additional heat is required for drying the manure and the emissions from the initial air drying (see more details in supplemental information).

In general, the gross energy (the total energy generated regardless of energy input) produced from biomass residues (in terms of heat, power, and biofuel) can reach 1.4–5.9 EJ (EJ), with net energy gain (the difference between the gross energy and the energy input) of 0.3–5.1 EJ, depending on the pathway and corresponding biomass residues type (Figure 3). Combined heat and power (CHP) technology enhances both energy production and efficiency of use. Regarding net energy, a significant portion of the gross energy is offset by energy consumption across all stages from biomass residues in the field to bioenergy generation, including feedstock collection and transportation, bioenergy conversion, and product transportation. Furthermore, many CCS processes (e.g., solvent regeneration, CO_2 compression, and CO_2 transportation and storage) are energy-intensive. As a result, pathways with CCS produce a considerably smaller net energy yield relative to those without CCS. In particular, biomass direct combustion cogeneration (D2), by converting biomass into electricity and heat, offers the highest gross energy production with an average of 10.2 GJ per ton biomass residues (9.81–11.35 GJ t^{-1} varies with different residues), followed by Fermentation (F1) and gasification cogeneration (G2), which yield 8.4 (8.0–9.1) and 8.3 (7.6–9.4) GJ t^{-1} of energy output, respectively (Figure 3). When focusing on the power-only paths (i.e., P1, G1, G3, D1), biomass integrated gasification combined cycle (BIGCC) (G3) can generate the highest net electricity, approximately 681 terawatt-hours (TWh) per year. The annual net power generation is more than four times the existing biomass power generation in 2020, accounting for over half of the annual residential electricity consumption at the national level.[38]

The net energy ratio, the ratio of the net energy gain to the energy input, varies significantly across pathways, ranging from 1.1 to 6.1 for pathways without CCS, and 0.3 to 1.9 with CCS (Figure 3). Notably, the net energy ratio reaches 3.3–10.0 for direct combustion cogeneration (D2), indicating roughly six times more energy produced than consumed. The net energy ratio for the other bioenergy (BE) pathways ranges from 1.1 (P1) to 5.9 (G2). Given that CCS technology requires substantial energy input, particularly in terms of high heat duty, the net energy ratio for CCS-related pathways is significantly lower, meaning less energy is available for external use than bioenergy. Remarkably, when manure is used as feedstock in identical pathways, both the net energy gain and ratio will be significantly lower than those achieved with agricultural and forest residues as feedstock. This difference arises due to the higher moisture content of manure, which requires additional heat for drying in various transformation pathways apart from anaerobic digestion cogeneration (A2).

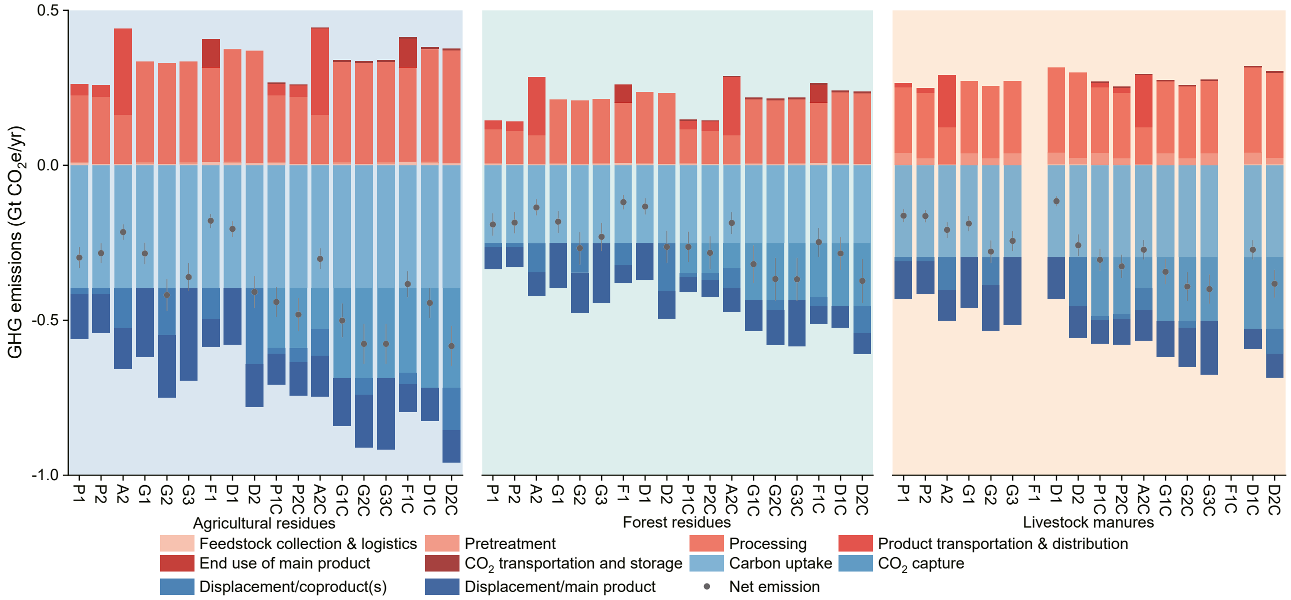


Figure 4. Life cycle GHG emissions by biomass type and pathway

The color of the bars indicates life cycle processes by pathway, and national emissions are based on region- and pathway-specific emissions intensity (Figure S3). The error bars show the 95% confidence interval for the net emissions of each pathway.

