Comparison of Biofuel Life Cycle GHG Emissions Assessment Tools

GHGenius | GREET | New EC | VSB

Phase II b: 2G ethanol

May 2019

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Background

- Phase I:

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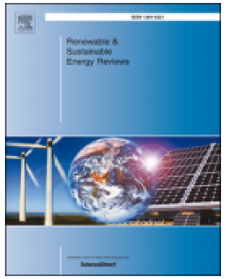

Comparison of biofuel life-cycle GHG emissions assessment tools: The case studies of ethanol produced from sugarcane, corn, and wheat

L.G. Pereira[a,b,*], O. Cavalett[a], A. Bonomi[a,c], Y. Zhang[d], E. Warner[d], H.L. Chum[d]

- Phase II a: Comparison of Biofuel Life Cycle Analysis Tools - FAME and HVO/HEFA (report – to be published)
- Phase II b: Comparison of Biofuel Life Cycle Analysis Tools - 2G ethanol (report – under development)

- New LCA study: Co-processing alternatives

Motivation

Bioenergy plays an important role in the decarbonization of the transportation sector.

Its medium and long-term benefits depend on the reduction of GHG emissions in substitution to their fossil counterparts.

Decarbonization impacts of biofuels can be quantitatively determined through a Life Cycle Analysis (LCA) methodology.

However, discrepant results are often obtained using different LCA tools.

Objectives

…to identify the main differences and commonalities in methodological structures, calculation procedures, and assumptions, providing a detailed understanding of how and why GHG results diverge.

This study focus on understanding the particularities of 2nd generation ethanol production systems from lignocellulosic residues: sugarcane straw and bagasse, wheat straw, corn stover, and forest residues.

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- Standalone 2G ethanol
  - All models with default feedstocks
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  - GHGenius
  - GREET

Models

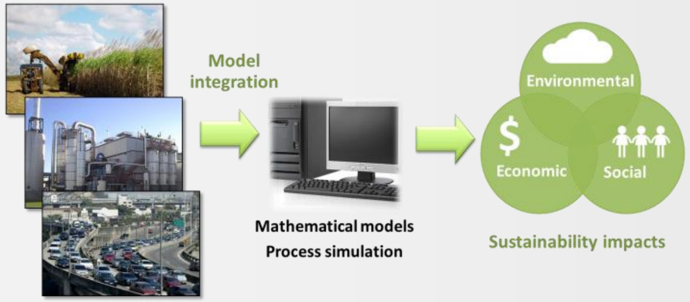
NEW EC

New EC - Biofuels pathways. Input values and GHG emissions.

(S&T)^2 Consultants Inc

GHGenius

The Greenhouse Gases. Regulated Emissions and Energy in Transportation



Virtual Sugarcane Biorefinery (VSB)

Models

	GHGenius	GREET	New EC	VSB
Model version	**5.0c (2018)**	**2018**	**2019**	**2019**
Developed for regulatory use	No[1]	No	Yes	No
IPCC GWP method	1995, 2001, 2007	AR5 2013	2013	2013
Default global warming gases	CO_2, CH_4, N_2O, CO, VOC, NO_x, fluorinated compounds	CO_2, CH_4, N_2O	CO_2, CH_4, N_2O	CO_2, CH_4, N_2O
Lifecycle data	Internal	Internal	New EC	Ecoinvent
Functional unit	Km, MJ	Km, mile Btu, MJ	MJ	km MJ
Default allocation	**Substitution**	**Substitution**	**Energy**	**Economic**
Land use change	-	CCLUB	C stocks	-
Possible boundaries	**Well-to-wheel**	**Well-to-wheel**	**Well-to-pump**	**Well-to-wheel**

[1] GHGenius has not been developed as a regulatory tool, although it is currently being used as one

