Evaluating the use of negative emission technologies under China's carbon-neutral target for 2060

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Outline

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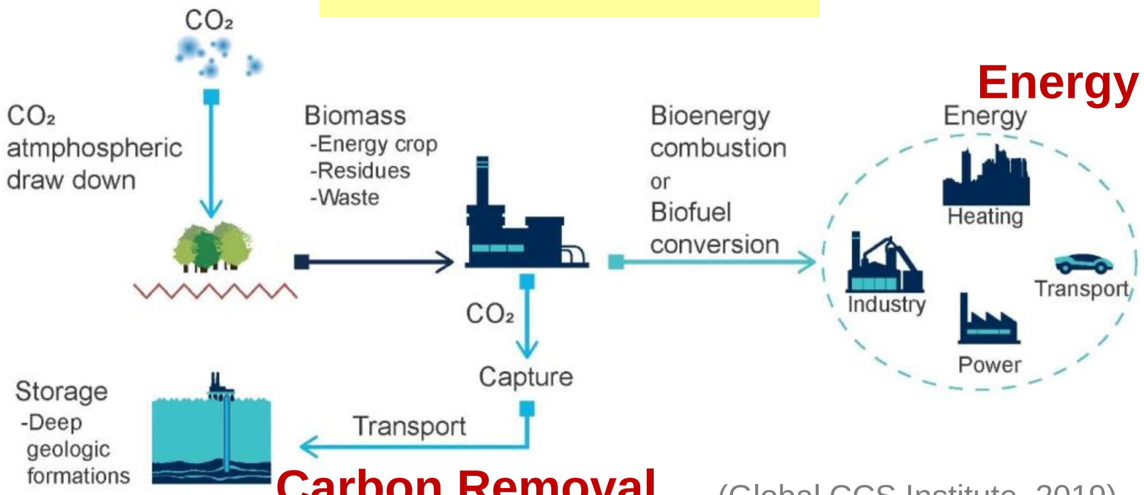
Background

BECCS and afforestation are two promising NET options

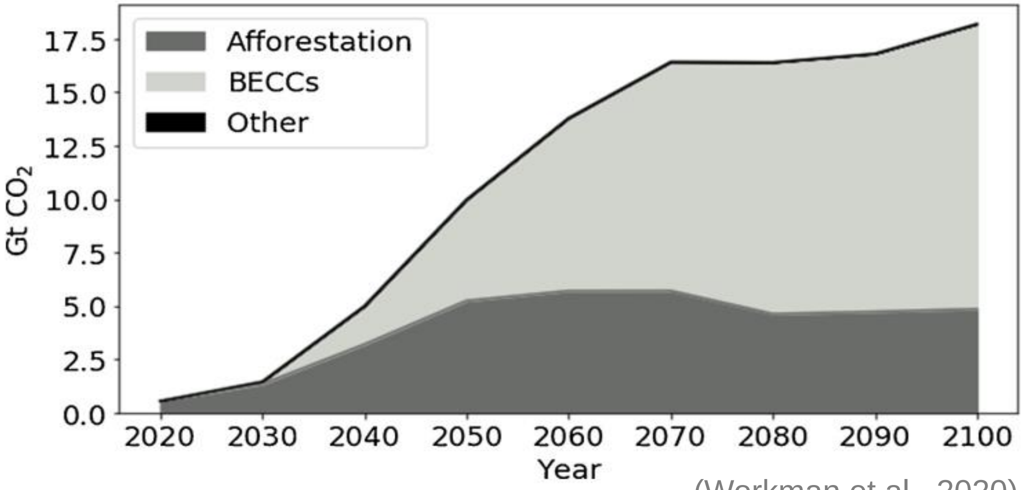
- **NET: negative emission technology**
- **BECCS: bioenergy with carbon capture and storage**
  - It was first proposed in paper *"Managing climate risk"*. (Obersteiner, Science 2001)

Schematic of BECCS



(Global CCS Institute, 2019)

Median scale of CO_2 removals in IAM scenarios under 1.5 ℃



(Workman et al., 2020)

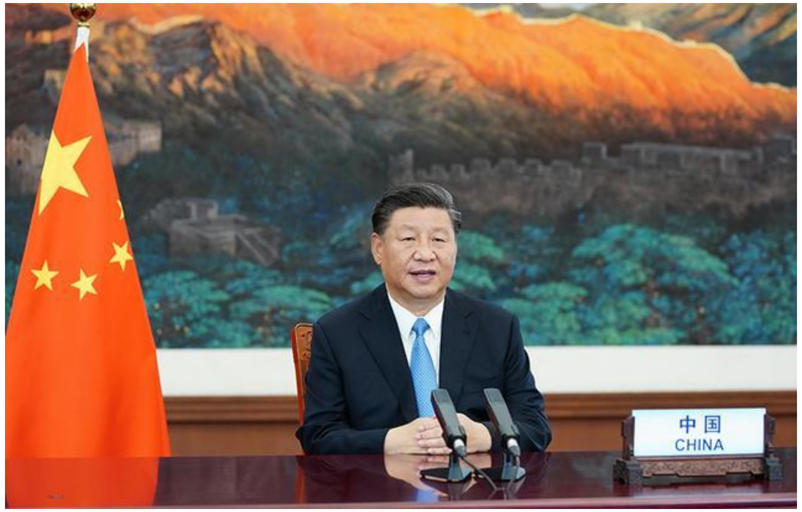
By 2100, the average carbon removals would reach 12 $GtCO_2\ yr^{-1}$ by BECCS and 4 $GtCO_2\ yr^{-1}$ by afforestation in <2°C scenarios.

(Smith et al., 2016; Turner et al., 2018)

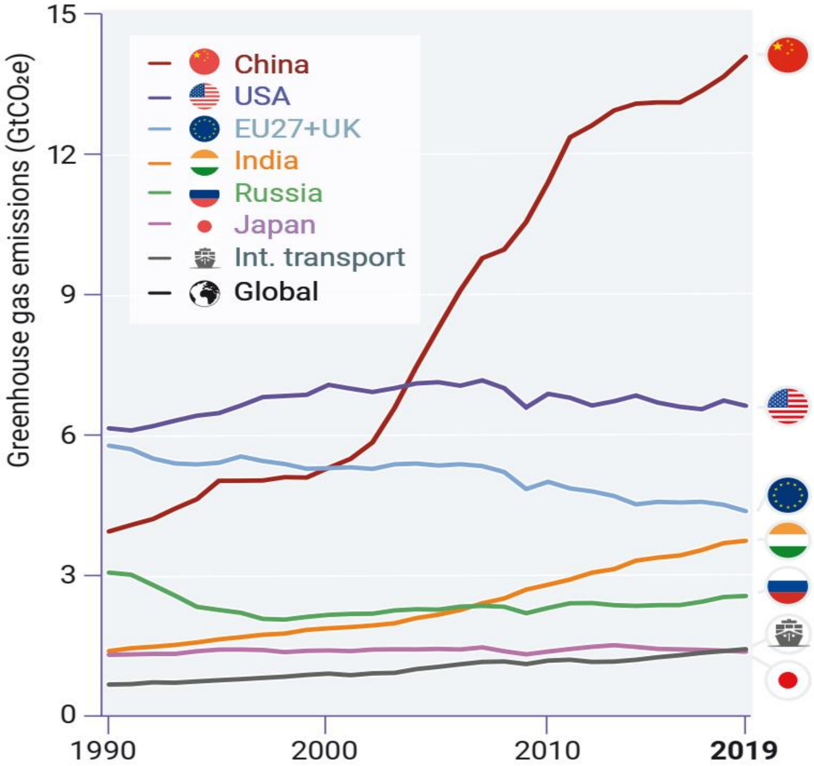
Background

Reaching China's 2060 target requires BECCS and afforestation

On 22 September 2020, China announced to scale up INDC under the Paris climate agreement by adopting more vigorous policies and measures, and to **reach carbon neutrality before 2060.**



(Xinhua News Agency, 2020)



Challenges

- Scale - from about 10 Gt CO_2 to Net-zero
- Time - only 30 years from carbon peak to neutrality

BECCS and afforestation can offset emissions from sectors that are difficult or too costly to reduce, so they might play significant roles in China's decarbonization pathway.

