Supplementary Material to:

Towards Comparable Carbon Credits: Harmonization of LCA Models of Cellulosic Biofuels

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1. VSB model

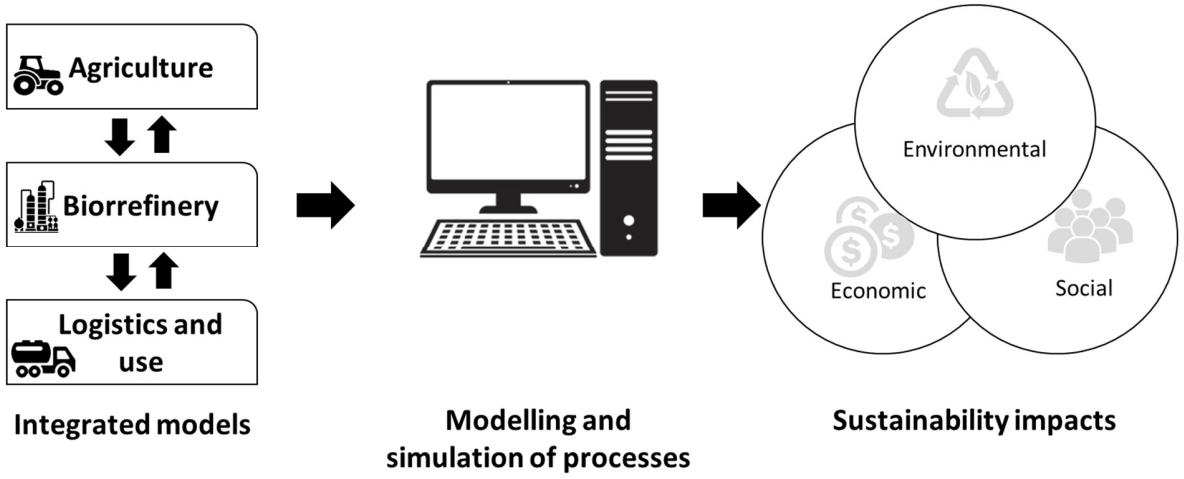


Figure S1. Simplified framework of VSB model.

2. Greenhouse gas emissions of 2G ethanol production

Table S1. Cradle-to-pump emissions associated with 2G ethanol production, in g CO_2eq. MJ^{-1} of ethanol, by phase of production.

	Wheat Straw		Corn Stover		Forest residues			Sugarcane straw	Sugarcane 1G2G
	GHGenius	New EC	GHGenius	GREET	GHGenius	GREET	VSB	VSB	VSB
Procurement of biomass residues	5.1	1.8	9.6	4.0	5.8[1]/-[2]	1.3	0.3	-1.1	12.1
Transport	2.3	5.5	2.3	2.7	3.6[1]/-[2]	4.0	0.1	1.1	-
Industrial processing	21.6	4.9	21.5	14.1	21.9	15.1	7.3	4.9	2.2
Ethanol distribution and storage	1.8	1.6	1.8	1.0	1.8	1.1	2.2	2.2	2.9
Emissions displaced by co-products (electricity)	-12.3	-	-12.3	-14.4	-12.3	-14.4	-	-	2.2
Total	**18.5**	**13.7**	**22.9**	**7.3**	**20.8[a]/11.4[b]**	**7.1**	**9.9**	**7.2**	**19.5**

