Supplementary Information File

Life Cycle Inventory:

Life cycle data were collected from literature sources and evaluated using data quality indicators, as described by the modified Weidema method in Table S1.[1] The scoring range is from 1-5, with 1 indicating that the data is most reliable while 5 is least reliable. Each item was qualified using a 6-digit score, with each digit ranging from 1 to 5. Each digit represents the reliability of the data in each of the 6 categories, with the first digit representing evaluation criteria A and the last digit representing criteria F, respectively.

Table S1: Evaluation criteria in the modified Weidema method and description of scores (adapted from Couillard et al.).[2]

	Evaluation criteria	Description	Scoring range
A	**Acquisition method**	Method of acquiring the data, whether measured directly or estimated based on assumptions	1: measured data 5: non-qualified estimate
B	**Independence of data supplier**	Source of information and its bias towards the concerned study	1: independent verified source 5: unverified source with bias
C	**Representativeness**	Degree of application of data to even out fluctuations	1: representative data from sufficiently large samples 5: incomplete data from relatively small samples
D	**Data age**	Temporal relevance of data	1: less than 3 years 5: unknown or greater than 20 years
E	**Geographical correlation**	Spatial relevance of data	1: data from area under study 5: data from area unknown or different conditions
F	**Technological correlation**	Technological relevance of data with processes in study	1: data from processes under study 5: data from related processes but different technology

Table S2: Life cycle input data for both Py-ECH and CE systems with their source and data quality indicator score.

Parameter	Value	Source	Data quality indicator (ABCDEF)
Technical data for Py-ECH system		Lam et al.[3]	211111
Technical data for CE system		Humbird et al.	211321
Annual C sequestration rate	0.174 Mg C/ha/yr	GREET[4]	211321
Corn stover storage losses	8.40%	GREET[4]	211321
Corn stover transport losses	2.00%	GREET[4]	211321
Corn stover farm handling losses	2.00%	GREET[4]	211321
Diesel for harvesting corn stover	3.58 gallons/acre	GREET[4]	211321
Fraction of N leached to surface waters	24% of total applied N	GREET[4]	211321
Fraction of P leached to surface waters	7% of total applied P	Powers et al.[5]	311421
Fraction of fertilizer N emitted as NO	0.8% of total applied N	GREET[4]	211321
Fraction of fertilizer N emitted as NH_3	10% of total applied N	IPCC[6]	211421
Fraction of fertilizer N emitted as N_2O	1.5% of total applied N	GREET[4]	211321
Corn stover yield	2.39 dry ton/acre	GREET[4]	211321
Distance from field to refinery for CE system	50 miles	Kim et al.[7]	212122
Weight limitation on trucks	80,000 lbs	Edwards et al.[8]	221311
Distance from refinery to pumps for both Py-ECH and CE systems	110 miles	Kumar et al.[9]	212322

Using the life cycle data in Table S2, the technical data from our previous work,[3] and the Humbird et al. report,[10] the contribution of all operations to each impact category was calculated for the Py-ECH and CE systems, respectively. These have been tabulated in Tables S3, S4, and S5.

Table S3: Contribution of different operations to greenhouse gas emissions (GHG) for CE and Py-ECH systems.

Operations	***Allocation Method 1***		***Allocation Method 2***	
	CE	***Py-ECH(F)***	***CE***	***Py-ECH(F)***

	(g CO_2/MJ)		***(g CO_2/MJ)***	
Supply Chain:				
Harvesting	*5.51*	*2.09*	*5.51*	*2.09*
Fertilizer Application	*3.09*	*1.17*	*1.26*	*4.78*
Fertilizer Production	*3.15*	*1.19*	*8.33*	*7.36*
Below ground C Sequestration	*0.00*	*0.00*	*-13.70*	*-5.19*
Feedstock Biomass to Energy	*-235.00*	*-64.20*	*-235.00*	*-64.20*
Corn Stover Losses	*5.35*	*2.03*	*5.35*	*2.03*
Processing				
Heat and Power	*132.00*	*12.40*	*132.00*	*12.40*
Fermentation CO_2	*39.50*	*0.00*	*39.50*	*0.00*
Feedstock Biomass to Biochar	*0.00*	*-13.30*	*0.00*	*-13.30*
Electricity	*-12.40*	*84.80*	*-12.40*	*84.80*
Transport				
Transportation	*1.46*	*0.37*	*1.46*	*0.37*
Combustion				
Fuel Combustion	*71.00*	*64.10*	*71.00*	*64.10*

Table S4: Contribution of different operations to eutrophication potential (EUP) for CE and Py-ECH systems.

