Technical Report

Comparison of Biofuel Life Cycle Analysis Tools

Phase 2, objective b: Comparison of LCA models for biochemical second-generation (2G) ethanol production and distribution

Prepared by

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Abbreviations

1G: first-generation ethanol

2G: second-generation ethanol

CHP: Combined heat and power generation

GHG: greenhouse gases

GWP: global warming potential

HHD: heavy heavy-duty truck

LCA: Life Cycle Analysis

LUC: land use change

USA: United States of America

VSB: Virtual Sugarcane Biorefinery

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Executive summary

Second-generation (2G) or lignocellulosic biofuels are deemed advanced in view of the several advantages when compared to first generation biofuels, such as no need for land expansion or competition with food production, thus producing more fuel within the same area, as in the case of 2G sugarcane ethanol, besides low climate change impact. If deployed in large scale, lignocellulosic ethanol will be a great ally in helping the world meeting the long-term requirements for the reduction of greenhouse gases (GHG) emissions.

The present report is the continuation of the Technical Report - Comparison of Biofuel Life Cycle Analysis Tools - Phase 2, Part 1: FAME and HVO/HEFA. Its main motivation is still the comparison of different LCA models and the identification of the main differences and commonalities in methodological structures, calculation procedures, and assumptions to demonstrate the possibility of obtaining homogeneous results for similar production chains.

With the presented analysis, it was possible to evaluate four selected models, comparing the LCA differences from each production system. The main reasons for each identified difference were pinpointed on a case-by-case basis.

The scope of this study is restricted to second generation ethanol produced from either corn stover, wheat straw, sugarcane bagasse and/or straw, and forest residues. The four LCA models compared in this study were:

- GHGenius (Canada): available in https://www.ghgenius.ca/index.php/downloads;
- GREET (United States of America): available in: https://greet.es.anl.gov/index.php?content=greetdotnet;
- New EC (European Community): available in http://data.jrc.ec.europa.eu/dataset/jrc-alf-bio-biofuels_jrc_annexv_com2016-767_v1_july17;
- VSB (Brazil): not available to external users (Bonomi et al., 2016).

Three models are publicly available and serve regulatory purposes (GHGenius / GREET / New EC). The VSB is not publicly available, the model was initially developed by

LNBR/CNPEM to assess the sugarcane production chain, having further expanded its scope to several other feedstocks and conversion pathways within a biorefinery context.

The results presented in this report are limited to the GHG emissions determined by each model with the default conditions to which they were developed using both cradle-to-gate and cradle-to-pump boundaries. The cradle-to-gate approach considers the emissions of biofuel production from the feedstock production up to the gate of the biofuel producing unit, while the cradle-to-pump analysis includes additional impacts of biofuel distribution to fuel pumps.

Table ES1 summarizes the total GHG emissions for second generation ethanol production for the four assessed models considered in this study.

Table ES1: Summary of cradle-to-pump emissions in g CO_2eq/MJ ethanol

	GHGenius	GREET	New EC	VSB	
Wheat straw	18.53	-	13.68	-	g CO_2eq/MJ
Corn stover	22.92	7.32	-	-	g CO_2eq/MJ
Sugarcane straw	-	-	-	7.18	g CO_2eq/MJ
Forest residue	11.42	7.07	-	9.88	g CO_2eq/MJ
Sugarcane 1G2G	-	-	-	19.45	g CO_2eq/MJ

In the case of wheat straw 2G ethanol, GHGenius presents higher emissions than New EC, mostly because GHGenius considers NPK replacement in the field due to straw removal, and higher energy inputs in the industrial phase. For corn stover 2G ethanol, GHGenius also presents higher emissions than GREET. This is due to higher energy inputs in the industrial phase, lower emissions displaced by co-products, no avoided emissions of N_2O and NOx due to corn stover removal, and no avoided LUC emissions. In the case of forest residues 2G ethanol, GHGenius presents the highest emissions among the 3 models assessed, GREET presents the lowest emissions and VSB is in between. The emissions in the industrial processes are higher in GHGenius compared to the other models. The results for sugarcane straw 2G ethanol obtained with VSB are close to the values presented for corn stover and forest residues 2G ethanol in GREET.

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The harmonization procedure carried for the corn stover ethanol and forest residues ethanol pathways show that it is possible to harmonize the results issued by the models through a series of steps considering only few parameters/operations. The reported analysis found differences in the input data and methodological choices, some of which could be harmonized, such as the divergences between energy inputs among the studied models, or the considered avoided emissions.