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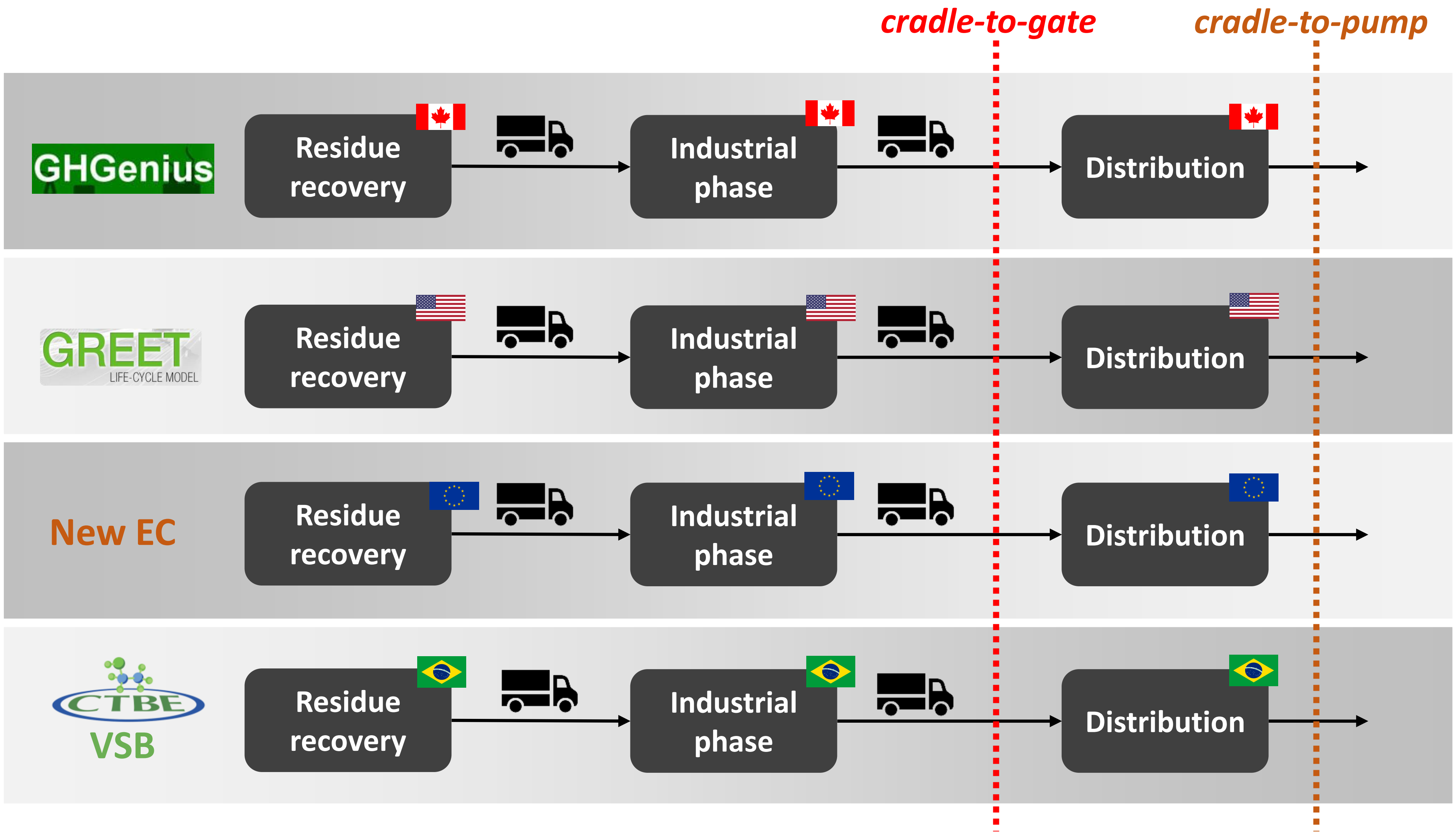
System boundaries: standalone 2G ethanol

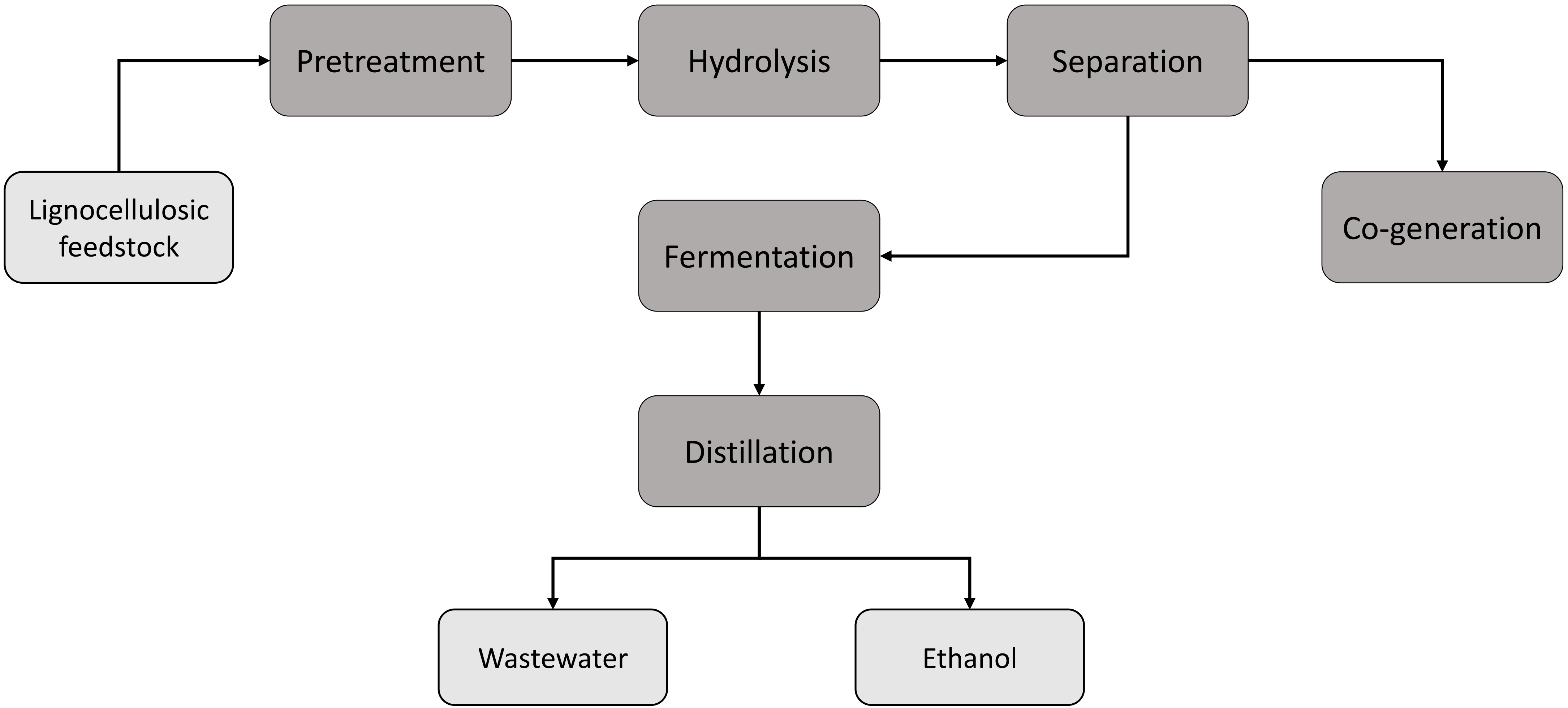


Particularities: standalone 2G ethanol

- All four models consider:
  - Ethanol as main product and electricity as a co-product
  - Co-generation system
  - Lignin for combined heat and power generation
- GHGenius and GREET consider substitution procedure (electricity)
- New EC considers energy allocation
- VSB
  - Considers economic allocation
  - Considers cells recycle for fermentation