However, only relatively small investments are being made

From modeled worlds to reality …

- Currently, there are **only 10 operating BECCS plants** worldwide, capturing 2.4 $GtCO_2$ per year.

  (Global CCS Institute, 2019; IEA, 2020)

(Global CCS Institute, 2019)

- "Increased biomass production and use has the potential to increase pressure on land and water resources, food production, biodiversity, and to affect air-quality." (IPCC SR15, 2018)

It is urgently needed to refine the deployment scale of NETs and to determine their political priorities.

Overview of existing BECCS studies

Research area	Literature	Climate targets		Scale		Implications	
		1.5°C/2°C	Others	Bioenergy demand	Biomass potential	Economic	Environmental/ Social
Global	Smith et al. 2016	✓		✓		✓	✓
	Butnar et al. 2020; Bauer et al. 2018; Muratori et al. 2016	✓		✓		✓	
	Humpenöder et al. 2018; Fuss et al. 2018	✓			✓	✓	✓
	Heck et al. 2018; Turner et al. 2018; Kato et al. 2018	✓		✓	✓		✓
	Hu et al. 2020; Jans et al. 2018; Bonsch et al. 2016	✓			✓		✓
	Rose et al. 2014; Azar et al. 2010		✓	✓			
Regional/ National	Pan et al. 2018; Pye et al. 2017	✓		✓			
	Huang et al. 2020	✓		✓		✓	
	van Meijl et al. 2018; Rodriguez et al. 2017		✓	✓		✓	
	Zhang et al. 2020; Nie et al. 2020; Baik et al. 2018		✓		✓		
	Gao et al. 2016; Scarlat et al. 2015; Sanchez et al. 2015		✓	✓	✓		
	Tsiropoulos et al. 2017		✓	✓			
	Machado et al. 2020; Holmatov et al. 2019; Weng et al. 2019		✓	✓			✓

- At global level, the potential deployment scales of BECCS by 2050/2100 and their socioeconomic and environmental implications were widely discussed.
- At regional/national level, the potential economic and environmental implications in assumed deep decarbonization scenarios have not been fully investigated.

Overview of important model approaches for NETs

Model type	Application	Timeframe	Strengths	Limitations
Integrated Assessment Models **(IAMs)**	Bioenergy resource potentials; Possible contribution to long-term climate policy; Impacts	Long term	Integrates various relevant systems into one modelling framework; Built around long-term dynamics	Too high a level of aggregation or systems too complex; Requires large number of assumptions
Bottom-up models	Wide variety of specific (technical) aspects of biomass production, conversion, and use	Short to long term	Gives detailed insights into techno-economic, environmental, and social characteristics and impacts of bio-based systems	Indirect and induced effects outside the boundaries of the study not included
Top-down models: Partial equilibrium **(PE)** models	Sectoral impacts of bioenergy policies on agriculture, forestry, land-use change, energy system, and emissions	Short to medium term	Explicitly represents biophysical flows and absolute prices; Gives more details on regional aspects, policy measures	Does not consider macroeconomic balances and impacts on not-represented sectors
Top-down models: Computable general equilibrium **(CGE)** models	Economy-wide impacts of biomass and bioenergy policies; Indirect substitution, land use, and rebound effects	Short to long term	Comprehensively covers economic sectors and regions to account for interlinkages; Measures the total, economy-wide effects	Level of aggregation may mask variation in underlying constituent elements

With broad coverage of economic activities, CGE models have strengths in **capturing comprehensive economic interactions among sectors as well as direct and indirect implications**.

Literature Review

NET modeling details in CGE models

Literature	Research area	Model name	Base year	Modeled NETs	Land use	Biomass			Bioenergy				
									Power		Liquid fuel		Bioheat
						1st gen	Residues	Dedicated energy crops	w/o CCS	w/ CCS	w/o CCS	w/ CCS	
Fajardy et al. (2020) [91]	Global	EPPA	2007	BECCS	yes			yes	yes	yes			
Winchester and Reilly (2015) [92]	Global	EPPA	2004	BECCS	yes	yes	yes	yes	yes	yes	yes	yes	yes
Taheripour et al. (2017) [93]	Global	GTAP-BIO	2011	None	yes						yes		
Laborde and Valin (2012) [94]	Global	MIRAGE-BioF	2004	None	yes	yes	yes				yes		
Fujimori et al. (2012) [95]	Global	AIM/CGE	2005	BECCS	yes				yes	yes			yes
Huang et al. (2020) [41]	China	C-GEM	2014	BECCS			yes	yes	yes	yes			
van Meijl et al. (2018) [66]	Netherlands	MAGNET	2015	None	yes	yes	yes	yes	yes		yes		yes
Sands et al. (2017) [96]	the U.S.	FARM	2007	BECCS	yes	yes	yes	yes	yes	yes	yes		
Hasegawa et al. (2016) [75]	Indonesia	AIM/CGE	2005	AFF	yes								
Michetti and Rosa (2012) [97]	Global	ICES	2005	AFF	yes								
Monge (2012) [35]	the U.S.	None	2018 (static)	AFF	yes								

Previous studies have made attempts to integrate BECCS and afforestation into **CGE frameworks**. Most of them are global-scale studies and analyzed BECCS and afforestation separately.

Research gaps in existing studies

Research area	At the national/regional level, the demand scale and potential implications of BECCS have not fully investigated yet.	1
NET type	Most previous studies analyzed BECCS and afforestation separately, so their combined effects have not been discussed.	2
Methodology	Broad economic interactions and complex technical detail bring challenges for traditional top-down or bottom-up models.	3

Research Question

This study aims to evaluate the use of representative NETs (BECCS and afforestation) in China's decarbonization pathway towards carbon neutrality by 2060.

Q1: What is the **scale of BECCS and afforestation** in mitigation pathways towards carbon neutrality?