[a] forest residues from standing timber

[b] forest residues from mill residues

3. Cellulosic ethanol conversion technologies

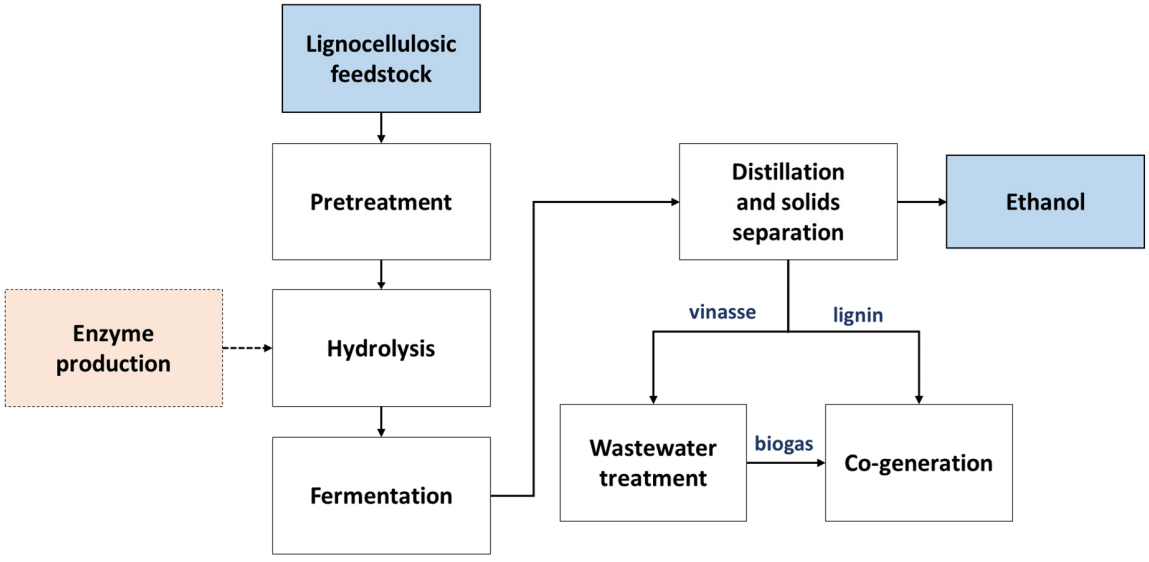


Figure S2. Flowchart of 2G ethanol production.

Table S2. Key emissions factors of the four assessed LCA models.

	GHGenius	GREET	New EC	VSB	Units
Biomass procurement systems					
Diesel	111	95	95	84	$gCO_2eq.\ MJ^{-1}$
Electricity	-	-	141	-	$gCO_2eq.\ MJ^{-1}$
N	3,103	4,548	-	2,799[a]	$gCO_2eq.\ kg^{-1}$
K_2O	426	686	-	545[a]	$gCO_2eq.\ kg^{-1}$
P_2O_5	2,012	1,807	-	1,468[a]	$gCO_2eq.\ kg^{-1}$
High density polyethylene	-	1,565	-	3,505	$gCO_2eq.\ kg^{-1}$
Industrial conversion					
Natural gas	60	70	-	-	$gCO_2eq.\ MJ^{-1}$
Diesel	99	95	-	-	$gCO_2eq.\ MJ^{-1}$
Ammonia	2,329	2,662	-	2,868	$gCO_2eq.\ kg^{-1}$
Lime	848	1,282	-	-	$gCO_2eq.\ kg^{-1}$
Sodium hydroxide	888	2,208	530	-	$gCO_2eq.\ kg^{-1}$
Phosphate nutrients (P_2O_5)	1,619	-	-	-	$gCO_2eq.\ kg^{-1}$
Diammonium phosphate	-	1,204	674.4	-	$gCO_2eq.\ kg^{-1}$
Sugar	424	-	-	296	$gCO_2eq.\ kg^{-1}$
Corn steep liquor	-	1,606	-	-	$gCO_2eq.\ kg^{-1}$
Sulfuric acid	217	45	-	177	$gCO_2eq.\ kg^{-1}$
Yeast	1,559	2,606	-	-	$gCO_2eq.\ kg^{-1}$
Cellulase	-	2,291	-	1,691	$gCO_2eq.\ kg^{-1}$
Urea	-	1,223	-	-	$gCO_2eq.\ kg^{-1}$
Ammonium sulphate	-	-	453	-	$gCO_2eq.\ kg^{-1}$
Monopotassium phosphate	-	-	265	-	$gCO_2eq.\ kg^{-1}$
Magnesium sulphate	-	-	192	-	$gCO_2eq.\ kg^{-1}$
Calcium chloride	-	-	39	-	$gCO_2eq.\ kg^{-1}$
Sodium chloride	-	-	13	-	$gCO_2eq.\ kg^{-1}$
Antifoam	-	-	3,275	-	$gCO_2eq.\ kg^{-1}$
Sulphur dioxide	-	-	53	-	$gCO_2eq.\ kg^{-1}$
Zeolite	-	-	-	4,191	$gCO_2eq.\ kg^{-1}$
Steel	-	-	-	1,795	$gCO_2eq.\ kg^{-1}$
Chromium steel	-	-	-	2,426	$gCO_2eq.\ kg^{-1}$
Concrete	-	-	-	159,512	$gCO_2eq.\ (m^3)^{-1}$
Building hall	-	-	-	309,058	$gCO_2eq.\ (m^2)^{-1}$