Sustainable bioenergy and emissions reduction by pathway

At the national level, GHG emissions can be potentially reduced by a total of 0.30–1.34 gigatons (Gt) CO$_2$e annually through single conversion technology, contingent upon the choice of biomass residues-to-bioenergy pathways, with the greatest contribution from agricultural residues (39%–60%), followed by manure (25%–37%) (Figure 4). Net emissions from all types of biomass residues range from −0.30 to −0.97 Gt CO$_2$e yr^{-1} for BE pathways, and −0.63 to −1.34 Gt CO$_2$e yr^{-1} for BECCS pathways. The application of CCS can enhance pathway-specific emissions reduction potential by 30%–136%, attributable to additional capture of CO$_2$. Furthermore, advanced technologies (i.e., CHP, BIGCC) effectively utilize residual energy (e.g., heat) to substitute conventional sources of energy (mostly fossil-based) that would otherwise be consumed in processing, which substantially reduces overall emissions.

Over 73% of greenhouse gas (GHG) emissions during the bioenergy life cycle are primarily from either the biomass residues to the bioenergy processing stage, which necessitates the input of electricity and heat and involves carbon release from feedstock, for most pathways, or the product transportation & distribution stage for anaerobic digestion related pathways (i.e., A2, and A2C) (Figure 4). In the context of emissions reduction, aside from CO$_2$ uptake during biomass growth, product displacement credits tend to dominate the overall negative effect. This is mainly because displaced products and co-products (e.g., heat) result in a substantial reduction in fossil fuel emissions. Particularly in BE pathways, G2, G3, and D2 present the greatest potential for reducing greenhouse gas (GHG) emissions (0.84–0.97 Gt CO$_2$e yr^{-1}), primarily due to their main products (i.e., electricity) and/or co-products (i.e., heat). Further, for BECCS, additional emissions reduction can be obtained via CCS, rendering the three pathways (i.e., G2C, G3C, and D2C) the most favorable options in net emissions (approximately −1.33 to −1.34 Gt CO$_2$e yr^{-1}).

The cost for bioenergy and bioenergy with carbon capture and storage

In terms of abatement cost for emissions reduction, most BE pathways tend to be more cost-effective than the BECCS pathways (Figure 5). Specifically, the abatement costs can vary from −10 to 44 USD t^{-1} CO$_2$e for BE pathways, contingent upon biomass residue type and the chosen pathway. In certain instances, net profits can be achieved through pathways such as direct combustion cogeneration, BIGCC, and pyrolysis cogeneration, applied to agricultural residues (i.e., D2, G3, and P2), as well as the utilization of manure in pathways of anaerobic digestion and cogeneration, direct combustion cogeneration, BIGCC, and pyrolysis cogeneration (i.e., A2, D2, G3, and P2), mainly due to sales of products (e.g., heat and electricity). While with BECCS, costs would increase significantly, ranging from 25 USD t^{-1} CO$_2$e for the anaerobic digestion cogeneration of livestock manure (A2C) to as high as 68 USD t^{-1} CO$_2$e for the direct combustion of livestock manure (D1C). More specifically, for agricultural residues, direct combustion cogeneration, BIGCC, and pyrolysis cogeneration are the only four pathways (D2, G3, and P2) that generate net gain from approximately 0.6 (pyrolysis cogeneration) to 1.0 (direct combustion cogeneration) USD per ton CO$_2$e. For forest residues, none of the pathways result in net economic gains. Among various pathways of manure utilization, anaerobic digestion cogeneration, direct combustion cogeneration, BIGCC, and pyrolysis cogeneration (A2, D2, G3, and P2) without CCS technology can yield net income due to the relatively low cost of feedstock, ranging from 1.1 (BIGCC) to 9.8 (anaerobic digestion cogeneration) USD per ton CO$_2$e. Generally, the costs of emissions abatement mainly stem from the procurement and transportation cost of feedstock if CCS is

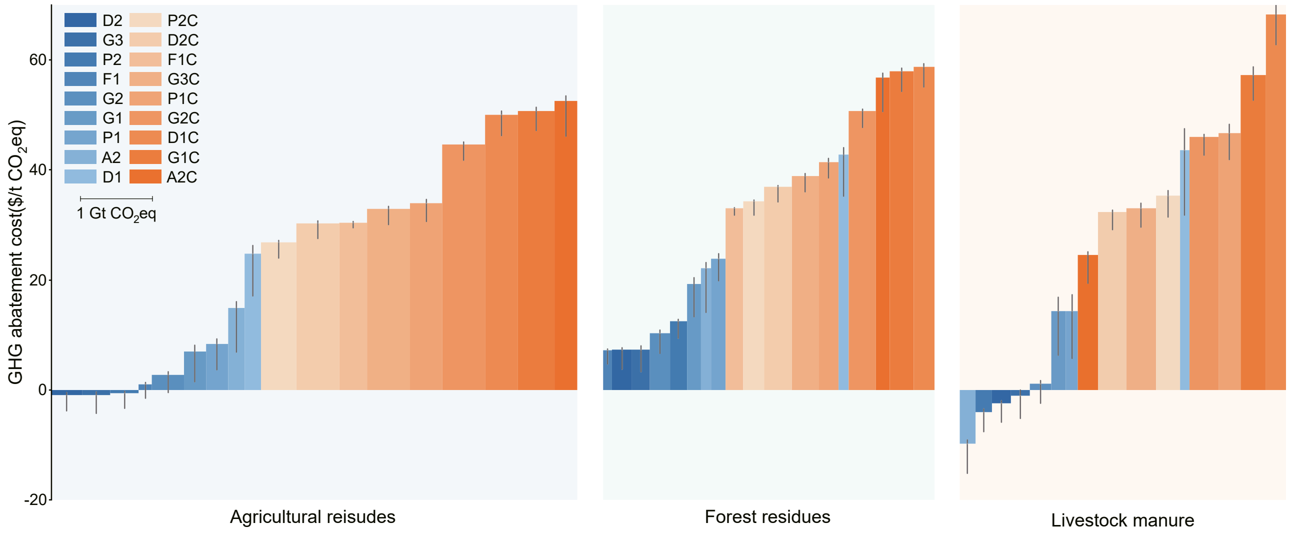


Figure 5. Abatement cost for emissions reduction differs with conversion pathways