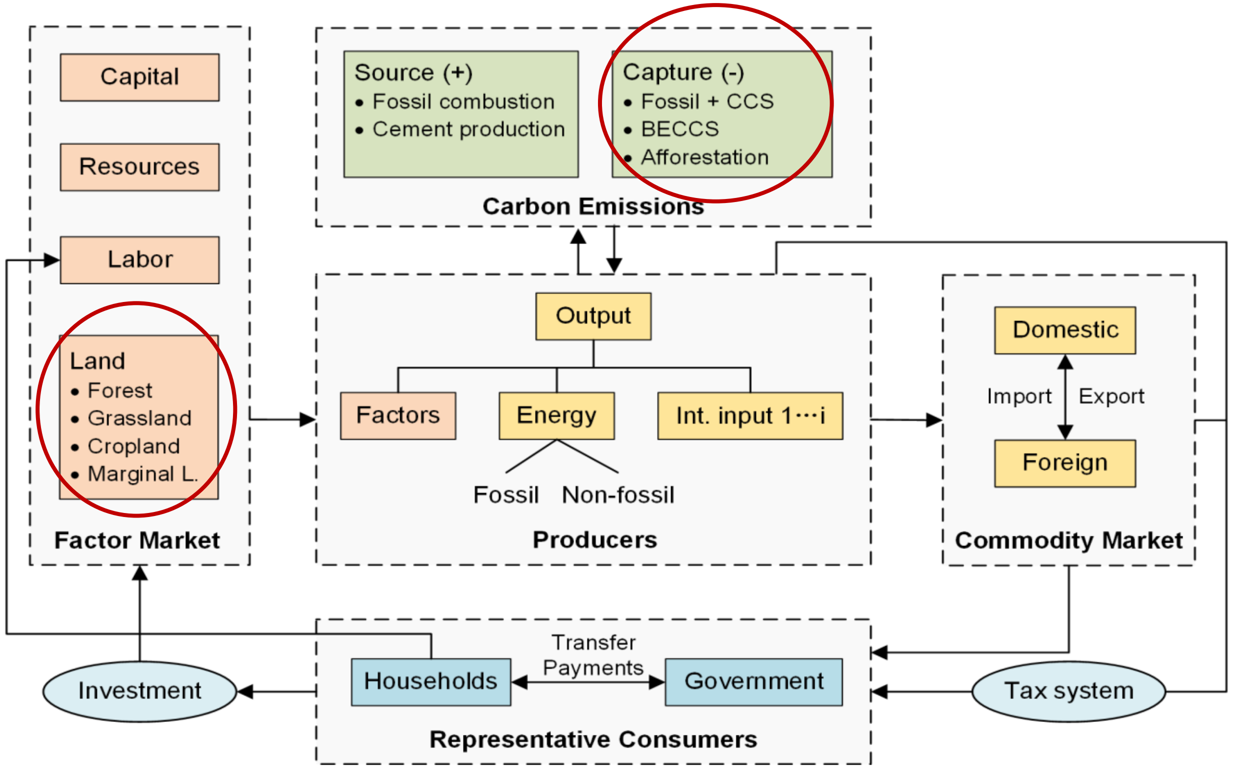
Q2: What are the **biomass types and their proportions** for the feedstocks required by BECCS?

Q3: What are the **macroeconomic implications and land-use consequences** of NET deployment?

Methods

A dynamic recursive national CGE model: CHEER-BE

China **H**ybrid **E**nergy and **E**conomic **R**esearch model for BioEnergy (**CHEER-BE**), an extension of the CHEER model developed by Mu et al. (2018)



Core model structure of CHEER-BE

Software: GAMS (PATH solver)
Modeling time: 2018-2060

CHEER-BE is improved in three aspects:

- Splitting subsectors for agriculture and bioenergy
- Modeling NETs, i.e., bioelectricity+CCS, biofuel+CCS, and afforestation
- Incorporating a land allocation module

Sectors in the CHEER-BE model

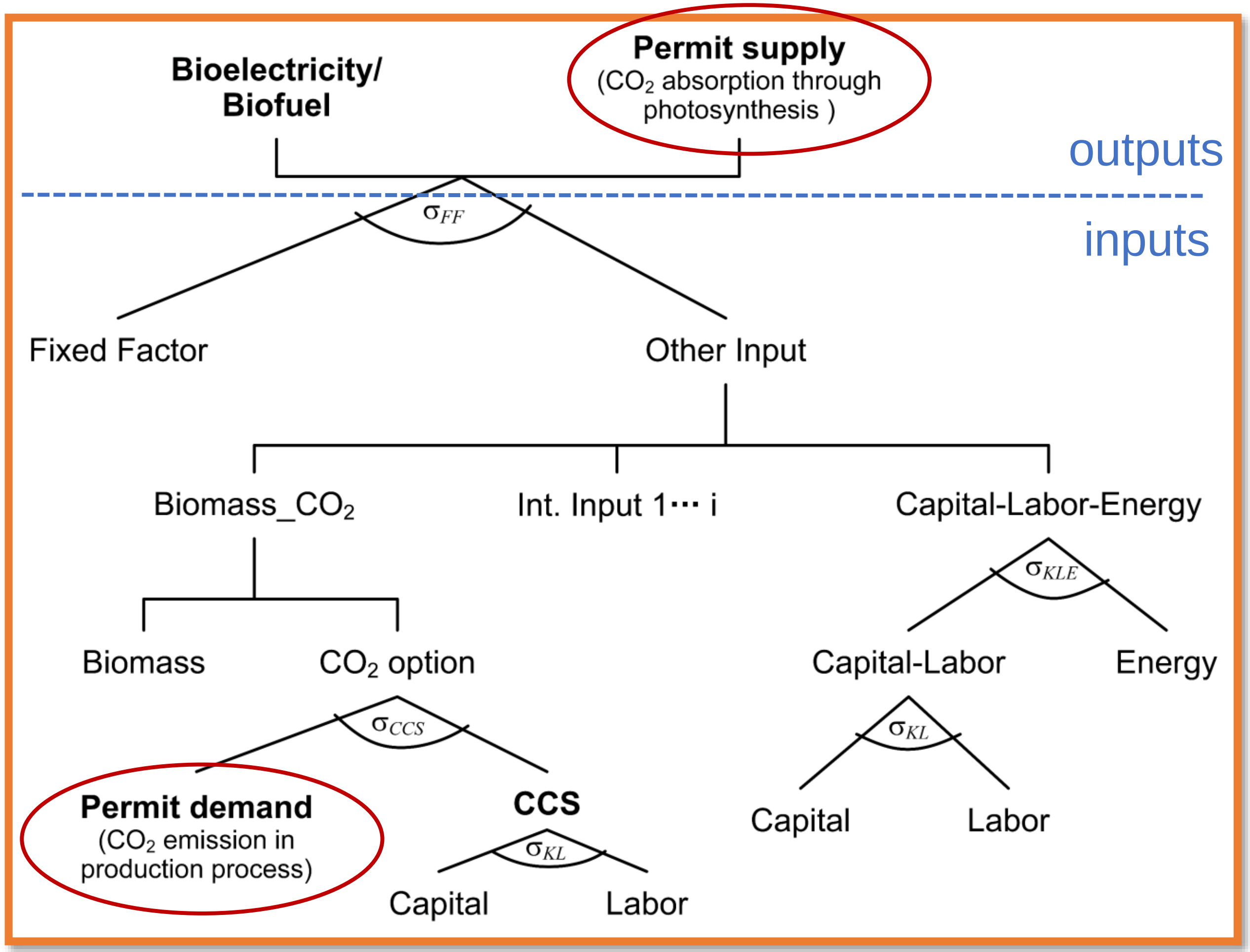
Sectors	Abbr.	Sectors	Abbr.
Energy Sectors (5)		***Other Sectors (14)***	
Coal and Coking	Coal	Iron and Steel	IST
Crude Oil	Oil	Mining	Mine
Refined Oil[a]	Roil	Paper Industry	Paper
Fossil-based refined oil, biofuel (grain-based, sugar-based, cellulosic)		Chemical Industry	Chem
		Construction Materials	CM
Natural Gas	Gas	Metal Products	Metal
Electricity[a]	Elec	General Equipment	GenEqp
Coal, gas, hydro, nuclear, wind, solar, biomass-residue/waste, transmission & distribution		Transportation Equipment	TranEqp
		Electronic Equipment	ElecEqp
Agricultural Sectors (4)		Other Manufacturing	OthMfg
Crops[a]	Crop	Construction Industry	Constr
Rice, wheat, corn, beans, tuber crops, sugar crops, oil crops, other crops		Transportation Industry	Tran
		Research & Development	RD
Forestry	Fores	Service	Serv
Livestock	Livst		
Fishery	Fish		

[a] These broad sectors have detailed subsectors listed below.