[a] Since VSB considers no additional fertilizers application due to straw removal, the emissions factors for NPK in this model are used only in the case of 1G2G ethanol production, where sugarcane is used as feedstock.

3.1. 2G ethanol from corn stover

Table S3. Biomass procurement parameters for corn stover recovery.

	GHGenius	GREET	Unit
Feedstock	Corn stover	Corn stover	
Biomass recovery yield	7.3	10.4	$t^{a}\ ha^{-1}\ yr^{-1}$
Location	Canada Central	USA	
Energy inputs for residue recovery			
Diesel	7.2	7.3	$L\ t^{-1}$
Inputs (due to residue removal)			
N	9.4	3.5	$kg\ N\ t^{-1}$
K_2O	1.3	2.5	$kg\ K_2O\ t^{-1}$
P_2O_5	9.9	15.0	$kg\ P_2O_5\ t^{-1}$
High density polyethylene	-	0.4	$Kg\ t^{-1}$
Avoided emissions[b]			
N_2O	-	-0.2	$kg\ N_2O\ t^{-1}$
NO_x	-	-0.1	$kg\ NO_x\ t^{-1}$

[a] t is tonne of corn stover (dry basis).

[b] avoided emissions due to residue removal.

Table S4. Industrial parameters for the conversion of corn stover into 2G ethanol.

	GHGenius	GREET	Unit
Feedstock	0.1	0.1	$kg\ MJ^{-1}$ Ethanol
Diesel	13.6	2.4	10^{-3} MJ MJ^{-1} Ethanol
Ammonia	2.0	0.5	$g\ MJ^{-1}$ Ethanol
Lime	1.6	1.0	$g\ MJ^{-1}$ Ethanol
Sodium hydroxide	3.9	1.5	$g\ MJ^{-1}$ Ethanol
Phosphate nutrients (P_2O_5)	0.2	-	$g\ MJ^{-1}$ Ethanol
Diammonium phosphate	-	0.2	$g\ MJ^{-1}$ Ethanol
Sugar[a]	4.2	1.6	$g\ MJ^{-1}$ Ethanol
Sulphuric acid	3.4	4.3	$g\ MJ^{-1}$ Ethanol
Yeast	0.2	0.3	$g\ MJ^{-1}$ Ethanol
Cellulase	-	1.3	$g\ MJ^{-1}$ Ethanol
Urea	-	0.3	$g\ MJ^{-1}$ Ethanol

[a] GREET considers corn steep liquor

Table S5. Transportation parameters for 2G ethanol from corn stover.

	GHGenius	GREET	Unit
Residue transportation			
Truck	100	153.2 (HHD)	km
Ethanol distribution			
Barge	-	836.9 (13.2%)	km
Train	700.0	1287.5 (78.9%)	km
Truck	225.3	128.8 (7.9%) (HHD)	km
Truck	-	48.3 (HHD)	km

HHD: heavy-heavy-duty truck

Table S6. Biomass boiler emissions and electricity output in the production of 2G ethanol from corn stover.