The width of the bars shows the relative size of national emissions reduction if all sustainable biomass residues are used. The error bars show the differences in GHG abatement costs for each pathway in different provinces.

not deployed (i.e., 26%–56%). Carbon capture and storage (CCS) technology significantly increases the overall abatement cost, despite the substantial enhancement in emissions mitigation potential. These additional costs primarily result from increased fixed costs and the added expense of CO_2 transportation and storage (Figure S4).

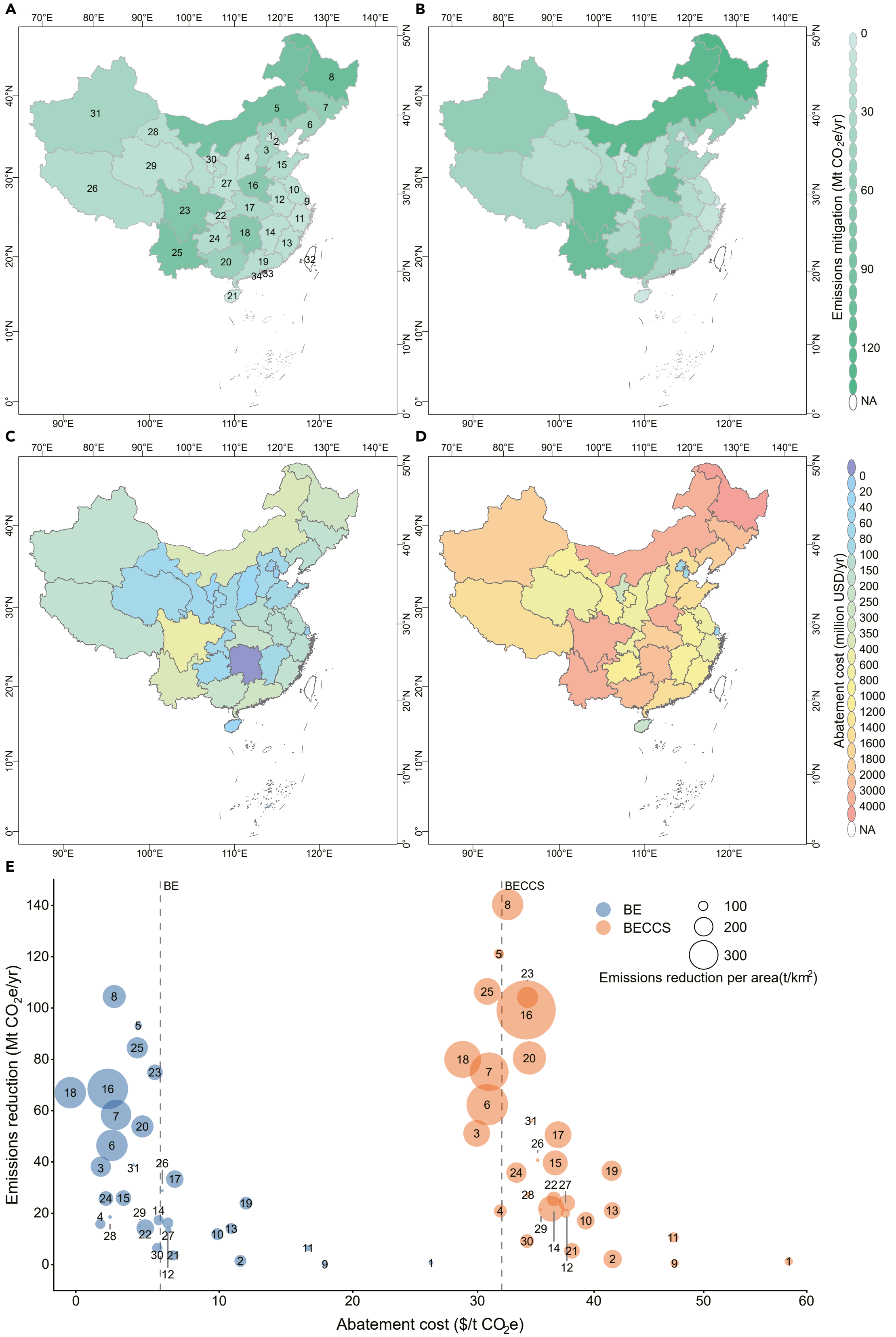
It is noteworthy that, compared to corresponding bioenergy (BE) pathways, bioenergy with carbon capture and storage (BECCS) can substantially augment the overall emissions reduction, raising the national maximum from 0.97 to 1.34 Gt CO_2e annually, via pathways with similar mitigation potential (i.e., gasification-CHP, gasification-BIGCC, and direct combustion-CHP). The increase in abatement cost, however, could fluctuate considerably, ranging from a minimum of 16 USD in the direct combustion of forest residues (i.e., D1C) to a maximum of 45 USD in the gasification cogeneration of manure (G2C). When considering only the marginal emissions reduction and abatement cost, for each extra ton of CO_2e reduction attributable to CCS, the cost could reach as high as 113 USD ($58-$167).