- **23 broad sectors**
  - 5 energy sectors
  - 4 agricultural sectors
  - 14 other sectors
- Refined oil, electricity, and crops are further split into **subsectors.**

Methods

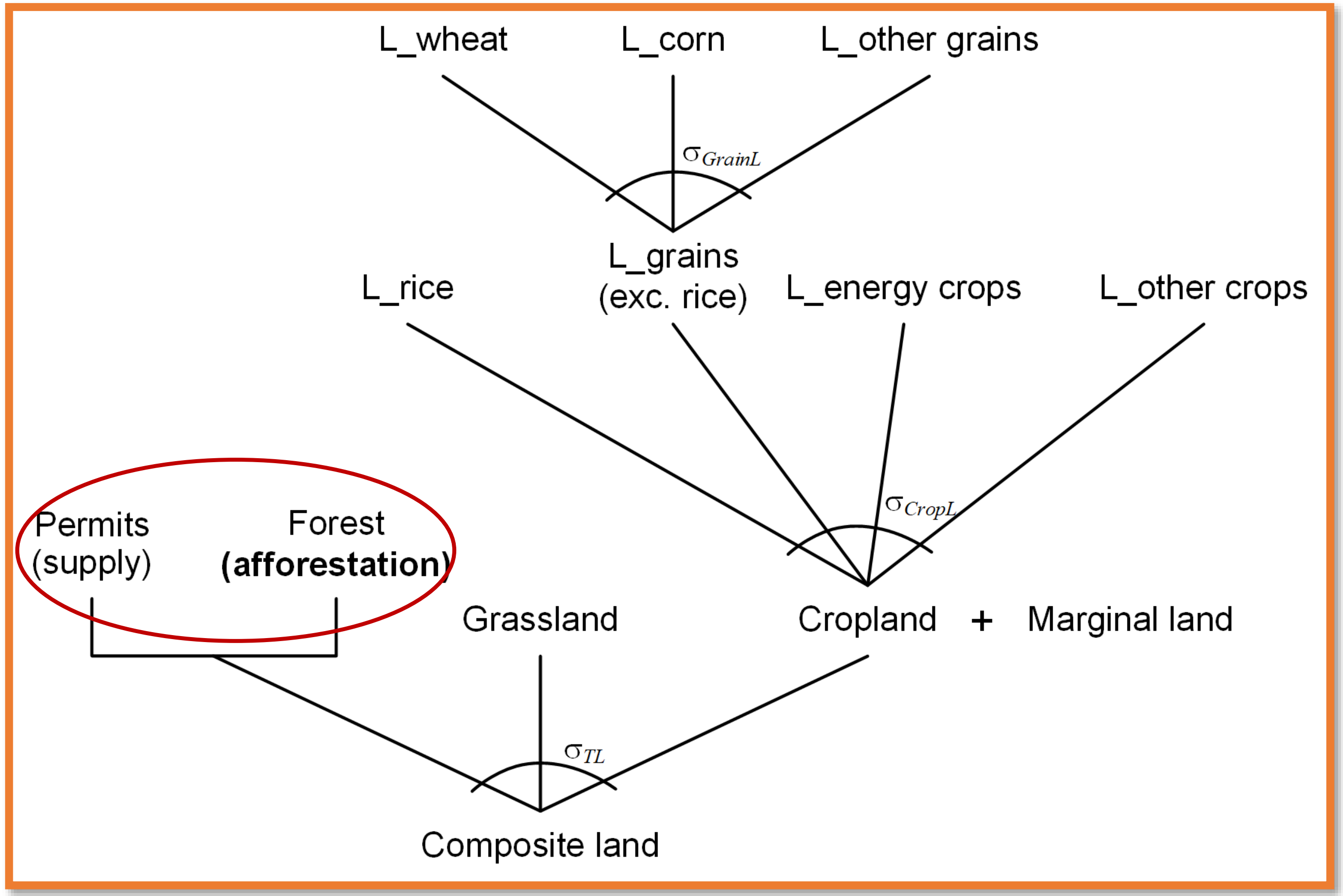
Nesting structure of bioenergy and BECCS production



- The factory has options to buy CO_2 permits for its emissions or to capture emissions by adopting CCS.
- This choice would be made based on the CO_2 price and the cost of CCS technology.

Net emission = *Permit demand (CO_2 emission in production process)*
- Permit supply (CO_2 absorption through photosynthesis)

Nesting structure of the land allocation module



- The total land endowment (i.e., composite land) can be allocated across alternative uses.
- Carbon permits are modeled as a by-product of afforestation.

Various decarbonization scenarios are designed

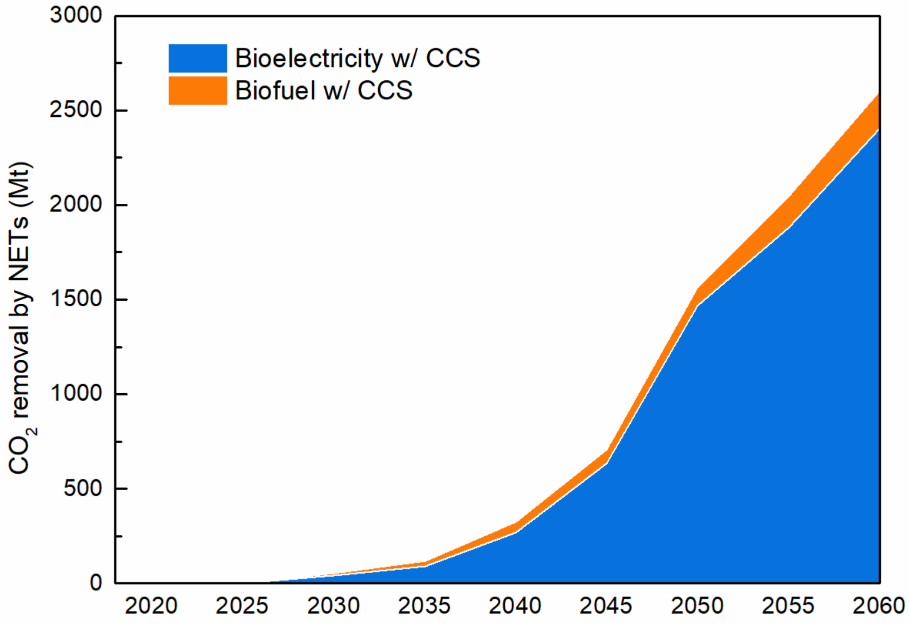
Scenario	Abbr.	Meaning
S-1 Reference	**REF**	No carbon constraint
S-2 Deep decarbonization without NETs	**DP-noNET**	Reach near-zero* emission by 2060. NETs cannot be used
S-3 Carbon-neutral with BECCS	**CN-BECCS**	Reach net-zero emission by 2060. The only difference is the types of NETs that could be used
S-4 Carbon-neutral with BECCS and Afforestation	**CN-BECCSAff**	