Standalone 2G ethanol: simplified flow chart

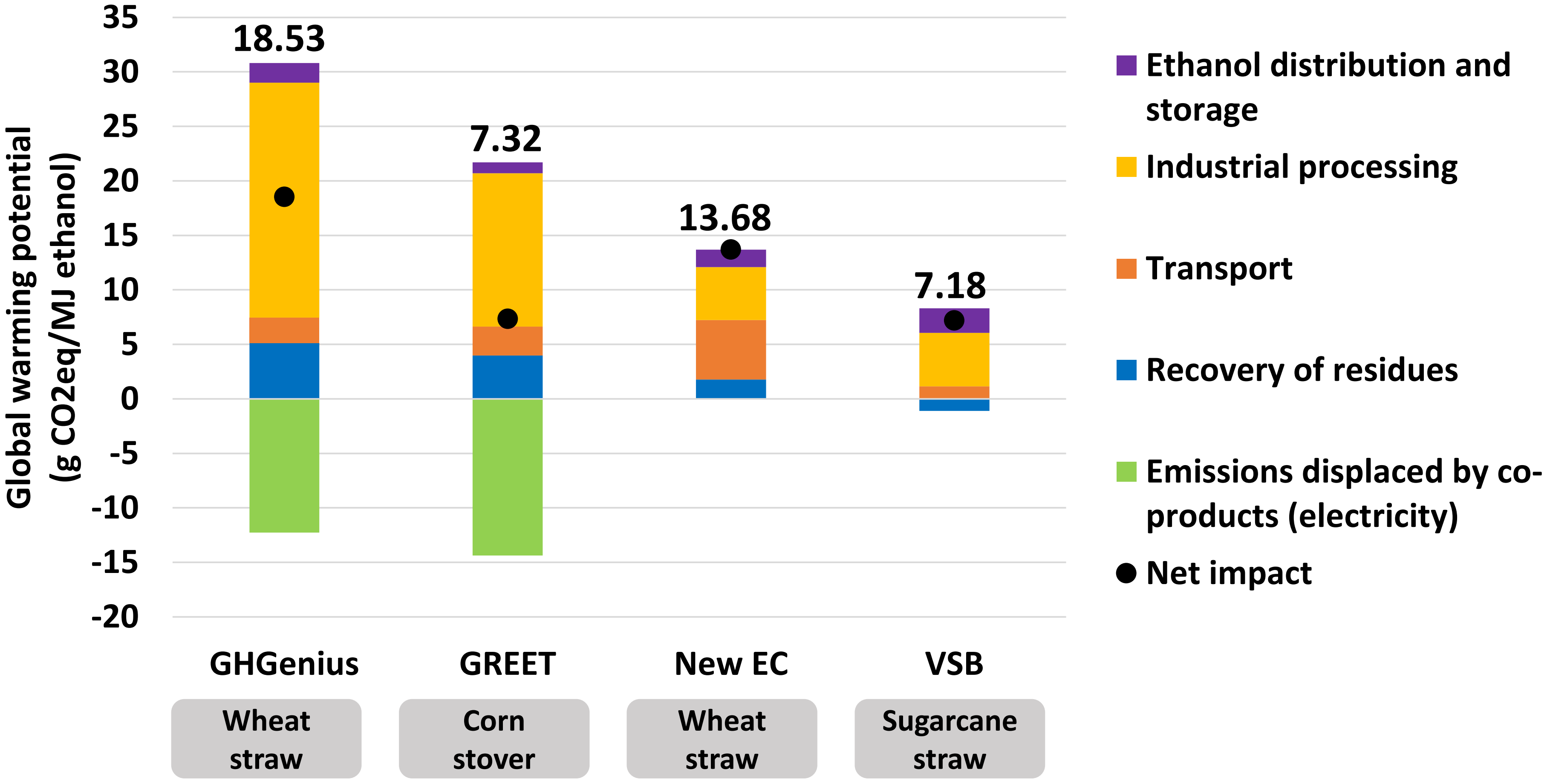
Lignocellulosic feedstock



Standalone 2G ethanol

Ethanol production emissions

Cradle-to-pump: g CO_2eq/MJ Ethanol



Standalone 2G ethanol: Major differences

	GHGenius	GREET	New EC	VSB
Residue recovery	• Additional NPK inputs due to biomass removal, no credit or debit for soil carbon changes, neither avoided emissions (N_2O) due to biomass removal	• Additional NPK inputs due to biomass removal. • N_2O and NO_x avoided emissions on the field, due to biomass removal	• No credit or debit for soil carbon changes, neither avoided emissions (N_2O) due to biomass removal. • CH_4 and N_2O emissions from baling operation • Considers biomass pelletization operation	• N_2O and NO_x avoided emissions on the field, due to biomass removal. • Considers machinery and tractor inputs on the field
Industrial production	• High energy inputs	• Low energy inputs • Considers avoided LUC emissions	• Enzymes are produced in the ethanol plant • No external energy inputs	• Considers zeolite and infrastructure material • No external energy inputs
Ethanol distribution	• High emissions • Low efficiency	• No ocean transportation, only local consumption	• Considers ocean transportation	• High emissions • No ocean transportation, only local consumption