Emissions reduction by region

By optimizing province- and biomass-specific conversion pathways to maximize emissions reduction, the potential for national climate mitigation using sustainable biomass residues can attain 1.02 Gt CO_2e yr^{-1} and 1.41 Gt CO_2e yr^{-1} for BE and BECCS, respectively (Figures 6A and 6B). On average, the associated abatement cost stands at 4.0 USD t^{-1} CO_2e for BE, and 33.6 USD t^{-1} CO_2e for BECCS, considerably lower than the cost of emissions removal in other sectors, e.g., iron and steel, coal power, and cement ($51-$174).[39] At the national level, the total cost would be around 4 billion USD if bioenergy were produced without CCS (Figure 6C), corresponding to roughly 0.03% of the gross domestic product (GDP) of China in 2020. The deployment of BECCS can obtain an additional 38% emissions reduction than bioenergy, but with a cost as much as 11.6 times higher (Figure 6D), due to the elevated expenses associated with CCS. However, the total annual cost at the national level for this BECCS scenario amounts to 47 billion USD, only 0.3% of the GDP of 2020. In the event of considering the most economical scenario, the potential economic gain can reach 1.2 billion US dollars per year, but the emissions reduction under this scenario would be constrained to only 0.74 Gt CO_2e yr^{-1}.

Energy production (Figure S5) and the resultant emissions reduction (Figure 6) are notably concentrated in the eastern region, where biomass residues predominantly originate (Figure 1). Approximately half of the national biomass residues are sourced from the top seven most productive provinces, with Heilongjiang ranking highest among them. By optimizing biomass residue utilization via biomass-specific pathways with the least life cycle emissions, the provincial contributions of emissions reduction follow a similar pattern to the spatial distribution of biomass residues (Figures 6A and 6B). The greatest emissions reduction occurs in the highly productive regions. Specifically, Heilongjiang alone has the potential to reduce total national emissions by approximately 10%, regardless of CCS deployment. Of all applicable pathways, gasification-CHP (G2 in BE) and BIGCC (G3 in BECCS) yield the most substantial emissions reduction across most provinces (Figure S6). The "optimal" pathway is contingent upon the region (Figure S6), mainly due to regionally determined parameters (e.g., emissions intensity of displaced heat and electricity, energy structure) affecting the provincial life cycle emissions estimates.

The difference in abatement cost between BECCS and BE varies from 27 to 33 USD t^{-1} CO_2e across provinces (Figure 6E). Province-wide annual total costs exhibit a broad spectrum, ranging from −25 million USD in Hunan province to 405 million USD in Sichuan for BE, and from 26 million USD in Shanghai to well over 4 billion USD in Heilongjiang for BECCS. It is highly dependent on the intensiveness of biomass residues


A
B
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70°E
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100°E
110°E
120°E
130°E
140°E
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10°N
20°N
30°N
40°N
50°N
Emissions mitigation (Mt CO$_2$e/yr)
0
30
60
90
120
NA
Abatement cost (million USD/yr)
0
20
40
60
80
100
150
200
250
300
350
400
600
800
1000
1200
1400
1600
1800
2000
3000
4000
NA
BE
BECCS
100
200
300
Emissions reduction per area(t/km^2)
Emissions reduction (Mt CO$_2$e/yr)
Abatement cost ($/t CO$_2$e)
0
10
20
30
40
50
60
0
20
40
60
80
100
120
140

Figure 6. The maximum emissions reduction and associated abatement cost vary by province

The GHG emissions reduction for (A) BE and (B) BECCS, and the abatement cost for (C) BE and (D) BECCS are estimated for individual provinces. The size of the circle (E) shows the overall reduction in GHG emissions per land area by province. NA, data are not available. The provinces/regions are the same as in Figure 1.

and therefore emissions reduction, as well as the local cost-effectiveness of technology (Figure 6E). For BE, provincial costs typically comprise less than 0.1% of the local GDP, although it could escalate significantly if CCS is factored in. Five provinces, collectively providing approximately one-fourth of national emissions reduction, will have to spend over 1% of their GDP on BECCS. In the most productive provinces, Heilongjiang and Tibet, the total cost exceeds 2% of their GDP.

In scenarios characterized by optimal emission reduction potential and minimal cost, the marginal cost of reducing emissions via both BE and BECCS increases steadily. This trend is influenced by the location and type of biomass residue resources employed in the development of BE and BECCS. Notably, deploying these technologies in numerous regions of China, particularly in the central and eastern provinces, offers a cost-effective strategy for addressing climate change. Nevertheless, regardless of the choice of scenario, substantial investment is essential to achieving the "last mile" of China's BE and BECCS emission reduction and unlocking their full potential.[40] Thus, it is crucial to optimize the technical pathways and development areas in China to achieve the ultimate goal of emission reduction through BE and BECCS and to avoid excessively significant financial commitments.