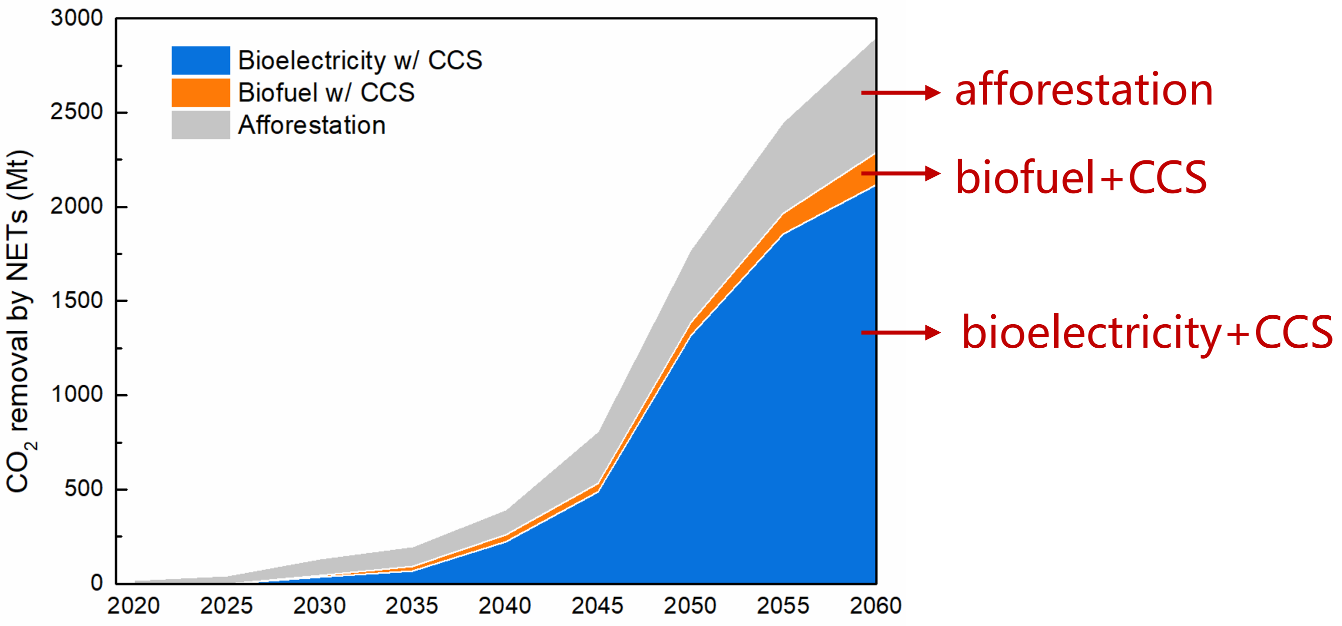
* The model cannot get feasible solutions about realizing net-zero when NETs are not deployed.

** The carbon budgets in S-2, S-3, and S-4 are the same. It was set at 220 $GtCO_2$ (2018-2060) according to global 1.5/2℃ studies (Kriegler et al., 2018;Rogelj et al., 2018).

Results

Deployment pathways and scales of NETs

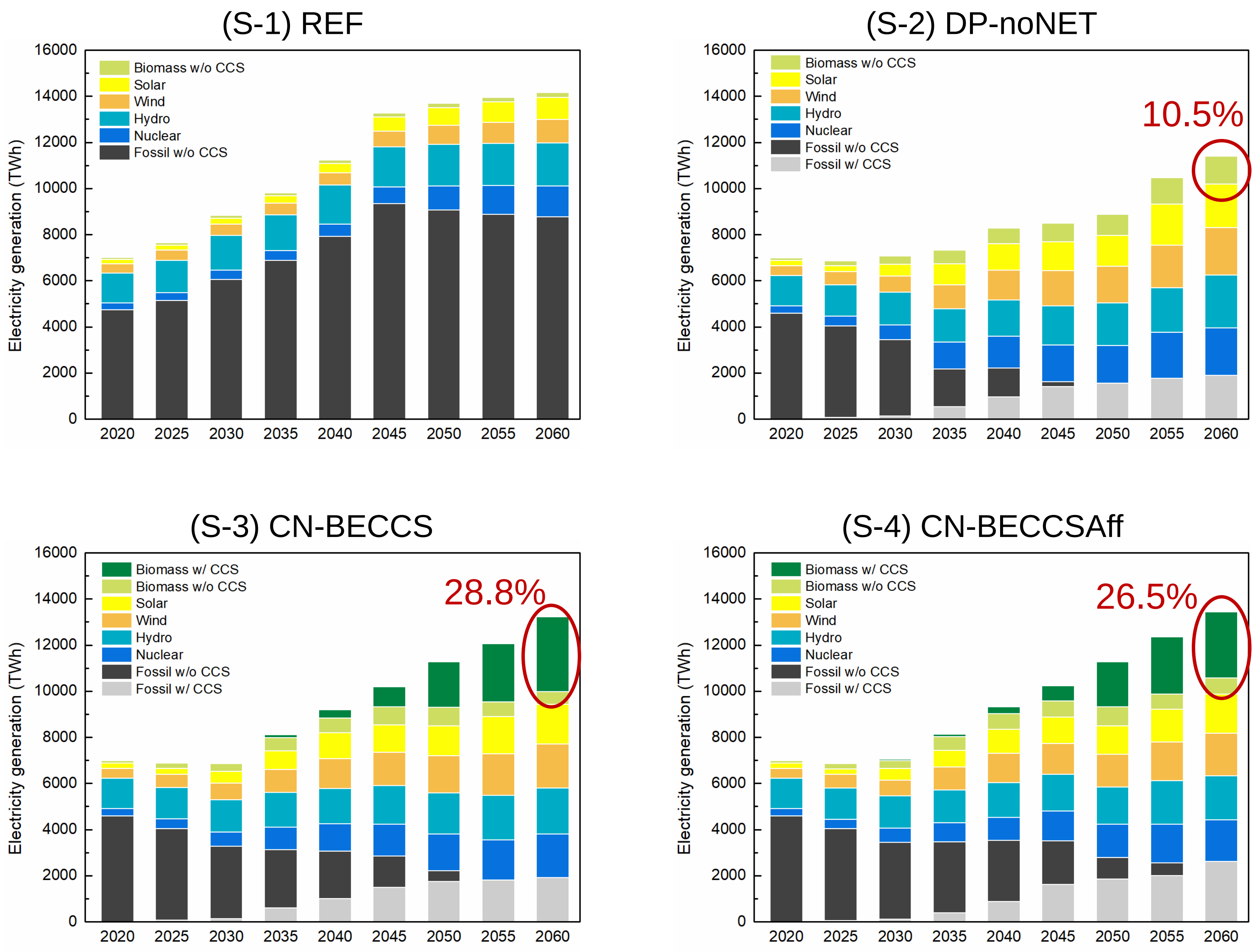




- The cumulative CO_2 removal by NETs would be about 30.6 Gt (S-3) and 37.0 Gt (S-4).
- BECCS would be more cost-effective than afforestation, so its share would be larger.
- In 2060, the negative emissions would be 2,118 $MtCO_2yr^{-1}$, 170 $MtCO_2yr^{-1}$, and 617 $MtCO_2yr^{-1}$ from bioelectricity with CCS, biofuel with CCS, and afforestation, respectively.