Operations	***Allocation Method 1***		***Allocation Method 2***	
	CE	***Py-ECH(F)***	***CE***	***Py-ECH(F)***
	(mg CO_2/MJ)		***(mg CO_2/MJ)***	
Supply Chain:				
Harvesting	*4.18*	*1.58*	*4.18*	*1.58*
Fertilizer Application	*6.86*	*2.60*	*28.00*	*10.60*
Nitrogen Runoff	*111.00*	*42.00*	*452.00*	*171.00*
Phosphorus Runoff	*70.20*	*26.60*	*139.00*	*52.70*
Fertilizer Production	*0.35*	*0.13*	*0.80*	*0.66*
Processing				
Refinery Operations	*15.10*	*0.66*	*15.10*	*0.66*
Electricity	*-0.43*	*2.94*	*-0.43*	*2.94*
Transport				
Transportation	*1.46*	*0.37*	*1.46*	*0.37*
Combustion				
Fuel Combustion	*71.00*	*64.10*	*71.00*	*64.10*

Table S5: Contribution of different operations to water scarcity footprint (WSF) for CE and Py-ECH systems.

Operations	*Allocation Method 1*		*Allocation Method 2*	
	CE	*Py-ECH(F)*	*CE*	*Py-ECH(F)*
	(L H_2O/MJ)		*(L H_2O/MJ)*	
Supply Chain:				
Farming	*0.00*	*0.00*	*12.80*	*4.85*
Fertilizer Production	*0.006*	*0.002*	*0.009*	*0.004*
Processing				
Refinery Operations	*2.42*	*0.38*	*2.42*	*0.38*
Electricity	*-0.32*	*2.18*	*-0.32*	*2.18*
Transport				
Transportation	*0.00*	*0.00*	*0.00*	*0.00*
Combustion				
Fuel Combustion	*0.00*	*0.00*	*0.00*	*0.00*

Table S6: Life cycle impact summary for the CE process. Allocation methods 1 and 2 are reported to observe the effects of avoiding allocation and applying minimal allocation to cultivation.

	GHG		**EUP**		**WSF**	
Allocation	**1**	**2**	**1**	**2**	**1**	**2**
	g CO2 eq /MJ		**g N eq/MJ**		**L H_2O/MJ**	
Supply Chain	-2.18E+02	-2.17E+02	1.92E-01	6.24E-01	5.98E-02	1.29E+01
Processing	1.60E+02	1.60E+02	1.46E-02	1.46E-02	2.10E+00	2.10E+00
Transport	1.46E+00	1.46E+00	3.02E-05	3.02E-05	0	0
Combustion	7.10E+01	7.10E+01	1.11E-03	1.11E-03	0	0
TOTAL	1.44E+01	1.54E+01	2.08E-01	6.39E-01	2.16E+00	1.50E+01

Table S7: Life cycle impact summary for the Py-ECH process. Allocation methods 1 and 2 are reported to observe the effects of avoiding allocation and applying minimal allocation to cultivation.

	GHG		**EUP**		**WSF**	
Allocation	**1**	**2**	**1**	**2**	**1**	**2**
	g CO2 eq /MJ		**g N eq/MJ**		**L H_2O/MJ**	

Supply Chain	-5.77E+01	-5.31E+01	7.29E-02	2.37E-01	2.27E-02	4.89E+00
Processing	8.11E+01	8.11E+01	3.60E-03	3.60E-03	2.56E+00	2.56E+00
Transport	3.68E-01	3.68E-01	7.61E-06	7.61E-06	0	0
Combustion	6.41E+01	6.41E+01	1.07E-03	1.07E-03	0	0
TOTAL	8.78E+01	8.82E+01	7.76E-02	2.41E-01	2.58E+00	7.45E+00