	GHGenius	GREET	Unit
VOC	-	8.7	mg MJ^{-1} Ethanol
PM10	71.9	10.6	mg MJ^{-1} Ethanol
PM2.5	61.5	1.8	mg MJ^{-1} Ethanol
CO	602.8	130.4	mg MJ^{-1} Ethanol
NOx	227.9	136.6	mg MJ^{-1} Ethanol
SOx	216.8	55.9	mg MJ^{-1} Ethanol
CO_2 LUC	-	-623.0	mg MJ^{-1} Ethanol
CH_4 biogenic	69.9	-	mg MJ^{-1} Ethanol
Output			
Electricity	0.1	0.1	MJ MJ^{-1} Ethanol

3.2. 2G ethanol from forest residues

Table S7. Biomass procurement parameters for forest residues recovery.

	GHGenius	GREET	VSB	Unit
Feedstock	Forest residues	Forest residues	Forest residues	
Recovery yield	9.2	7.9	6.6	t^a ha^{-1} yr^{-1}
Location	20% Canada East. 50% Canada Central, 30% Canada West	USA	Brazil	
Energy inputs for residue recovery				
Diesel	9.5[b]/-[c]	4.3	0.4	L t^{-1}

[a] t is tonne of forest residue (dry basis).

[b] forest residues from standing timber

[c] forest residues from mill residues

Table S8. Industrial parameters for the conversion of forest residues into 2G ethanol.

	GHGenius	GREET	VSB	Unit
Feedstock	0.1	0.1	0.2	kg MJ^{-1} Ethanol
Diesel	13.6	4.4	-	10^{-3} MJ MJ^{-1} Ethanol
Natural gas	-	42.4	-	10^{-3} MJ MJ^{-1} Ethanol

Ammonia	2.0	0.5	1.4	g MJ^{-1} Ethanol
Lime	1.6	1.0	-	g MJ^{-1} Ethanol
Sodium hydroxide	3.9	1.5	-	g MJ^{-1} Ethanol
Phosphate nutrients (P_2O_5)	0.2	-	-	g MJ^{-1} Ethanol
Diammonium phosphate	-	0.2	-	g MJ^{-1} Ethanol
Sugar[a]	4.2	1.6	0.1	g MJ^{-1} Ethanol
Sulphuric acid	3.4	4.3	0.1	g MJ^{-1} Ethanol
Yeast	0.2	-	-	g MJ^{-1} Ethanol
Cellulase	-	-	0.7	g MJ^{-1} Ethanol
Urea	-	0.3	-	g MJ^{-1} Ethanol
Steel	-	-	0.2	g MJ^{-1} Ethanol
Chromium steel	-	-	10.0	g MJ^{-1} Ethanol
Concrete	-	-	0.2	cm^3 MJ^{-1} Ethanol
Building hall	-	-	0.1	cm^2 MJ^{-1} Ethanol

[a] GREET considers corn steep liquor

Table S9. Transportation parameters of forest residues 2G ethanol.

	GHGenius	**GREET**	**VSB**	
		Residue transportation		
Truck	100.0[a]/-[b]	144.8 (HHD)	100.0	km
		Ethanol distribution		
Barge	-	836.9 (13.2%)	-	km
Train	700.0	1287.5 (78.9%)	-	km
Truck	225.3	128.8 (7.9%) (HHD)	400.0	km
Truck	-	48.3	-	km

[a] forest residues from standing timber

[b] forest residues from mill residues

HHD: heavy-heavy-duty truck

Table S10. Biomass boiler emissions and electricity output in the production of 2G ethanol from forest residues.