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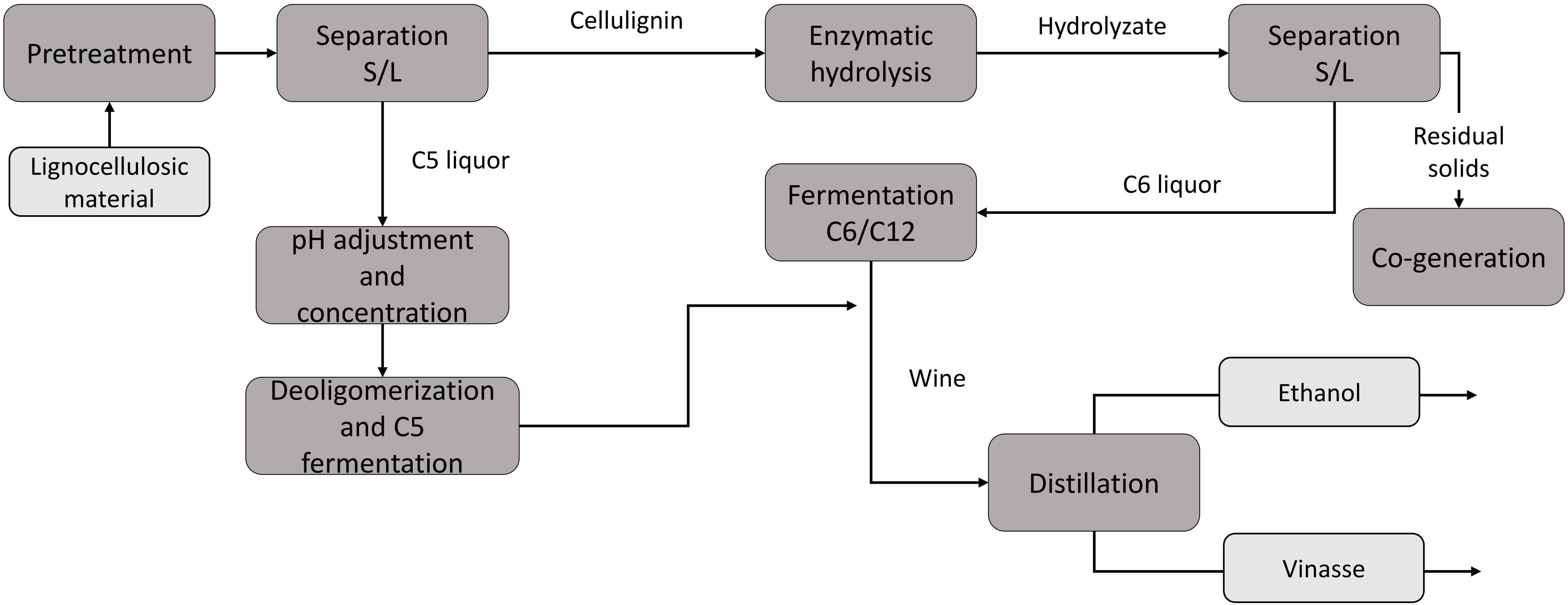
Integrated 1G2G ethanol: particularities

Sugarcane bagasse and straw

- 2G ethanol plant integrated to 1G ethanol plant
- Pre-treatment: steam explosion of both bagasse and straw
- Separate fermentation for C6 and C5 sugars
- Considers cells recycle for fermentation
- Part of the lignocellulosic material (sugarcane bagasse and straw) is diverted to 2G production
- Co-generation system and electricity exportation
- CHP: lignocellulosic material (sugarcane bagasse and straw) + cellulignin