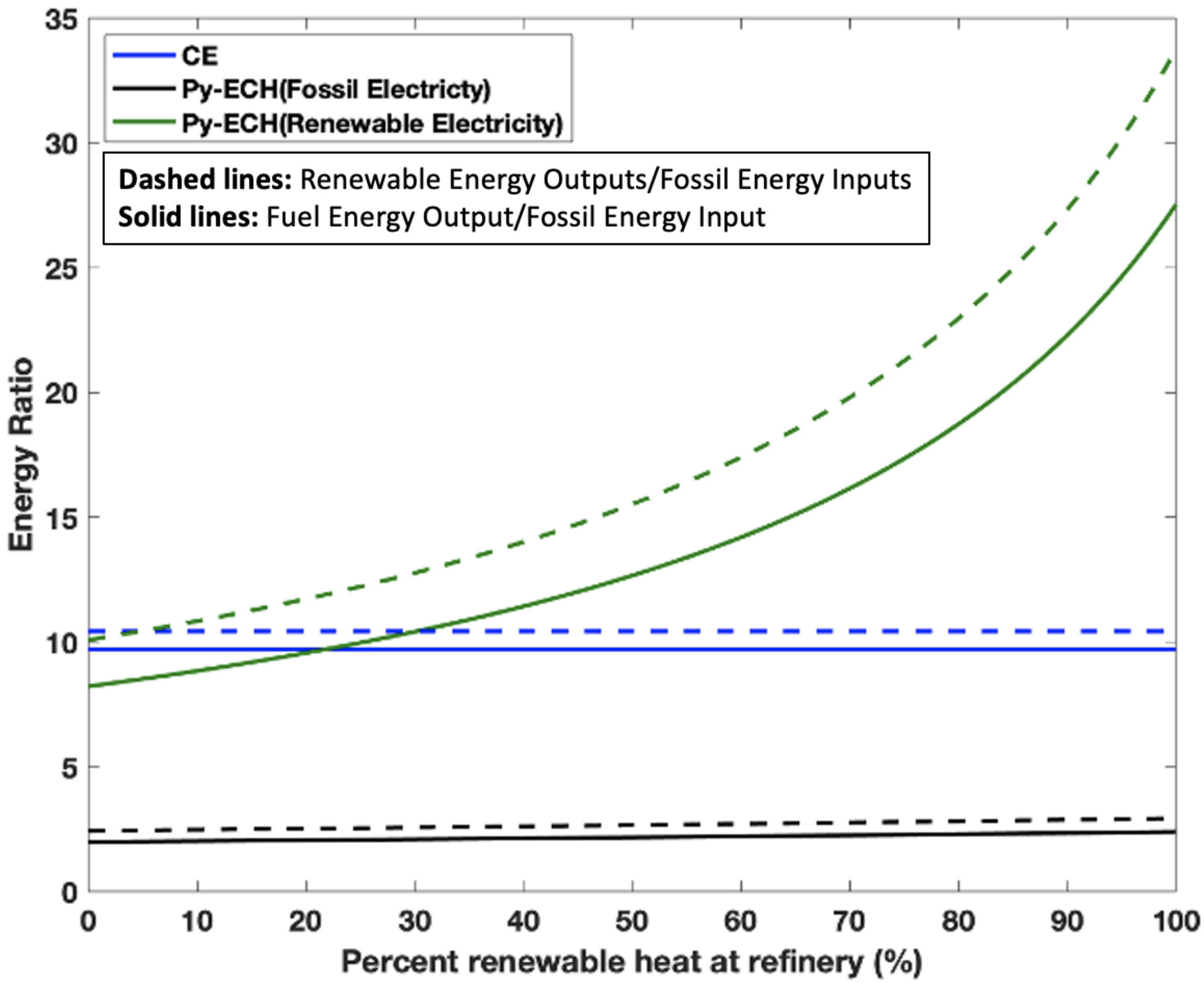

Figure S1: Sensitivity of system RF and ER_f with % renewable heat at refinery. Fossil electricity implies all the electricity is provided by the MRO-West electrical grid; Renewable electricity implies that all the electricity being provided is from renewable sources. The breakeven is at about 25% renewable heat and 100% renewable electricity.