Results

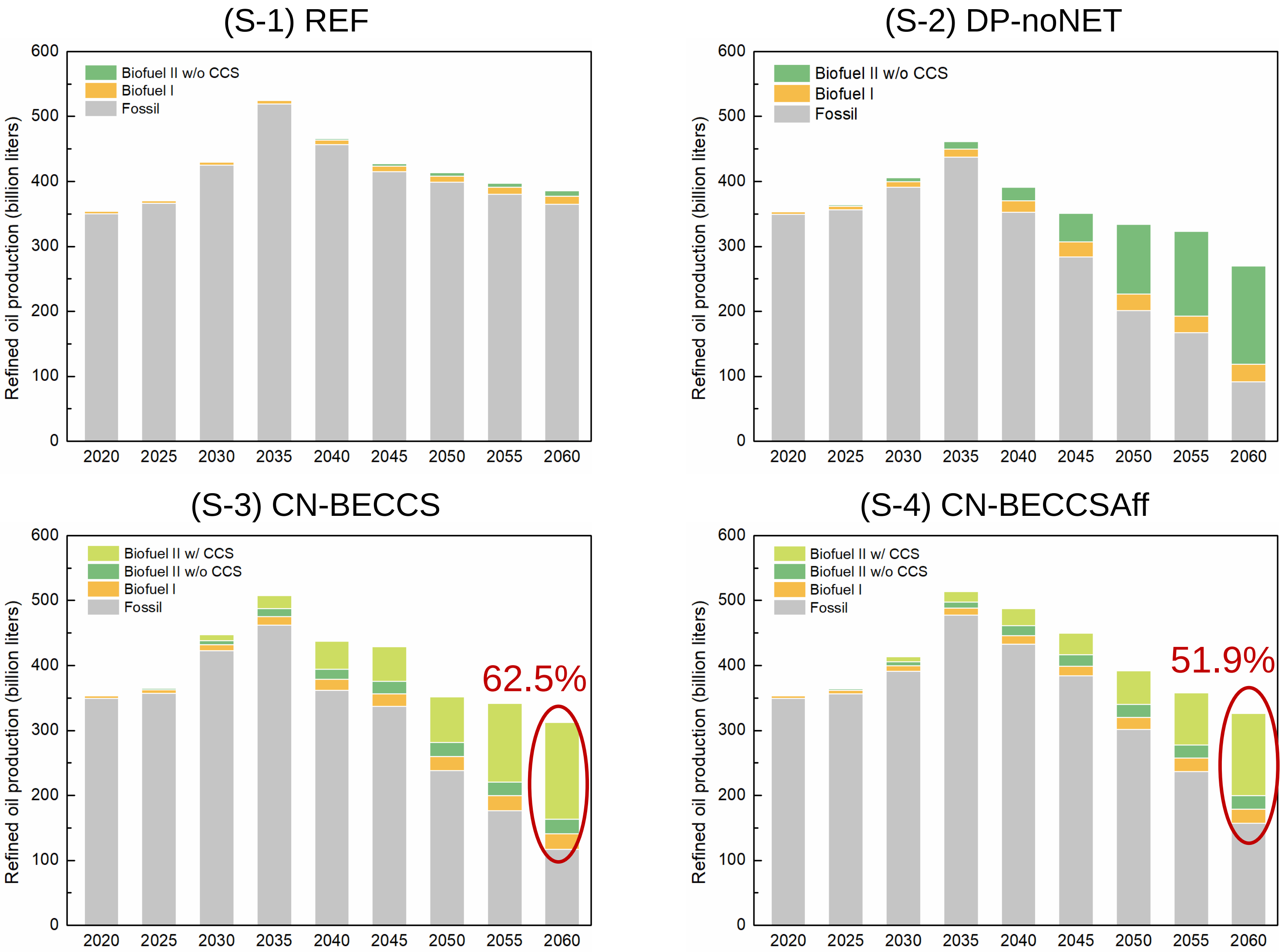
The use of BECCS in the power sector



- In S-2/3/4, fossil-based electricity would tend to phase out and more renewable and nuclear energy would be applied (>80%).
- In 2060, the shares of bioelectricity would be 28.8% (S-3) and 26.5% (S-4).
- Limiting the use of NET will accelerate the phase-out of fossil fuels.

Results

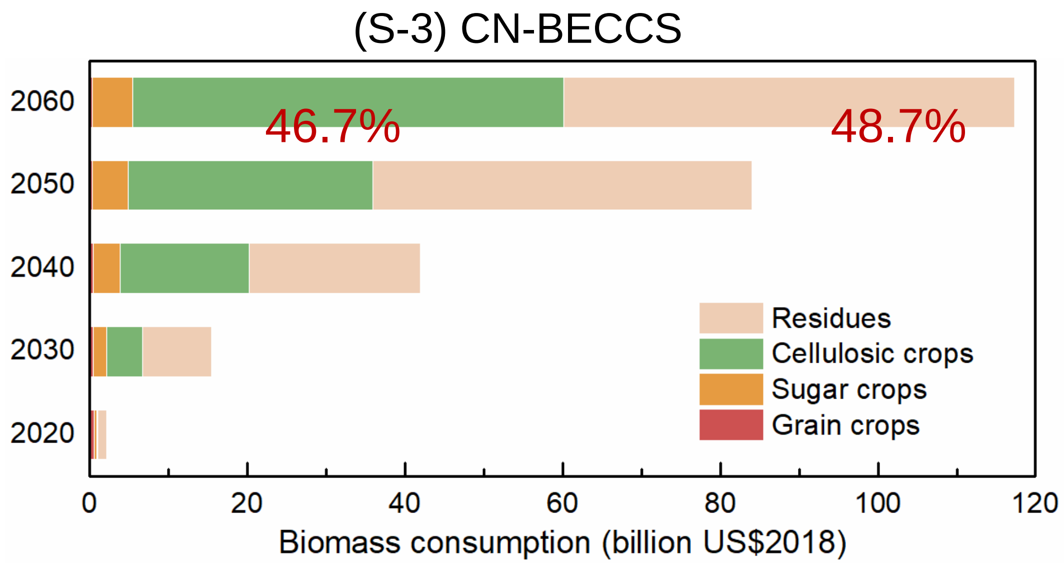
The use of BECCS in the refined oil sector