DISCUSSION

Emissions reduction resulting from bioenergy development (0.4–1.4 Gt CO_2e yr^{-1}) corresponds to approximately 5–14% of current national GHG emissions from fossil sources (2010s),[41] suggesting the potential of BE, especially BECCS, for limiting future emissions rises. For terrestrial ecosystems, the carbon sinks in China over the past several decades ranged from 0.6 to 1.3 Gt CO_2 annually.[42] By implementing additional measures to improve ecosystems, future carbon sequestration could reach a total of 1.4–1.7 Gt CO_2e yr^{-1} through management[43] or an extra 0.6–1.0 Gt CO_2e yr^{-1} via natural climate solutions.[44] Bioenergy, if well developed, could offer a comparable mitigation potential from all terrestrial ecosystems nationwide, potentially aiding China in its transition toward national carbon neutrality.[45] It is important to note that the estimated total emissions reduction resulting from bioenergy development in this study is generally lower than that of some previous reports, which did not fully account for potential biomass losses, existing uses, and sustainability returns.[14] This study takes a relatively conservative approach regarding the availability of biomass residues. If other biomass or energy crops are incorporated, emissions reduction could increase substantially, potentially leading to land use changes and impacting food security.[19]

In terms of nationwide deployment, not all sustainable biomass residues can be equally utilized if the cost becomes a barrier to local government investment. This is particularly evident in the less developed northeastern and western regions, where biomass residues are relatively abundant (e.g., Heilongjiang). National investment and carbon markets may be required to incentivize the optimal utilization of bioenergy, especially with costly CCS under current technologies.[19,45] Given that a significant amount of biomass residues is distributed in economically underdeveloped regions, large-scale deployment of bioenergy at a national level would significantly strain local finances and pose substantial risks in the event of market fluctuations.[22] Furthermore, current estimates are unable to quantify any collateral or second-order effects of the full industrialization of large amounts of biomass residues at the country level for specific pathways.[46–49] Though earlier deployment has been encouraged to avoid any delay causing threat to future climate and food security,[1,50] the impact on pollution (e.g., air pollution, and nitrogen pollution of ground and freshwater resources), and human health are also important considerations in the development of bioenergy.[9,46,51–53]

It is noteworthy that advancements in technology, the future carbon market, potential competing uses of biomass, and decarbonization of the energy sector, among other factors, could significantly influence the estimation of bioenergy, emissions, and costs, thereby potentially reshaping the bioenergy industry in China. Firstly, advancements in technology aimed at enhancing biomass productivity and conversion efficiency could lead to increased overall emissions reduction and net energy ratios, while simultaneously reducing the abatement costs for both BE and BECCS (Figure S7). Over existing land, total emissions reduction with BECCS could reach 1.76–2.36 Gt CO_2e yr^{-1}, and 2.75–6.63 Gt CO_2e yr^{-1}, in 2030 and 2050, respectively. Moreover, with enhanced conversion efficiency, the net energy ratio of the BECCS scenario could potentially reach 2.15 and 5.41 in 2030 and 2050, respectively. By 2030 and 2050, the cost could be reduced to \$27 and \$14 per ton of CO_2e, lowering the total cost to less than 1% of current GDP across all provinces. Even for BE, the emissions reduction could rise by 23%–64% and 87%–351% in 2030 and 2050, respectively, compared to the current level. Secondly, our current cost estimates (e.g., Figures 5 and 6) do not benefit from carbon credits, however, abatement costs could be further reduced if the carbon market is well-developed in the future. Given that the current social cost of carbon is about \$23 in China,[54] and the carbon price in Europe could reach as high as \$76 in 2021,[55] bioenergy development, regardless of CCS, is expected to be much more profitable in the future. Thirdly, competing or alternative uses of biomass residues in the future, especially higher-value or other value-added products, may potentially threaten the availability of biomass for bioenergy.[56,57] Integrating biomass supply into existing agriculture and forest landscapes to contribute to other sustainability objectives (e.g., increasing yield, and improving climate resilience) may also result in less mitigation.[58–61] This should be further examined under future scenarios, especially with advanced biotechnology and biomanufacturing in a bioeconomy era. From the perspective of future projections, the Integrated Assessment Models (IAM) can aid in delineating regional and global land usage within an evolving market landscape, consequently facilitating the estimation of overall biomass supply and requirements through a "top-down" approach.[13,62] Finally, with China transitioning toward low- or zero-carbon emissions in the future,[63] the emission reduction potential of bioenergy may undergo significant shifts. Decarbonizing the energy sector (e.g., supercritical power plants) could alter the baseline emissions from conventional energy sources such as thermal power generation and heat supply,[64] thereby affecting the emissions displaced by bioenergy and its co-products.

Given that uncertainties persist with modeling in all stages of the analyses, we explicitly quantify the impact of inputs, including variables and parameters, on the outputs of biomass (Figure S2), energy (Figure 3), emissions (Figure 4), and cost (Figure 5), which are shown as error bars in the corresponding results. For instance, the inclusion of uncertainties in the amount of biomass residue production (Figure S2) could increase the uncertainty in the overall emission reduction potential (i.e., from 3% to 13%).

Limitations of the study

It is important to note that additional factors influencing estimates or the decision-making process for bioenergy deployment have not been thoroughly evaluated in this analysis, mainly due to constraints in data availability for comprehensive quantification. For instance, the willingness of farmers, forest farms, and livestock farms to sell biomass residues is not considered in this study. Biomass residues may potentially be diverted to other sectors, such as paper manufacturing and fertilizer production, which could be more profitable.[65] Also, opportunity cost may be incurred in such circumstances, which increases overall abatement cost.[13] Furthermore, current estimates are unable to quantify any collateral or second-order effects of the full industrialization of large amounts of biomass residues at the country level for specific pathways.[46–49] Costs associated with all life cycle stages may contribute to the overall abatement cost, including factors such as electricity price volatility and subsidies.[66] Spatial heterogeneity of economic inputs is also crucial to consider, as they significantly impact bioenergy deployment.[67] Further investigation into optimizing spatial economic parameters in the model is warranted.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2024.110232.