2G ethanol production: flow chart

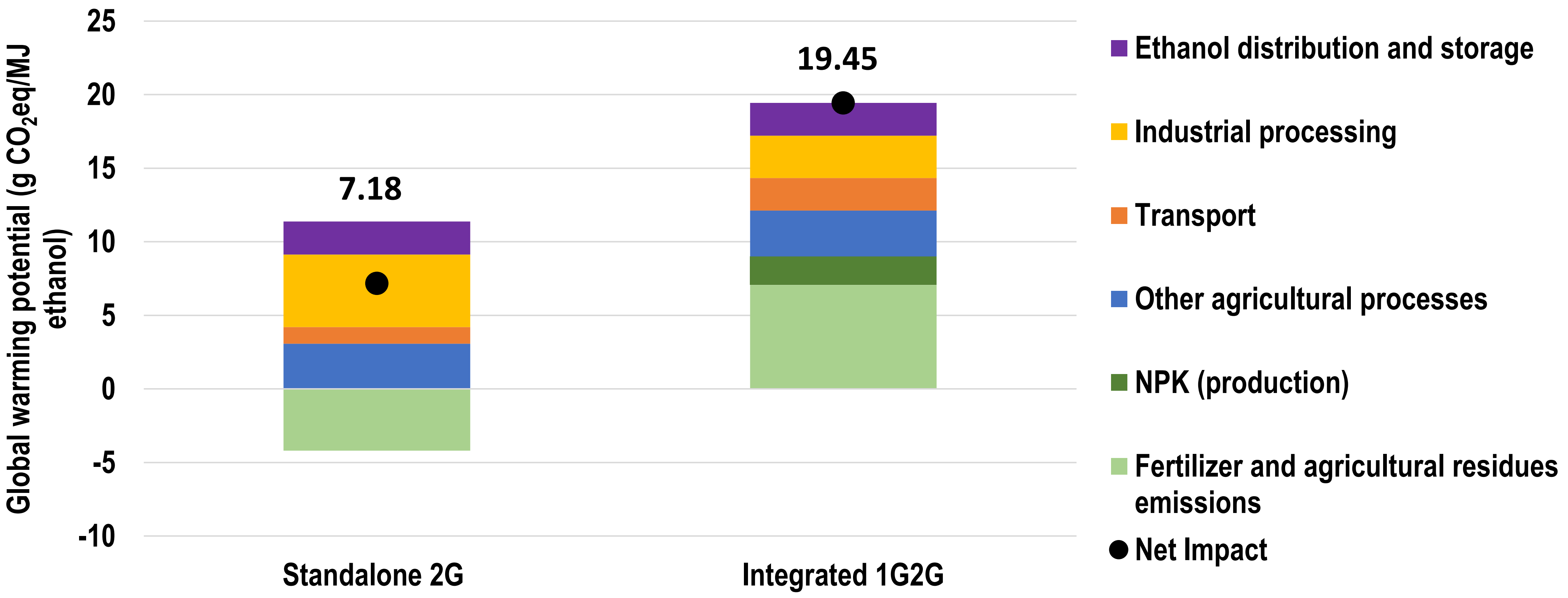
Sugarcane bagasse and straw



Adapted from Milanez et al 2015

VSB Sugarcane ethanol: 2G x 1G2G

Ethanol production emissions



Sugarcane straw

Sugarcane bagasse and straw

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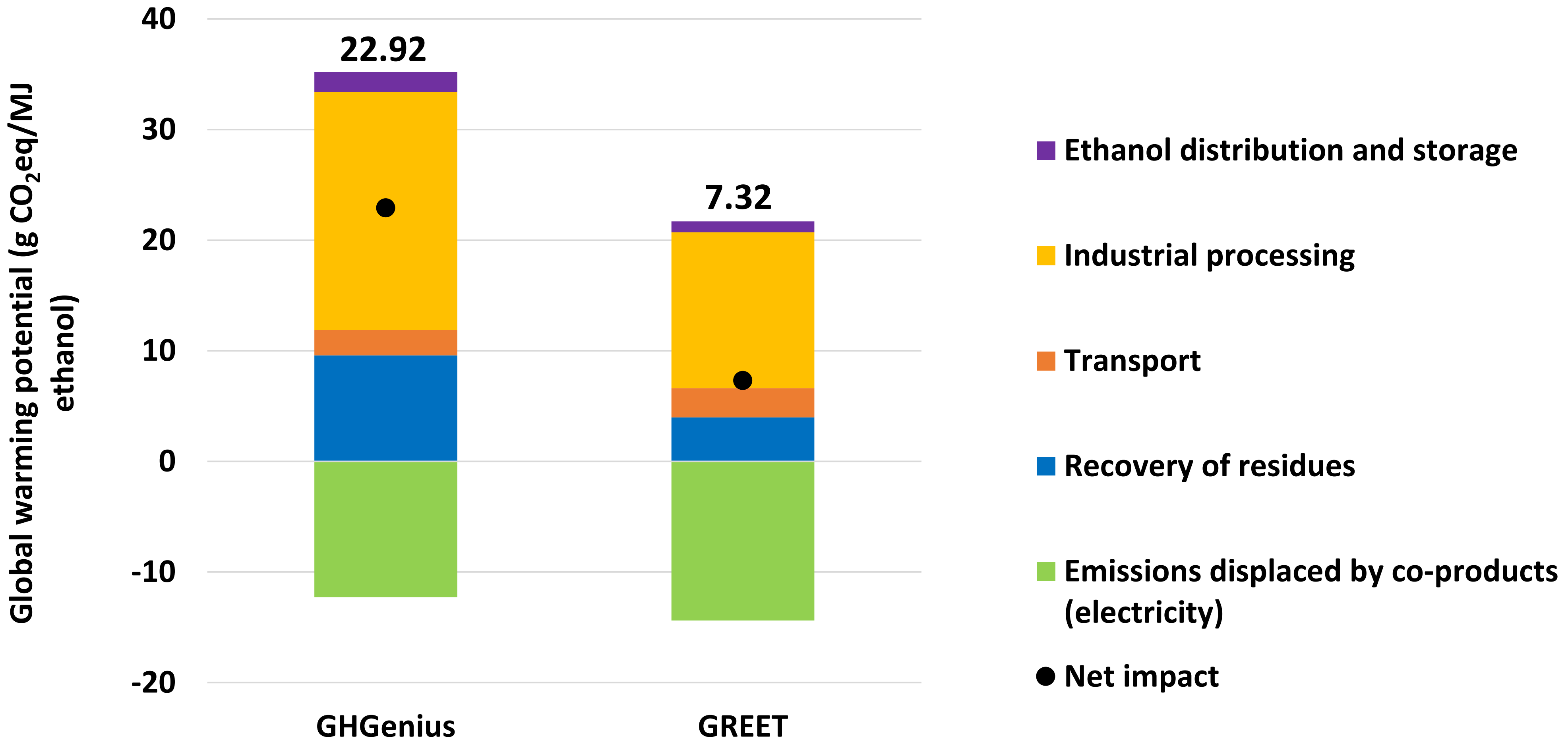
Corn stover 2G ethanol

Ethanol production emissions

Cradle-to-pump: g CO_2eq/MJ Ethanol



Corn stover 2G ethanol: Major differences

	GHGenius	GREET
Residue recovery	• No credit or debit for carbon changes are considered, neither avoided emissions (N_2O) due to biomass removal	• Considers N_2O and NOx avoided emissions on the field, due to biomass removal
Industrial production	• High energy inputs • No enzyme (cellulase) input	• Low energy inputs • Considers avoided LUC emissions and only lignin for combined heat and power generation
Ethanol distribution	• Local consumption	• Local consumption