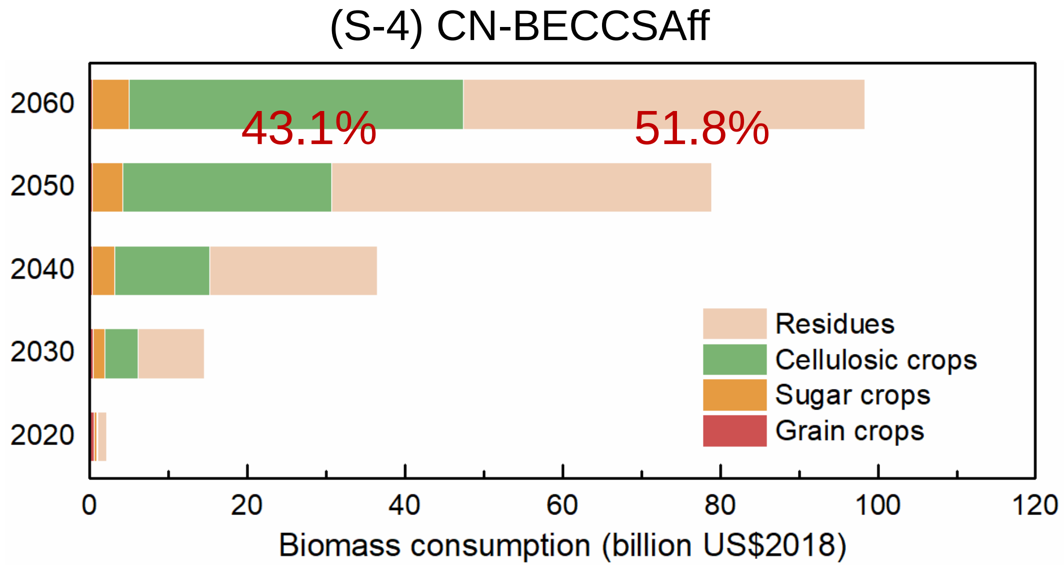


Notes: “biofuel I” refers to grain-based and sugar-based bioethanol (generation 1 and 1.5); “biofuel II” refers to cellulosic bioethanol (generation 2).

- Fossil fuels would dominate in REF. In S-2/3/4, their share would fall to 33.8-48.1% by 2060.
- In carbon-neutral scenarios, the proportion of biofuels would increase, reaching 62.5%(S-3) and 51.9%(S-4) by 2060.
- Biofuel I would keep a small share while biofuel II would increase gradually.

Feedstock structure for bioenergy production

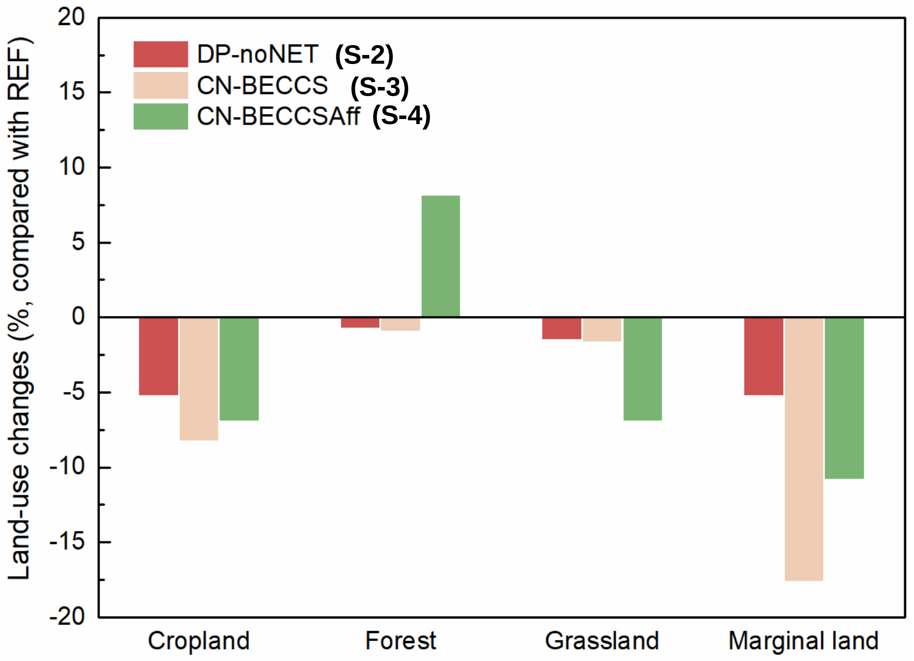




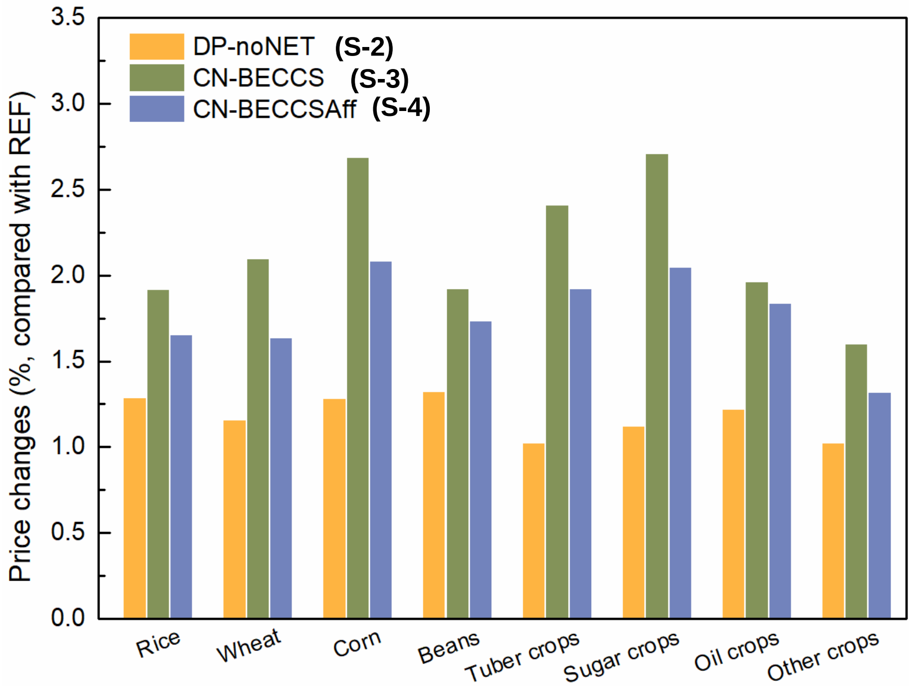
- The shares of cellulosic crops and residues would grow rapidly.
- Sugar crops would present a slow-growth trend and its share in 2060 would be about 4.4-8.0%.
- Grain crops would be reduced to a very little share (less than 1%).
- The demand for total biomass in S-3 is nearly 20% higher than that of S-4.

Results

Implications on land use and food price



Land-use changes (%) in deep decarbonization scenarios in 2060 relative to REF



Food price changes (%) in deep decarbonization scenarios in 2060 relative to REF

- Cropland would decrease by 5.5%, 8.3%, and 6.9% in S-2, S-3, and S-4, respectively.
- For marginal land, the decline rates would be 5.3%, 17.6%, and 10.8% in S-2, S-3, and S-4.

- Price variation in S-2 would be about 1.0-1.3%, while it would increase by about 1.3-2.7% in two carbon-neutral scenarios.