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AUTHOR CONTRIBUTIONS

Z. Q. conceived and designed the research. Y. X. and Z. Q. collected the data and conducted modeling. Z. Q. and P. S. helped with the interpretation of the results and discussion. Z. Q. and Y. X. wrote the article, with contributions from P. S.

DECLARATION OF INTERESTS

Z. Q. and Y. X. are inventors of a patent entitled "A life cycle assessment method for bioenergy" (ZL 2023 1 1239670.4). The authors declare no other competing interest.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
ArcGIS for Desktop	ESRI	https://www.esri.com/en-us/arcgis/about-arcgis/overview
Origin	OriginLab	https://www.originlab.com/

RESOURCE AVAILABILITY

Lead contact

Further information and requests should be directed to and will be fulfilled by the lead contact, Prof. Zhangcai Qin (qinzhangcai@mail.sysu.edu.cn).

Materials availability

This study did not generate new unique materials.

Data and code availability

- The data are available in supplemental information.
- This paper does not report original code.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

METHOD DETAILS

The bioenergy-emissions-economics model

In this study, we developed an integrated bioenergy-emissions-economics model (BEE model) to estimate biomass residues production, energy production, GHG emissions, and costs and benefits associated with bioenergy production (supplemental information). The model combines ecosystem model, life-cycle analysis (LCA), and techno-economic analysis (TEA) to track mass, energy, and cash flows through the life-cycle stages of biomass (n=5), i.e., feedstock production (field production, collection of residues), feedstock transportation and logistics, conversion (pretreatment, processing), product transportation and distribution, and product use. CO_2 capture and storage processes are included specifically for BECCS pathways, as extended use of CO_2 (Figure S8). In this study, the residues collected for bioenergy use do not change the way land used or managed, therefore the net change of GHG fluxes due to feedstock production is zero. Major co-products and/or by-products are also included when available in specific pathways (Figure 2). The functional unit of the LCA is 1 ton of dry biomass residues, for ease of comparison among biomass feedstock and pathways.[17,68]

The BEE model uses four major modules to identify biomass residues production, energy production (gross and net energy), GHG emissions, and costs and benefits. The common life-cycle processes (e.g., biomass residues collection) and relevant parameters (e.g., moisture content by biomass type) are shared among modules for ease of use and consistency. The model can be regionalized, or parameterized at the regional level to offer insights into spatial differences in the estimation. Here, our analyses are based on province-level estimates, making the optimal utilization of reliable biomass data from provincial statistics. The biomass residues availability, bioenergy production, and associated emissions and cost analyses are also based on the province- or region-specific characteristics reflected by the process- and region-based model parameters (supplemental information). To be scientifically robust and also policy-relevant, we used sustainable biomass residues to reflect regional and national biomass residues availability. A total of 18 pathways are included in the model to represent currently available and widely acceptable biomass-to-bioenergy conversion technologies in China, with nine pathways for BE and BECCS (Figure 2). For each pathway, both gross energy production, and net energy production are evaluated. Three major GHG gases are included, i.e., carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The cost of GHG emissions is based on USD for the year 2015. The pathway- and province-specific model outputs are aggregated at the national level based on regional biomass residues distribution. The uncertainties from data inputs and model parameters are included for both provincial and national level results, based on the error propagation equation of IPCC.[69]

The BEE model is originally designed for use at any temporal and/or spatial scale. In this study, we base our analysis on biomass production in 2020 (current), 2030 (mid-term), and 2050 (long-term), at provincial level. The model is parameterized at province scale, to the best of currently available data (Table S1). In cases where data is not available or applicable, we use national data as a proxy. Besides time and space, another dimension in the model is related to feedstock type-conversion pathway.

In terms of data sources, quantification of biomass residues is primarily based on the China Statistical Yearbook,[70] China Forest Statistical Yearbook,[71] China Forest Census Data,[72] China Rural Statistical Yearbook,[73] and China Animal Husbandry and Veterinary Yearbook.[74]

Modeling parameters are collected from relevant reports or calculated based on reasonable assumptions. Parameters for energy consumption, energy conversion, and greenhouse gas emissions are obtained mainly from published literature and databases. More specific data sources are listed below and in the supplemental information (Tables S8–S17).

Biomass residues availability

In the biomass module, the production of biomass residues is estimated for three major biomass types in China, i.e., agricultural residues, forest residues, and livestock manure. Specifically, the biomass residues include agricultural residues from 16 crops (i.e., rice, wheat, corn, beans, tubers, other grains, cotton, peanuts, rapes, sesame, other oil, jute, other fiber crops, sugar cane, sugar beet, and tobacco), forest residues in three categories (i.e., tending/thinning, logging, and processing residues), and livestock manure from 15 typical livestock (i.e., pigs, draft cattle, beef cattle, dairy cows, sheep, horses, donkeys, mules, camels, rabbits, broiler chickens, laying hens, broiler ducks, laying ducks, and geese).