Harmonization of corn stover ethanol production

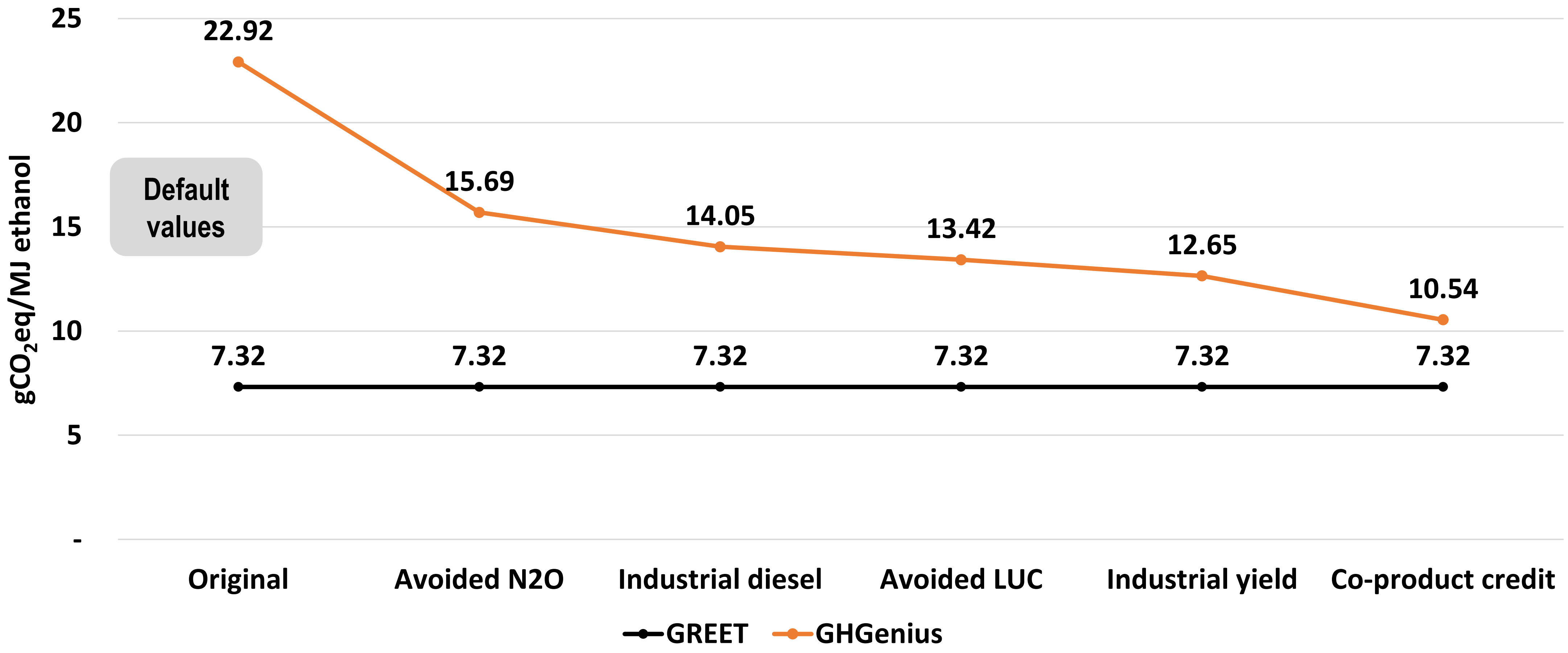
Remarks: *Cradle-to-pump*

- Harmonization of N_2O avoided emissions on the field
  - This input was added to GHGenius, since the model does not consider such emissions
- Harmonization of industrial inputs
  - Diesel
  - LUC avoided emissions
- Harmonization of industrial yield
  - GREET yield value was added to GHGenius
- Harmonization of allocation procedure
  - Both methods consider substitution of electricity. Co-product's credit value from GREET was inserted in GHGenius

Corn stover 2G ethanol

Harmonization of corn stover ethanol emissions

Cradle-to-pump: g CO_2eq/MJ Ethanol



Major differences after harmonization

Harmonization of corn stover ethanol production emissions

Cradle-to-pump

- Particularities of each model
- Characterization factors differ among models

	GREET	GHGenius[1]	New EC	VSB
CO_2	1	1	1	1
CH_4	30	25	23	25
N_2O	265	298	296	298

[1] GHGenius also takes into account several characterization factors to convert several other compounds (such as VOC. NO_x. fluorides. etc.) into CO_2eq using 2007 IPCC GWP data

- Calculation procedures also differ from one model to another
- Emission factors
- Remaining steps that were not harmonized can cumulatively account for the differences found in the final result

CTBE

CNPEM

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EMISSION FACTORS

Main general emission factors: standalone 2G ethanol

Agricultural phase

	GHGenius	GREET	New EC	VSB	
Diesel	111	95	95	84	g CO_2eq/MJ
Electricity	-	-	141	-	g CO_2eq/MJ
N	3,103	4,548	-	-	g CO_2eq/kg
K_2O	426	686	-	-	g CO_2eq/kg
P_2O_5	2,012	1,807	-	-	g CO_2eq/kg
High density polyethylene	-	1,565	-	3,505	g CO2eq/kg

Some models consider NPK replacement due to residue removal

Main general emission factors: standalone 2G ethanol

Industrial phase: part I

	GHGenius	GREET	New EC	VSB	
Natural gas	60	70	-	-	g CO_2eq/MJ
Diesel	99	95	-	-	g CO_2eq/MJ
Ammonia	2,329	2,662	-	2,868	g CO_2eq/kg
Lime	63	1,282	-	-	g CO_2eq/kg
Sodium hydroxide	888	2,208	530	-	g CO_2eq/kg
Phosphate nutrients (P_2O_5)	1,619	-	-	-	g CO_2eq/kg
Diammonium phosphate	-	1,204	674	-	g CO_2eq/kg
Sugar	424	-	-	296	g CO_2eq/kg
Corn steep liquor	-	1,606	-	-	g CO_2eq/kg
Sulfuric acid	217	45	-	177	g CO_2eq/kg
Yeast	1,559	2,606	-	-	g CO_2eq/kg
Cellulase	-	2,291	-	1,691	g CO_2eq/kg
Urea	-	1,223	-	-	g CO_2eq/kg