	GHGenius	**GREET**	**VSB**	
VOC	-	8.7	3.6	mg MJ^{-1} Ethanol
PM10	76.7	10.6	58.6	mg MJ^{-1} Ethanol
PM2.5	65.6	1.8	29.3	mg MJ^{-1} Ethanol
CO	643.2	130.4	52.0	mg MJ^{-1} Ethanol
NO_x	231.3	136.6	51.7	mg MJ^{-1} Ethanol
N_2O	14.3	-	2.9	mg MJ^{-1} Ethanol
SO_x	231.3	55.9	2.8	mg MJ^{-1} Ethanol
CH_4 biogenic	74.5	-	21.4	mg MJ^{-1} Ethanol
		Output		
Electricity	0.1	0.1	0.2	MJ MJ^{-1} Ethanol

3.3. 2G ethanol from wheat straw

Table S11. Biomass procurement parameters for wheat straw recovery.

	GHGenius	New EC	Unit
Feedstock	**Wheat straw**	**Wheat straw**	
Recovery	2.6	-[a]	t[b] ha^{-1} yr^{-1}
Location	Canada West	Europe	
Energy inputs for residue recovery			
Diesel	1.5	4.2	L t^{-1}
Electricity	-	47.3	kWh t^{-1}
Inputs (due to residue removal)			
N	6.0	-	kg N t^{-1}
K_2O	1.6	-	kg K_2O t^{-1}
P_2O_5	13.3	-	kg P_2O_5 t^{-1}
Baling emissions			
CH_4	-	0.2	g CH_4 t^{-1}
N_2O	-	0.5	g N_2O t^{-1}

[a] The New EC model does not disclose the amount of wheat straw recovered per hectare as straw is treated as a residue with zero emissions ascribed to it (before baling) and the straw yield is not relevant for the GHG calculation under the RED.
[b] t is tonne of wheat straw (dry basis).

Table S12. Industrial parameters for the conversion of wheat straw into 2G ethanol.

	GHGenius	New EC	Unit
	Wheat straw	**Wheat straw**	
Feedstock	0.2	0.2	kg MJ^{-1} Ethanol
Diesel	13.6	-	10^{-3} MJ MJ^{-1} Ethanol
Ammonia	2.0	0.4	g MJ^{-1} Ethanol
Lime	1.6	1.9	g MJ^{-1} Ethanol
Sodium hydroxide	3.9	4.9	g MJ^{-1} Ethanol
Phosphate nutrients (P_2O_5)	0.2	-	g MJ^{-1} Ethanol
Diammonium phosphate	-	0.3	g MJ^{-1} Ethanol
Sugar[a]	4.2	-	g MJ^{-1} Ethanol
Sulphuric acid	3.4	-	g MJ^{-1} Ethanol
Yeast	0.2	-	g MJ^{-1} Ethanol
Ammonium Sulphate	-	0.2	g MJ^{-1} Ethanol
Monopotassium phosphate	-	0.2	g MJ^{-1} Ethanol
Calcium Chloride	-	0.1	g MJ^{-1} Ethanol
Sodium Chloride	-	0.4	g MJ^{-1} Ethanol
Antifoam	-	0.7	g MJ^{-1} Ethanol
Sulfur dioxide	-	0.1	g MJ^{-1} Ethanol

[a] GREET considers corn steep liquor

Table S13. Transportation parameters of wheat straw 2G ethanol.

	GHGenius	New EC	
Residue transportation to ethanol plant			
Truck	100.0	500.0	km
Ethanol distribution			
Barge	-	153.0 (50.8%)	km
Ocean	-	1118.0 (31.6%)	km
Train	700.0	-	km
Truck	225.3	305 (13.2%)	km

Table S14: Biomass boiler emissions and output of electricity per MJ of wheat straw 2G ethanol

	GHGenius	New EC	
PM10	72.4	-	mg MJ^{-1} Ethanol
PM2.5	62.0	-	mg MJ^{-1} Ethanol
CO	607.7	-	mg MJ^{-1} Ethanol
NOx	229.7	-	mg MJ^{-1} Ethanol
N_2O	13.5	-	mg MJ^{-1} Ethanol
SOx	218.6	-	mg MJ^{-1} Ethanol
CH_4 biogenic	70.4	-	mg MJ^{-1} Ethanol
Output			
Electricity	0.1	0.4	MJ MJ^{-1} Ethanol

3.4. 2G ethanol from sugarcane straw.