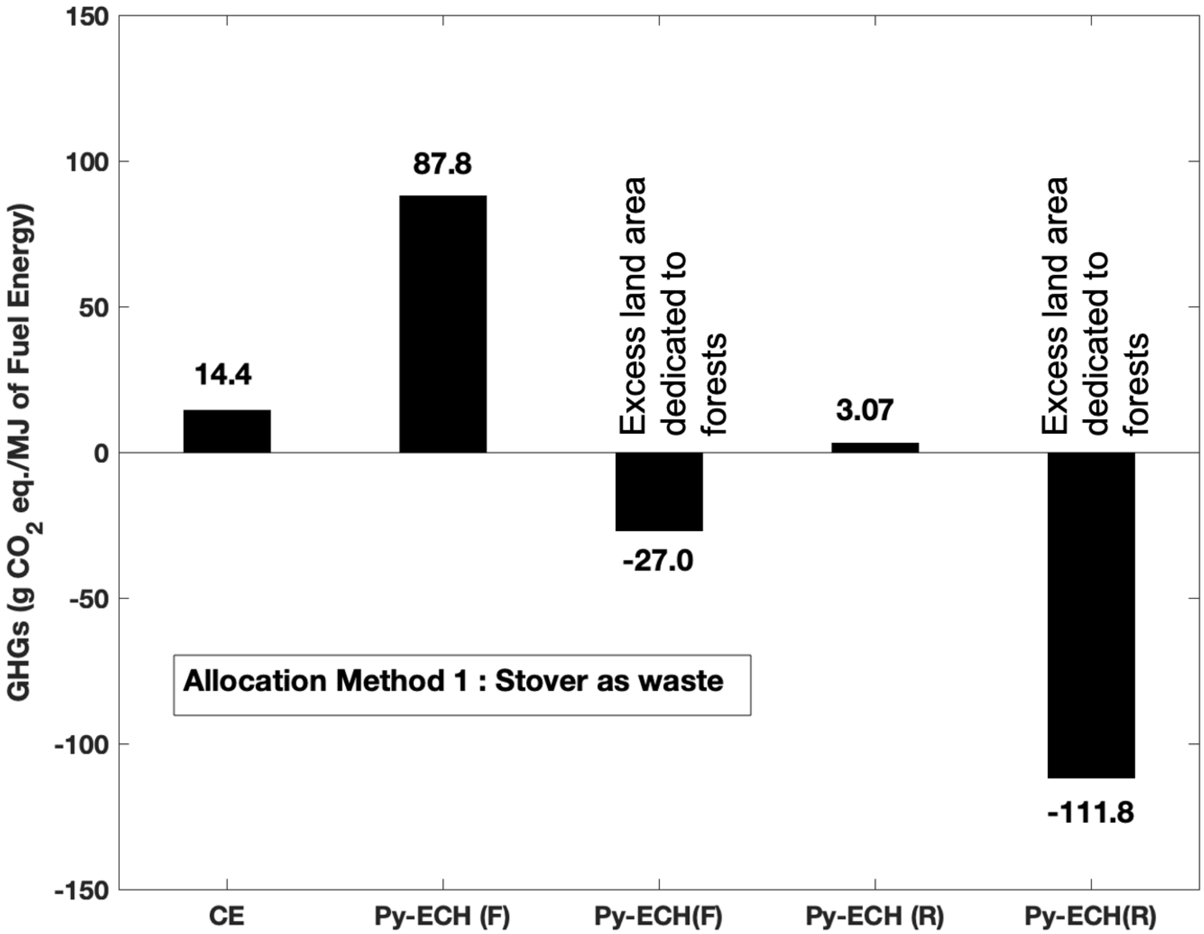

Figure S2: Net GHG emissions of Py-ECH and CE processes using allocation method 1 on a "per MJ fuel energy" basis; 'F' indicates 2020 electrical grid including 70.8% fossil electricity and 'R' refers fully renewable power. Excess land area of ~0.2 million hectares. The annual rate of carbon accumulation in forests can vary from 0.8 tonnes/ha/yr to 5.1 tonnes/ha/yr, depending on the type of forest.[11] The CCLUB model from GREET estimates an annual carbon sequestration rates from forests in the United States at 2.4 tonnes C/ha/yr, which is well within this range. The annual carbon sequestration rate for forests have been assumed conservatively to be 0.8 tonnes/ha/yr.