As in the Phase 2 Part 1, we emphasize that there is room for discussion and standardization of models in order to decrease the variation of input data and approaches and thus "pre-harmonize" all models.

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1. Introduction

Global population is expected to increase and, therefore, demands of food and energy will rise over the next few decades (Popp et al, 2017). In parallel, climate change concerns have driven the world to seek for cleaner ways of manufacturing products and generating energy. In this context, biofuels are considered a key strategy to decarbonize the transport sector and contribute to climate change mitigation (Lynd et al, 2017; Wang et al, 2012). Among the many options, ethanol is a biofuel produced in large volumes mostly from the fermentation of corn starch in the USA and sugarcane-derived sucrose in Brazil (RFA, 2019; (S&T)2 Consultants Inc., 2012) - the so-called first-generation (1G) ethanol. The production of conventional biofuels, such as 1G ethanol and biodiesel, has raised a worldwide food vs. fuel debate, i.e. over the competition for land and water associated to the production of biofuels or food/feed products from conventional sources of carbohydrates and lipids. Second-generation (2G) or lignocellulosic biofuels are deemed advanced in view of the several advantages, when compared to first generation biofuels (SCOPE, 2015), such as in the case of sugarcane 2G ethanol, with no need for land expansion or competition with food production, thus producing more fuel within the same area (CGEE, 2012; Manochio et al, 2018), besides low climate change impact (EPA, n.d.). If deployed in large scale, lignocellulosic ethanol will be a great ally in helping the world meeting the long-term requirements for the reduction of greenhouse gases (GHG) emissions (OECD/IEA, 2017; Wang et al, 2012).

There are 5 commercial-scale plants and 40 pilot-scale plants worldwide (Brazil, Europe, US) dedicated to the production of 2G ethanol, however actual production remains low (OECD/IEA, 2017; RFA, 2018; SCOPE, 2015; RFA, 2018; World Energy Council, 2016). Among the potential feedstocks for second generation ethanol production there are agricultural residues (e.g., corn stover, wheat straw, rice straw and sugarcane straw and bagasse), dedicated energy crops (e.g., switchgrass, miscanthus, mixed prairie grasses and short-rotation trees), forest residues, and industrial wastes (Baeyens et al, 2015; SCOPE, 2015; Wang et al, 2012).

Worldwide, the recovery of agricultural residues for biofuels production has been gaining increased attention (CGEE, 2012). Annually, billions of tonnes of agricultural residues are

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available worldwide (World Energy Council, 2016). These residues have great potential for bioenergy production: according to the World Bioenergy Association (2016), around 128 EJ of energy could be produced from agriculture residues annually and another 4.64-7.64 EJ from forest residues. The corn value chain alone could supply an average of one tonne of dry corn stover per tonne of corn grain harvested in the USA (Wu et al, 2006), of which up to 50% could be sustainably recovered (DOE, 2011). In Brazil, due to an increase in the mechanization of sugarcane harvest and an ensuing reduction in pre-harvest burning of sugarcane fields, a huge amount of lignocellulosic material, known as straw (tops and leaves), has become available, which can be recovered to produce bioelectricity or 2G ethanol (CGEE, 2012). Around 140 kg of straw are produced per tonne of sugarcane (Hassuani et al, 2005). In Europe, around 30% of agriculture residues, equivalent to 122 million tons, are sustainably available for bioenergy production - 40% being wheat straw; around 50% of forest residues (40 million tonnes) could be sustainably harvested for bioenergy purposes (Searle and Malins, 2013). Only ¼ of agricultural residue and 2/3 of forest residues is currently recovered in Europe (Camia et al, 2018). In Canada around 82.4 million tonnes (db) of agricultural residues are produced annually, being mostly wheat straw (Li et al, 2012). Besides, around 58% of the available agriculture residues in the country could be sustainably recovered for biofuels production (Li et al, 2012).