Main general emission factors: standalone 2G ethanol

Industrial phase: part II

	GHGenius	GREET	New EC	VSB	
Ammonium sulphate	-	-	453	-	g CO_2eq/kg
Monopotassium phosphate	-	-	265	-	g CO_2eq/kg
Magnesium sulphate	-	-	192	-	g CO_2eq/kg
Calcium chloride	-	-	39	-	g CO_2eq/kg
Sodium chloride	-	-	13	-	g CO_2eq/kg
Antifoam	-	-	3,275	-	g CO_2eq/kg
Sulphur dioxide	-	-	53	-	g CO_2eq/kg
Zeolite	-	-	-	4,191	g CO_2eq/kg
Steel	-	-	-	1,795	g CO_2eq/kg
Chromium steel	-	-	-	2,426	g CO_2eq/kg
Concrete	-	-	-	159,512	g CO_2eq/m^3
Building hall	-	-	-	309,058	g CO_2eq/m^2

STANDALONE TABLES

Standalone 2G ethanol

Agricultural inputs per tonne of residue

	GHGenius	GREET	New EC	VSB	
Feedstock	**Wheat straw**	**Corn stover**	**Wheat straw**	**Sugarcane straw**	
Recovery	2.58	10.42		3.40	t/ha.yr
Location	Canada West	USA	Europe Union	Brazil	
		Energy inputs for residue recovery			
Diesel	1.48	7.26	4.15	5.53	L/t
Electricity	-	-	47.3	-	kWh/t
		Inputs (due to residue removal)			
N	6.01	3.51	-	-	kg N/t
K_2O	1.64	2.51	-	-	kg K_2O/t
P_2O_5	13.29	15.04	-	-	kg P_2O_5/t
High density polyethylene	-	0.37	-	0.49	kg/t
		Baling emissions			
CH_4	-	-	0.18	-	g CH_4/t
N_2O	-	-	0.45	-	g N_2O/t
		Avoided emissions[1]			
N_2O	-	-0.17	-	-0.10	kg N_2O/t
NOx	-	-0.07	-	-0.02	kg NOx/t

[1] avoided emissions due to residue removal

Standalone 2G ethanol

Industrial inputs per MJ of ethanol: part I

	GHGenius	GREET	New EC	VSB	
Feedstock	0.15	0.13	0.21	0.15	kg/MJ EtOH
Diesel	13.64	2.36	-	-	10^{-3} MJ/MJ EtOH
Ammonia	2.03	0.52	0.42	0.75	g/MJ EtOH
Lime	1.56	0.95	1.93	-	g/MJ EtOH
Sodium hydroxide	3.87	1.46	4.85	-	g/MJ EtOH
Phosphate nutrients (P_2O_5)	0.24	-	-	-	g/MJ EtOH
Diammonium phosphate	-	0.17	0.31	-	g/MJ EtOH
Sugar[1]	4.15	1.63	-	0.08	g/MJ EtOH
Sulphuric acid	3.40	4.30	-	0.13	g/MJ EtOH
Yeast	0.19	0.33	-	-	g/MJ EtOH
Cellulase	-	1.33	-	0.85	g/MJ EtOH
Urea	-	0.26	-	-	g/MJ EtOH
Ammonium Sulphate	-	-	0.16	-	g/MJ EtOH
Monopotassium phosphate	-	-	0.23	-	g/MJ EtOH
Magnesium Sulphate	-	-	0.03	-	g/MJ EtOH

[1]GREET considers corn steep liquor

Standalone 2G ethanol

Industrial inputs per MJ of ethanol: part II

	GHGenius	GREET	New EC	VSB	
Calcium Chloride	-	-	0.05	-	g/MJ EtOH
Sodium Chloride	-	-	0.35	-	g/MJ EtOH
Antifoam	-	-	0.70	-	g/MJ EtOH
Sulfur dioxide	-	-	0.05	-	g/MJ EtOH
Zeolite	-	-	-	0.01	g/MJ EtOH
Steel	-	-	-	0.17	g/MJ EtOH
Chromium steel	-	-	-	0.01	g/MJ EtOH
Concrete	-	-	-	0.23	cm^3/MJ EtOH
Building hall	-	-	-	0.05	cm^2/MJ EtOH

Standalone 2G ethanol

Industrial emissions/outputs per MJ of ethanol

	GHGenius	GREET	New EC	VSB	
VOC	-	8.69	-	3.45	mg/MJ EtOH
PM10	-	10.63	-	56.04	mg/MJ EtOH
PM2.5	-	1.81	-	28.04	mg/MJ EtOH
CO	-	130.38	-	49.71	mg/MJ EtOH
NOx	-	136.59	-	49.43	mg/MJ EtOH
N_2O	-	-	-	2.73	mg/MJ EtOH
SOx	-	55.88	-	2.65	mg/MJ EtOH
CH_4 biogenic	-	-	-	20.48	mg/MJ EtOH
CO_2 LUC	-	-622.96	-	-	mg/MJ EtOH
			Output		
Electricity	0.08	0.11	0.40	0.13	MJ/MJ EtOH