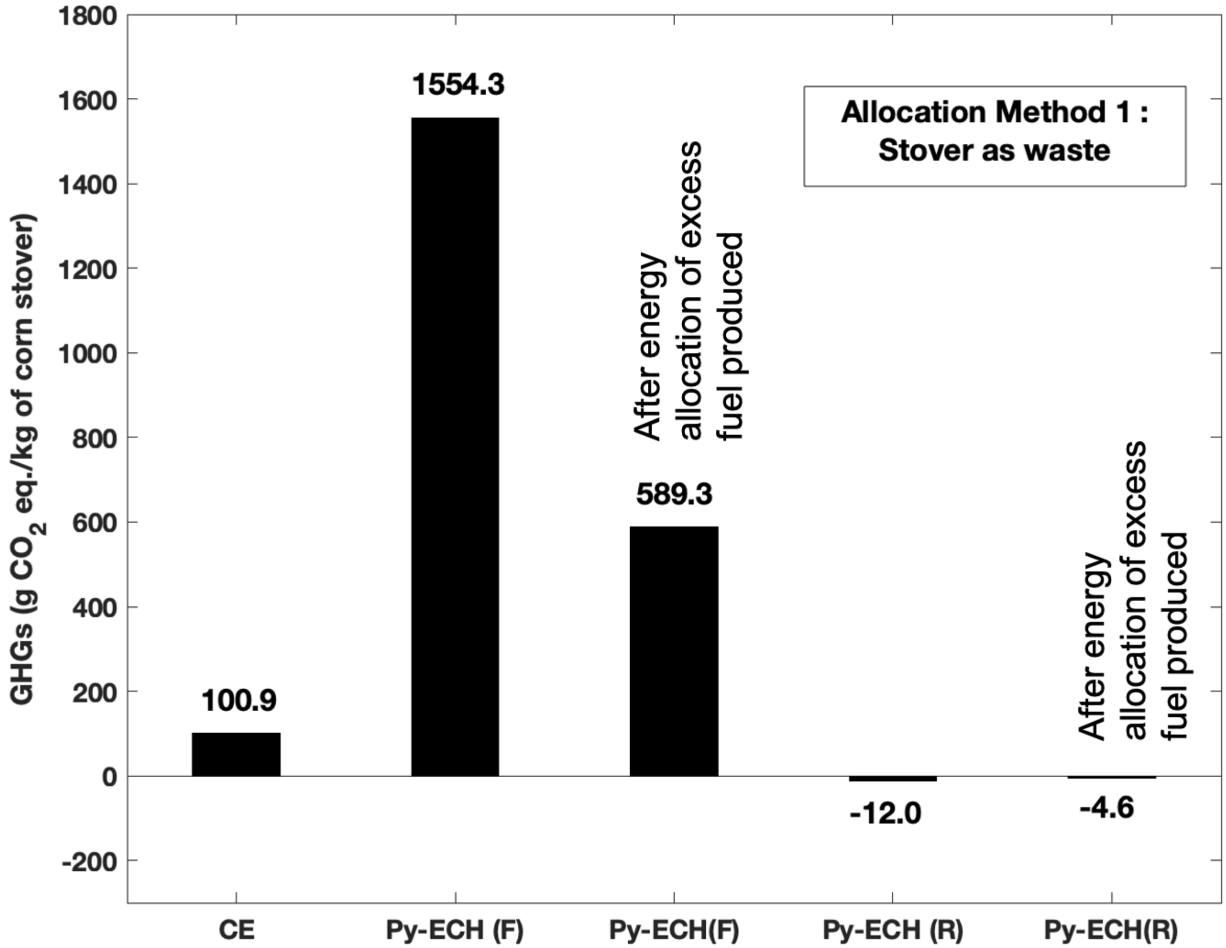

Figure S3: Net GHG emissions of Py-ECH and CE processes using allocation method 1 on a "per kg corn stover processed" basis; 'F' indicates 2020 electrical grid including 70.8% fossil electricity and 'R' refers fully renewable power. Excess fuel energy of of ~11-12 MJ is produced in the Py-ECH process per kg corn stover processed. An energy allocation percentage of~ 38% has been applied as the fuel energy of the primary product must be made equal to the fuel energy of the CE process, which is about ~7 MJ/kg corn stover processed.

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