Theoretically, all biomass produced from agricultural residues, forest residues, and livestock manure can be collected and harvested for utilization.[14] The theoretical biomass residues production can be quantified with biomass type-specific annual yield (e.g., crop yield, forest productivity, and number of animals) and the residue-to-yield ratio. However, the proportion of theoretical biomass residues that can be used sustainably for energy purposes is largely limited, and the sustainable biomass residues are further determined by the region-specific parameters, e.g., collection coefficient, and utilization coefficient to account for potential losses in processes such as collection, harvest, transportation, and distribution (Tables S1–S4). Firstly, not all theoretical biomass residues can be obtained under technical and logistic constraints. For instance, certain parts of crop residues (e.g., stubble) or a small portion of residues (e.g., branches and leaves detached during harvesting) are considered uncollectable.[75] For forest residues, only a certain percentage can be collected, depending on the equipment used.[76] For livestock manure, there is a consensus that only large-scale livestock and poultry manure can be made available for industrial use;[77] it is difficult, if not impossible, to collect all the livestock and poultry manure in household farms.[78] In addition, loss of biomass during logistics is also taken into account.[79] Secondly, in our model, it is considered that not all collectible biomass residues can be used for energy production. In China, a large amount of biomass residues is already used as fertilizers, feed, or industrial raw materials. The utilization of this residue for energy production would have additional impacts.[5,6,15,16] Therefore, in the BEE model, only sustainable residues, that is, fractions that have not yet been resourcefully utilized in the current situation (e.g., wasted or open-burned), are considered as potential feedstock for sustainable bioenergy.

Energy production, life-cycle GHG emissions, and costs and benefits by pathway

The selection of different biomass residues as feedstock for each bioenergy pathway may result in different environmental impacts due to differences in calorific value, elemental composition, and energy conversion efficiency. Following the life cycle of biomass residues, we estimate energy production, GHG emissions, and cash flow by biomass residues type and conversion pathway.

In the energy module of the model, we make specific parameterization schemes for different conversion pathways of different biomass residues. For selected biomass residues and conversion pathways, the gross energy output is calculated based on the conversion efficiency of each pathway. The net energy gain (Equation 1) and net energy ratio (Equation 2) are further estimated by considering energy input from the energy flow of various stages (n=7):[17,26,80,81]

$$E_{i,j}^{net} = E_{i,j}^{gross} - \sum_{k=1}^{7}\sum_{l=1} E_{i,j,k,l}^{input} \qquad \text{(Equation 1)}$$

$$NER_{i,j} = \frac{E_{i,j}^{net}}{\sum_{k=1}^{7}\sum_{l=1} E_{i,j,k,l}^{input}} \qquad \text{(Equation 2)}$$

where $E_{i,j}^{net}$ is the net energy gain of biomass residues i through pathway j; $E_{i,j}^{gross}$ is the gross energy output of biomass residues i through pathway j; $E_{i,j,k,l}^{input}$ is the energy l input of biomass residues i in stage k through pathway j; $NER_{i,j}$ is the net energy ratio of biomass residues i through pathway j. Detailed calculation procedures and parameters can be found in the supplemental information.

In the GHG emissions module, the update (through photosynthesis), emissions, and removals (when applicable, e.g., CCS) of CO_2, CH_4, and N_2O are estimated through life-cycle stages (n=5) by biomass residues type and conversion pathway. The analysis is based on GHG emissions factors, biomass characteristics and assumptions about the biomass carbon conversion efficiency at each stage, and composition of main/co products. For most pathways, GHG emissions are associated with energy and materials use in processes including transportation, production, and distribution[17,19,26]; GHG removals may happen for certain pathways, e.g., carbon sequestered in biochar applied to soil (i.e., Pyrolysis),[20,82] reduced emissions due to biochar and digestate application (i.e., Pyrolysis and Anaerobic digestion),[26,30,35,83] and CO_2 capture and storage by CCS (i.e., BECCS pathways).[79,84] Note that emissions associated with electricity and human labor used in plant construction are negligible[26] and therefore not taken into account in the analysis. Also, GHG emissions or removals that often occur in ecosystems (i.e., agroecosystem, forest) do not apply in our cases, as the collection of waste or direct incineration residues does not lead to extra change of land use[85] or land management.[86] The ecosystem modeling only accounts for the carbon uptake during the crop or forest growth (Figure S8). For similar reasons, the raw material and energy inputs during cultivation and breeding of crops are attributed to crop's main product (i.e., grain, fiber), and are not considered within the system boundaries.[87] The 100-year global warming potentials (GWP-100) for non-CO_2 GHG is based on IPCC Sixth Assessment Report.[88] The life-cycle emissions are net GWP resulting from all stages that contribute to the flow of GHGs, and possible burdens and credits from product displacement (Equations 3, 4, 5, and 6).[17,20,26,81,89]

$$EF_{l,m} = \frac{\sum_n (FC_{l,m,n} \times NCV_n \times EF_n)}{EG_{l,m}} \quad \text{(Equation 3)}$$

$$GWP^{net}_{i,j} = \sum_{k=1}^{7} GWP^{stage}_{i,j,k} - GWP^{soil}_{i,j} - GWP^{displace}_{i,j} - GWP^{uptake}_{i} \quad \text{(Equation 4)}$$

$$GWP^{stage}_{i,j,k} = \sum_{l=1} E^{input}_{i,j,k,l} \times EF_{l,m} \quad \text{(Equation 5)}$$

$$GWP^{displace}_{i,j} = \sum_{l=1} E^{displace}_{i,j,l} \times EF_{l,m} + \sum_{p=1} Q^{displace}_{i,j,p} \times EFP_p \quad \text{(Equation 6)}$$