Implications on GDP loss and carbon price

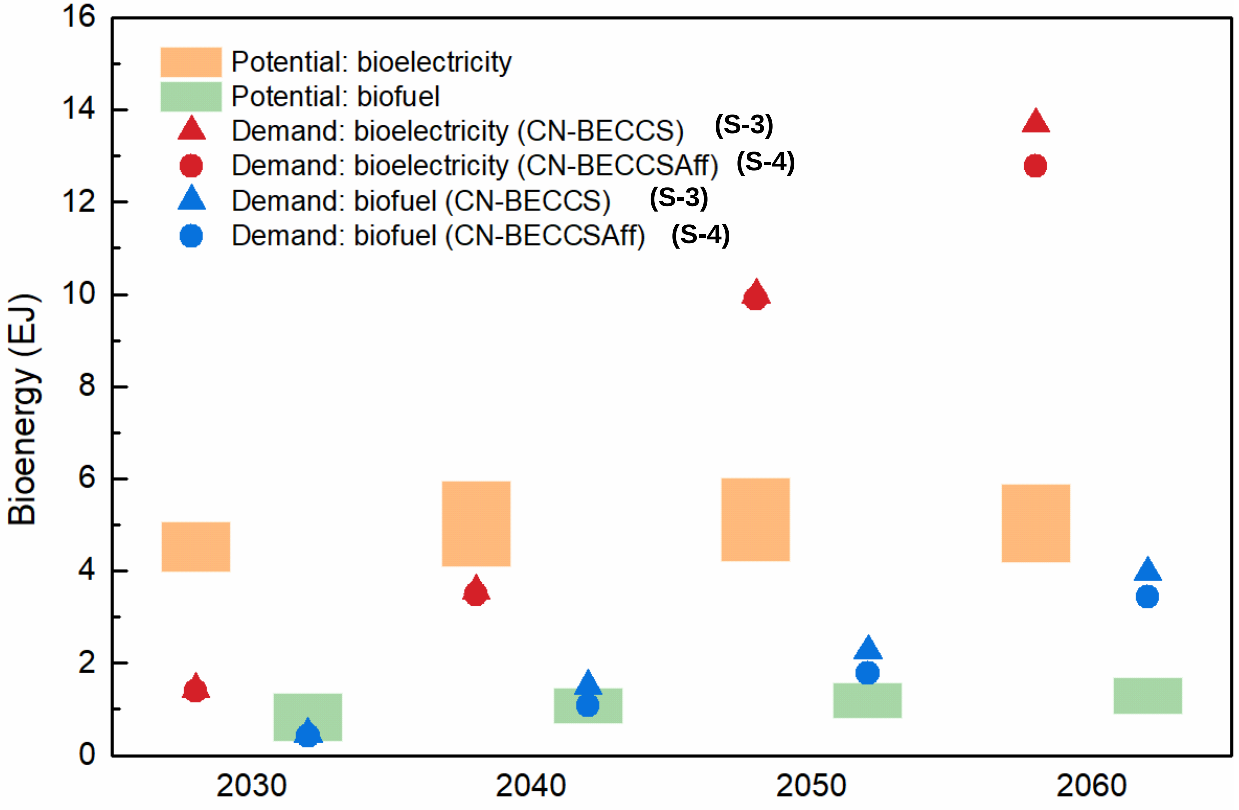
Gross domestic product (GDP) loss and carbon price in deep decarbonization scenarios.

Year	GDP loss (%, compared with REF)			Carbon price (2010 US$/t CO_2)		
	(S-2) DP-noNET	**(S-3)** CN-BECCS	**(S-4)** CN-BECCSAff	**(S-2)** DP-noNET	**(S-3)** CN-BECCS	**(S-4)** CN-BECCSAff
2030	-1.7%	-1.7%	-1.5%	22.8	22.4	16.1
2040	-3.5%	-3.1%	-2.6%	336.9	303.7	272.0
2050	-5.8%	-4.6%	-4.3%	667.2	496.1	424.3
2060	-6.4%	-5.1%	-4.8%	811.8	632.2	522.6

- If NETs are adopted, the GDP loss would be alleviated, from -6.4% to -5.1% (S-2) and -4.8% (S-3).
- In 2060, the carbon price in S-2 is the highest. The use of BECCS would reduce it by 22.1% and adopting both BECCS and afforestation would reduce it by 35.6%.

Discussion

Bioenergy demand VS technical bioenergy potential



- In 2030 and 2040, the potential of bioelectricity could satisfy the demand, while biofuel might face a feedstock shortage in deficit irrigation conditions.
- Both bioelectricity and biofuel would not have enough energy potential after 2040.
- In S-3 in 2060, the gaps for bioelectricity and biofuel would be 7.78 EJ and 1.72 EJ, respectively under full irrigation conditions.

When considering economic and environmental constraints, the actual bioenergy potential would be even lower …

Discussion

Compare the carbon removal with other studies

	Sectors including BECCS	Climate target	CO_2 removal in 2050 ($GtCO_2yr^{-1}$)	Cumulative CO_2 removal by 2050 (Gt)
Pan et al., (2018)	Electricity, refined oil, hydrogen, and industrial activities	2℃ and 1.5℃	0.02-1.4[a]	--
Jiang et al., (2018)	Electricity	1.5℃	0.82	--
Wang et al., (2019)	Electricity	2℃	0.985	9.9-11.7[b]
Duan and Wang (2019)	Electricity	1.5℃	1.296	--
Huang et al., (2020)	Electricity	2℃ and 1.5℃	0.59 and 0.95	--
This study	Electricity, refined oil	Carbon neutral in 2060	1.38 and 1.56[c]	8.1 and 9.9[c]

[a] The range comes from the different assumptions about the emission narratives.
[b] The range comes from the different assumptions about the start year (2020 or 2030) of deep decarbonization.
[c] The results are based on different scenario settings, i.e., CN-BECCS and CN-BECCSAff.

- Under ambitious climate targets, CO_2 removal by BECCS in 2050 would be about 1 Gt and cumulative CO_2 removal would be around 10 Gt.
- There exist some differences among the results of these studies, but not large.

Conclusion

- **BECCS and afforestation could play significant roles in China's mitigation pathways to realize carbon neutrality.** In 2060, NETs would capture 2.91 $GtCO_2$ yr^{-1}. Among them, 21.2% would come from afforestation and the others are contributed by BECCS.

- **Planting dedicated energy crops is essential for bioenergy and BECCS development.** Nearly half of the feedstocks would consist of energy crops in 2060. Even under full irrigation conditions, the gaps for bioelectricity and biofuel would be 6.88-7.78 EJ and 1.72-2.26 EJ.

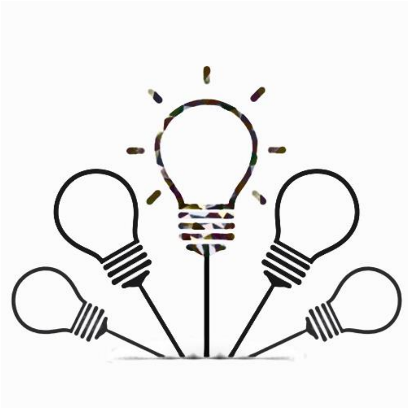
- **Adopting BECCS and afforestation could reduce mitigation cost and alleviate land-use changes.** Under carbon-neutral targets, adopting NETs could reduce the GDP loss by 1.6%. If BECCS and afforestation are both adopted, the mitigation cost would be lower than only one NET is deployed.

Contributions

- Through the sector disaggregation and incorporating BECCS and afforestation, CHEER-BE can depict key technologies detailly, breaking the highly aggregated feature of traditional CGE models.

- Two promising NETs are integrated into the same modeling framework while previous studies usually analyzed them separately.

- As a national-scale study, it can provide local insights to supplement existing global studies and help to refine the local actions.



Limitations

- The coverage of bioenergy types is limited.
- Regional environmental constraints are not taken into account.
- The settings of model structure, parameters, and assumptions would bring uncertainties.

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Thanks for your attention!

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