Table S15. Biomass procurement parameters for sugarcane straw recovery.

VSB		
Feedstock	**Sugarcane straw**	
Recovery	3.4	t[a] ha^{-1} yr^{-1}
Location	Brazil	
Energy inputs for residue recovery		
Diesel	5.5	L t^{-1}
Inputs for residue recovery		
High density polyethylene	0.5	kg t^{-1}
Avoided emissions[b]		
N_2O	-0.1	kg N_2O t^{-1}
NOx	-0.02	kg NOx t^{-1}

[a] t is tonne of sugarcane straw (dry basis).

[b] avoided emissions due to residue removal.

Table S16. Industrial parameters for the conversion of sugarcane straw into 2G ethanol.

VSB		
Sugarcane straw		
Feedstock	0.2	kg MJ^{-1} Ethanol
Ammonia	0.8	g MJ^{-1} Ethanol
Sugar[1]	0.1	g MJ^{-1} Ethanol
Sulphuric acid	0.1	g MJ^{-1} Ethanol

Cellulase	0.9	g MJ^{-1} Ethanol
Steel	0.2	g MJ^{-1} Ethanol
Concrete	0.2	cm^3 MJ^{-1} Ethanol
Building hall	0.1	cm^2 MJ^{-1} Ethanol

Table S17. Biomass boiler emissions and electricity output in the production of 2G ethanol from sugarcane straw.

	VSB	
VOC	3.5	mg MJ^{-1} Ethanol
PM10	56.0	mg MJ^{-1} Ethanol
PM2.5	28.0	mg MJ^{-1} Ethanol
CO	49.7	mg MJ^{-1} Ethanol
NOx	49.4	mg MJ^{-1} Ethanol
N_2O	2.7	mg MJ^{-1} Ethanol
SOx	2.7	mg MJ^{-1} Ethanol
CH_4 biogenic	20.5	mg MJ^{-1} Ethanol
Output		
Electricity	0.1	MJ MJ^{-1} Ethanol

Table S18. Transport parameters of sugarcane straw 2G ethanol.

	VSB	
Residue transportation to ethanol plant		
Truck	45.0	km
Ethanol distribution		
Truck	400.0	km

3.5. 1G2G ethanol from sugarcane

Table S19. Biomass procurement parameters for sugarcane production and straw recovery.

	VSB	
Sugarcane	**76.80**	t^a ha^{-1} yr^{-1}
Recovered straw	3.5	t ha^{-1} yr^{-1}
Inputs		
Diesel	1.8	L t^{-1}
Limestone	5.2	kg L t^{-1}
Gypsum	2.6	kg L t^{-1}
N	1.3	kg N L t^{-1}
K_2O	0.9	kg K_2O L t^{-1}
P_2O_5	0.2	kg P_2O_5 L t^{-1}
Vinasse	0.9	m^3 L t^{-1}
Filter cake	10.0	kg L t^{-1}
Ashes from boilers	6.3	kg L t^{-1}
Agricultural machinery	0.3	kg L t^{-1}
Emissions		
Fossil carbon dioxide	4.3	kg L t^{-1}
Dinitrogen monoxide	4.3	g L t^{-1}
Ammonia	50.3	kg L t^{-1}

Nitrogen oxides	0.5	g L t^{-1}

[a] t is tonne of sugarcane produced (wet basis).

Table S20. Industrial parameters for the conversion of sugarcane into 1G and 2G ethanol.