2G ethanol has a potential to decrease greenhouse gas emissions due to its carbon intensity lower than either fossil competitors or even 1G ethanol (Wang et al, 2007; 2012). GHG emissions of fuels and products alike can be quantitatively determined through a Life Cycle Analysis (LCA) methodology. Differences in feedstock, recovery systems, and feedstock handling/processing (transportation, storage, pre-treatment, and conversion), among other factors can lead to different carbon intensities (SCOPE, 2015). Each model has its own location of feedstock production as well as specific industrial process used. For this reason, the results vary from one model to another. In view of this, the scope of the present study was the comparison and harmonization of 2G ethanol production from lignocellulosic residues considering four LCA models: GHGenius (Canada), GREET (USA), New EC (European Community) and VSB (Brazil). The main differences and commonalities among the methodological structures, calculation procedures and assumptions of each LCA model were identified. The differences in the inputs data and in the methodological choices were then harmonized in order to obtain similar results within the different models assessed.

2. Motivation and objectives

As in the first part of Phase 2 study (IEA Bioenergy, 2018), the main motivation of comparing different LCA models lies in the identification of the main differences and commonalities in methodological structures, calculation procedures, and assumptions to demonstrate the possibility of obtaining homogeneous results for similar production chains.

The second part of Phase 2 (this study) targets the understanding of the particularities of GHG emissions of 2G ethanol production systems from different lignocellulosic biomasses, which includes wheat straw, corn stover, sugarcane bagasse and straw and forest residues in Brazil, Canada, Europe and the USA. The main objective is to provide a detailed understanding of how models determine GHG emissions for 2G ethanol. With the presented analysis, it was possible to use and assess the four selected models, comparing the LCA differences for each production system. The main reasons for each identified difference are pinpointed on a case-by-case basis (for example, higher use of energy inputs for residue recovery, higher transport distances, consumption of energy and inputs in industrial processes, transport efficiencies in all phases of the biofuel production chain and use, among other factors and particularities).

3. Assessed models

Four LCA models were compared in this study:

- **GHGenius** ($(S\&T)^2$ Consultants Inc. – Canada)
- **GREET** (Argonne National Laboratory – United States of America) - *The Greenhouse Gases, Regulated Emissions and Energy Use in Transportation Model*
- **New EC** model/data (JRC – European Community) - *Biofuels pathways. Input values and GHG emissions. Database*
- **VSB** (LNBR/CNPEM – Brazil) - *Virtual Sugarcane Biorefinery*

The main characteristics of each model are presented in Table 1.

Table 1: Main characteristics of the four assessed models

	GHGenius	GREET	New EC	VSB
Model version	5.0c (2018)	2018	2017	2019
Developed for regulatory use	No[1]	No	Yes	No
IPCC GWP method	1995, 2001, 2007, 2013	2013	2007	2007
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	Internal	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

In this study, default values were used in the comparisons. This means that, even if there is the possibility of changing the input values in all models, the study only considers the numbers obtained from the unmodified versions just as any user would if they downloaded the models directly from their host websites.

Finally, boundaries must be set so as the LCA analysis is consistent throughout the models. The results presented in this report are limited to cradle-to-gate and cradle-to-pump analyses to avoid performing comparison of vehicle fleets with completely different characteristics – those of the United States of America, Canada, Europe and Brazil. Despite that, GHGenius, GREET and VSB are models which easily allow users to model vehicle emissions whenever needed; New EC, on the other hand, limits user interaction to agricultural, industrial and logistic inputs.

4. Assessed feedstock and pathway duos

The conversion pathways assessed in this study are those of standalone 2G ethanol production (for all the four models), and the integrated 1G and 2G ethanol production (VSB model only). Feedstocks for 2G ethanol vary among the models:

- Wheat straw: GHGenius and New EC;
- Corn Stover: GHGenius and GREET;
- Forest Residue: GHGenius, GREET and VSB;
- Sugarcane bagasse and straw: VSB.

For each feedstock, a comparison is carried out considering the results obtained through LCA for the default conditions to which the four models (GHGenius/GREET/New EC/VSB) were developed. All four models consider the whole production chain (feedstock recovery, biofuel production, and its distribution) taking place in the country of origin of each LCA model (Figure 1).