where $EF_{l,m}$ is the emission factor of energy l in province m; $FC_{l,m,n}$ is the consumption of fuel n to generate energy l in province m;[38] NCV_n is the net caloric value of fuel n;[90] EF_n is the GHG (CO_2, CH_4, and N_2O) emission factors of fuel n;[69] $EG_{l,m}$ is the annual production of energy l in province m;[38,91] $GWP^{net}_{i,j}$ is the net GHG emissions of biomass residues i through pathway j; $GWP^{stage}_{i,j,k}$ is the GHG emissions of biomass residues i in stage k through pathway j; $GWP^{displace}_{i,j}$ is the emissions of conventional energy (i.e., thermal power generation, heat, and gasoline) and chemical products (i.e. N, P_2O_5, and K_2O fertilizers) displaced by main and co-products of biomass residues i through pathway j; GWP^{uptake}_{i} is the CO_2 uptake from atmosphere by biomass residues i; $E^{input}_{i,j,k,l}$ is the energy l input of biomass residues i in stage k through pathway j; $E^{displace}_{i,j,l}$ is the energy l displaced by biomass residues i through pathway j; $Q^{displace}_{i,j,p}$ is the quantity of fertilizer p displaced by co-product of biomass residues i through pathway j; EFP_p is the GHG emissions factor of fertilizer p. The model is regionally parameterized at provincial level by conversion pathways with different biomass residues as feedstock. Specifically, the regional GHG emissions intensity of secondary energy (i.e. thermal power generation and heat supply) is based on the energy structure of each province.[38]

In the economics module of BEE model, the costs and benefits are modeled along the life-cycle stages, following the TEA approach.[92–94] Considering that China's carbon market is still in its infancy, with low carbon prices, low activity, and low liquidity,[95] carbon credits are not taken into account when calculating costs. Also, China's special subsidy funds for biomass power generation projects determine the amount of subsidies based on specific projects, it is very difficult to quantify the subsidy amount in large-scale deployment assessments.[22] Therefore, the carbon credits from emissions reduction are not currently included in the cost equation. The costs and benefits involved in specific conversion pathway (Figure S4) include primarily capital costs and operation and maintenance costs to cover costs in feedstock, utilities (e.g., electricity, diesel, and gasoline), materials, labor, revenue, and others (Tables S18–S20). Most benefits are obtained from product sales (i.e., main and co-products).[96,97] Most of the costs and model parameters are based on provincial statistic data and published literature (supplemental information).

The total capital investment is divided into two major parts, fixed capital investment and working capital. Fixed capital investment, one of the important input variables of the economic module in the BEE model, is calculated from reported plant data (Table S18). Because the flow of revenue from product sales is often delayed for at least one full billing cycle (usually 30 days) from plant start-up, working capital is required to cover initial plant operating costs at plant start-up.[98] The working capital is closely related to the fixed capital investment.[96]

All expenses directly related to operating and maintaining the process equipment are included in O&M costs. These expenses are commonly deconstructed into feedstock costs and non-feedstock costs,[97] and non-feedstock costs are further itemized into variable production costs, fixed production costs, and general expenses (Table S19). The O&M costs related to labor and energy are regional-specific, and they are derived from the data of the National Development and Reform Commission, the National Energy Administration, and the National Bureau of Statistics.[99–102]

For the cost of carbon capture that is not widely available in China, we follow a location factor approach to estimate the cost in China by applying a factor of 0.61 over the cost in the US Gulf Coast.[98] Then the equipment cost for the newly built carbon capture unit with different pathways is modeled as a function of CO_2 flow (Equations 7 and 8):[98,103,104]

$$C_1 = C_0 \left(\frac{S_0}{S_1} \right)^n \quad \text{(Equation 7)}$$

$$NPV = \frac{\sum_{t=0}^{q} \left(B_{j,t} - CC_{j,t} - K_{j,t} \right)}{(1+r)^t} \quad \text{(Equation 8)}$$

where C_1 is the equipment cost for the unit with S_1 capacity (reflecting CO_2 flow); C_0 is the initial equipment cost with S_0 capacity;[98,103,104] n is the scaling factor, 0.6 for CO_2 removal system and FGD (flue gas desulfurization) system;[98] B_t and CC_t is the benefits and cost in tth year through pathway j; $K_{j,t}$ represents the investment in the t^{th} year through pathway j; and r indicates the discount rate. Net present value (NPV) method is adopted in economics module to calculate the cost of different conversion pathways, in terms of 2015 USD.

Regional optimization and future assumptions

With BEE model modeled pathway, and region-specific biomass residues, energy, emissions, and cost estimates, we can further evaluate the nationally optimized use of biomass residues by maximizing either of the outputs, i.e., energy, emissions reduction, and economic benefit. In this study, the maximum provincial emissions reduction is determined by optimizing conversion pathways (nine for BE and BECCS each) for the three types of biomass residues, to achieve the lowest net emissions or highest net emissions reduction possible. Thus, the highest national emissions reduction results from the use of all sustainable biomass residues, but with potential different conversion pathways at the provincial level.

For future estimation in BEE model, we only focused on the change in biomass productivity and conversion efficiency that strongly impact the emissions reduction.[14,105,106] Here we assume four future biomass scenarios, where biomass resources grow at an annual rate of 1% (base-case scenario), 2% (high-yield scenario 1), 3% (high-yield scenario 2), and 4% (high-yield scenario 3),[18,107] respectively. Two conversion scenarios reflect bioenergy conversion efficiencies increase linearly to a relatively high level in 2030 and 2050, respectively (Tables S21 and S22). Other model parameters are kept constant, and the national estimation follows the same approach for regional optimization.