	VSB	
Sugarcane	0.4	kg MJ^{-1} Ethanol
Straw	18.1	g MJ^{-1} Ethanol
Lime	0.2	g MJ^{-1} Ethanol
Sulphuric acid	0.2	g MJ^{-1} Ethanol
Ammonia	0.2	g MJ^{-1} Ethanol
Sugar	31.8	mg MJ^{-1} Ethanol
Phosphoric acid	68.7	mg MJ^{-1} Ethanol
Flocculating polymer	1.0	mg MJ^{-1} Ethanol
Antibiotic	0.6	mg MJ^{-1} Ethanol
Cellulase	0.2	g MJ^{-1} Ethanol
Steel	0.1	g MJ^{-1} Ethanol
Chromium steel	4.8	mg MJ^{-1} Ethanol
Concrete	0.1	cm^3 MJ^{-1} Ethanol

Table S21. Biomass boiler emissions and electricity output in the production of 1G and 2G ethanol from sugarcane.

	VSB	
VOC	3.9	mg MJ^{-1} Ethanol
PM10	64.0	mg MJ^{-1} Ethanol
PM2.5	32.0	mg MJ^{-1} Ethanol
CO	56.8	mg MJ^{-1} Ethanol
N_2O	3.1	mg MJ^{-1} Ethanol
NOx	56.5	mg MJ^{-1} Ethanol
SOx	3.0	mg MJ^{-1} Ethanol
CH_4 biogenic	23.4	mg MJ^{-1} Ethanol
	Output	
Electricity	0.1	MJ MJ^{-1} Ethanol

Table S22. Transportation parameters of 1G and 2G ethanol from sugarcane.

	VSB	
	Sugarcane and straw transportation	
Truck	36.0	km
	Ethanol distribution	
Truck	400.0	km

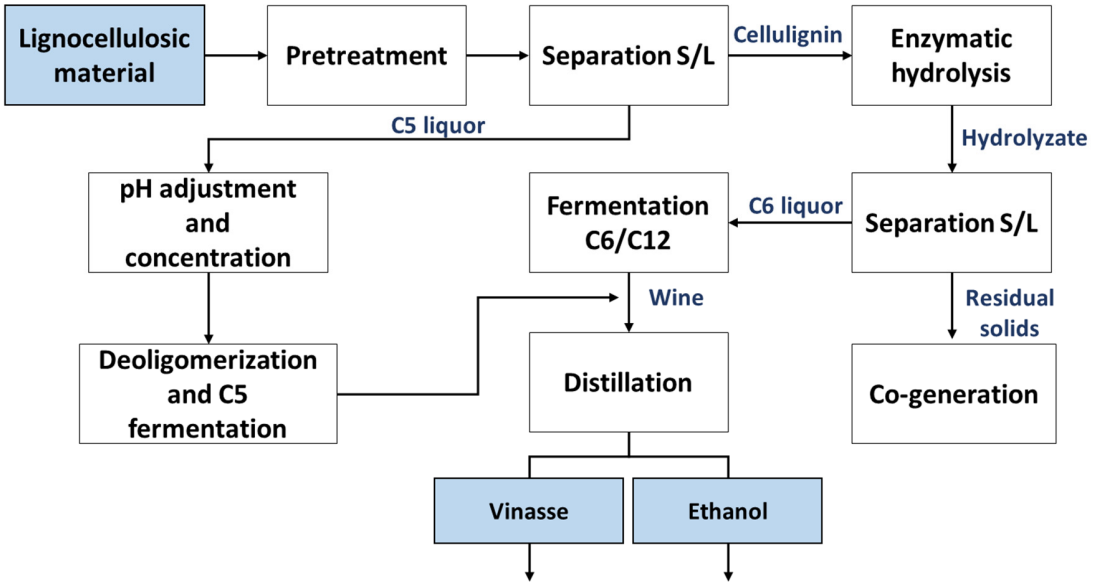


Figure S3. Flowchart of 2G ethanol production in the integrated 1G and 2G ethanol plant in the VSB model.