Standalone 2G ethanol

Transportation parameters

	GHGenius	GREET	New EC	VSB	
		Bales transportation to pelletisation plant			
Truck	-	-	50	-	km
		Residue transportation to ethanol plant			
Truck	100	153.22 (HHD)	500[1]	45	km
		Ethanol distribution			
Barge	-	836.86 (13.2%)	153 (50.8%)	-	km
Ocean	-	-	1118 (31.6%)	-	km
Train	700	1287.48 (78.9%)	-	-	km
Truck	225.26	128.75 (7.9%) (HHD)	305 (13.2%)	400	km
Truck	-	48.28 (HHD)	-	-	km

[1]New EC considers pellets transportation to ethanol plant

1G2G TABLES

VSB: Integrated 1G2G ethanol

Agricultural inputs per tonne of sugarcane

VSB		
Sugarcane	**76.80**	t/ha.yr
Recovered straw	3.52	t/ha.yr
Inputs[1]		
Diesel	1.82	L/t
Limestone	5.21	kg/t
Gypsum	2.60	kg/t
N	1.30	kg N/t
K_2O	0.93	kg K_2O/t
P_2O_5	0.21	kg P_2O_5/t
Vinasse	0.90	m^3/t
Filter cake	10.00	kg/t
Ashes from boylers	6.30	kg/t
High density polyethylene	0.02	kg/t
Pesticides	0.02	kg/t
Harvester, tractor and other agricultural machinery	0.29	kg/t
Emissions[1]		
Carbon dioxide, fossil	4.34	kg/t
Dinitrogen monoxide	50.26	g/t
Ammonia	0.52	kg/t
Nitrogen oxides	10.56	g/t

[1]per tonne of sugarcane

VSB: Integrated 1G2G ethanol

Industrial inputs per MJ of ethanol

VSB		
Sugarcane	0.39	kg/MJ EtOH
Straw	18.08	g/MJ EtOH
Lime	0.24	g/MJ EtOH
Sulphuric acid	0.20	g/MJ EtOH
Ammonia	0.19	g/MJ EtOH
Sugar	31.79	mg/MJ EtOH
Phosphoric acid	68.68	mg/MJ EtOH
Flocculating polymer	1.01	mg/MJ EtOH
Antibiotic	0.58	mg/MJ EtOH
Cellulase	0.23	g/MJ EtOH
Lubricating oil	0.01	g/MJ EtOH
Zeolite	0.01	g/MJ EtOH
Steel	0.08	g/MJ EtOH
Chromium steel	4.80	mg/MJ EtOH
Concrete	0.11	cm^3/MJ EtOH
Building hall	0.00	cm^2/MJ EtOH

VSB: Integrated 1G2G ethanol

Industrial emissions/outputs per MJ of ethanol

VSB		
VOC	3.9	mg/MJ EtOH
PM10	64.0	mg/MJ EtOH
PM2.5	32.0	mg/MJ EtOH
CO	56.8	mg/MJ EtOH
N_2O	3.1	mg/MJ EtOH
NOx	56.5	mg/MJ EtOH
SOx	3.0	mg/MJ EtOH
CH_4 biogenic	23.4	mg/MJ EtOH
Output		
Electricity	0.10	MJ/MJ EtOH

VSB: Integrated 1G2G ethanol

Transportation parameters

VSB		
Sugarcane and straw transportation		
Truck	36	km
Ethanol distribution		
Truck	400	km

CORN STOVER TABLES

Corn stover 2G ethanol

Agricultural inputs per tonne of residue

	GHGenius	GREET	
Feedstock	Corn stover	Corn stover	
Recovery yield	7.26	10.42	t/ha.yr
Location	Canada Central	USA	
Energy inputs for residue recovery			
Diesel	7.20	7.26	L/t
Inputs (due to residue removal)			
N	9.40	3.51	kg N/t
K_2O	1.33	2.51	kg K_2O/t
P_2O_5	9.92	15.04	kg P_2O_5/t
High density polyethylene	-	0.37	Kg/t
Avoided emissions[1]			
N_2O	-	-0.17	kg N_2O/t
NOx	-	-0.07	kg Nox/t

[1] avoided emissions due to residue removal

Corn stover 2G ethanol

Industrial inputs per MJ of ethanol: part I

	GHGenius	GREET	
Feedstock	0.14	0.13	kg/MJ EtOH
Diesel	13.64	2.36	10^{-3} MJ/MJ EtOH
Ammonia	2.03	0.52	g/MJ EtOH
Lime	1.56	0.95	g/MJ EtOH
Sodium hydroxide	3.87	1.46	g/MJ EtOH
Phosphate nutrients (P_2O_5)	0.24	-	g/MJ EtOH
Diammonium phosphate	-	0.17	g/MJ EtOH
Sugar[1]	4.15	1.63	g/MJ EtOH
Sulphuric acid	3.40	4.30	g/MJ EtOH
Yeast	0.19	0.33	g/MJ EtOH
Cellulase	-	1.33	g/MJ EtOH
Urea	-	0.26	g/MJ EtOH

[1]GREET considers corn steep liquor

Corn stover 2G ethanol

Industrial emissions/outputs per MJ of ethanol

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NOx	-	136.59	mg/MJ EtOH
SOx	-	55.88	mg/MJ EtOH
CO_2 LUC	-	-622.96	mg/MJ EtOH
	Output		
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Corn stover 2G ethanol

Transportation parameters

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Residue transportation			
Truck	100	153.22 (HHD)	km
Ethanol distribution			
Barge	-	836.86 (13.2%)	km
Train	700	1287.48 (78.9%)	km
Truck	225.26	128.75 (7.9%) (HHD)	km
Truck	-	48.28 (HHD)	km

HHD: heavy-heavy-duty truck