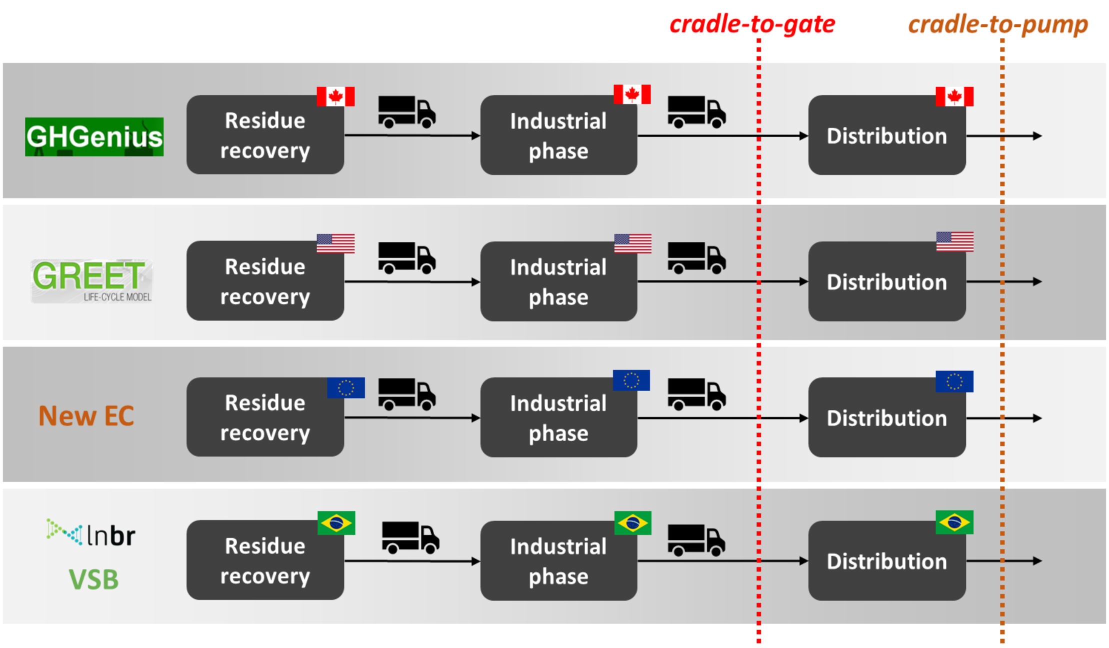

Figure 1: System boundaries considered in the four assessed models for 2G ethanol production

For instance, all four models consider ethanol as the main product of the process and electricity as the co-product, considering a co-generation unit partially or fully powered by

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lignin for combined heat and power generation. Except for forest residues ethanol plant in GREET, the four assessed models consider that the 2G ethanol plants are energetically self-sufficient. GHGenius and GREET consider substitution procedure for electricity generated in the process, while the New EC considers energy allocation and the VSB considers economic allocation.

The characterization factors (GWP-100) differ among models in the default version (Table 2); this, however, can be easily changed in GHGenius and GREET. GHGenius also takes into account several characterization factors to convert other compounds (such as VOC, NOx, fluorides, etc) into CO2eq using 2007 IPCC GWP data. GREET considers black carbon, albedo, VOC, CO, and NOx as optional GHGs.

Table 2: Characterization factors (GWP-100) considered in the four assessed models

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

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

Some other particularities of each model include different calculation procedures and different emission factors. The next pages detail the agricultural recovery systems and the industrial comparison strategy for each feedstock presented above.

4.1. Description of biomass recovery systems

Worldwide, the recovery of agricultural residues for biofuels production has been gaining prominence (CGEE, 2012). It is important to determine the best pathways for collecting such residues as well as the amount that can be sustainably recovered (OECD/IEA, 2017; SCOPE, 2015), since excessive removal can ultimately decrease soil quality (Carvalho et al, 2017a; 2019; SCOPE, 2015).

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4.1.1. Standalone 2G ethanol production

The defaults feedstocks of each model are analyzed in this first section of the study:

- GHGenius: wheat straw
- GREET: corn stover
- New EC: wheat straw
- VSB: sugarcane straw

Residue recovery alternatives are further detailed, followed by the particularities of each model.

4.1.1.1. Wheat straw

In Europe and Canada, the most abundant agriculture residue is wheat straw (Li et al, 2012; Searle and Malins, 2013). The collection of wheat straw includes windrowing, cutting (depending on the size of remaining stalks), baling, transportation to the side of field to be stacked and picked up for transport and transportation to final destination; straw stacked in bales can also be pelletized to facilitate handling and storage in the plant (Li et al, 2012; NL Agency, 2013).

4.1.1.2. Corn stover

A large amount of corn stover is available in the corn-belt region in the USA - on average, one tonne of harvested corn grain results in one tonne of dry stover (Wu et al, 2006). One-third to one half of produced corn stover can be sustainably recovered in the USA (DOE, 2011).

Usually, corn stover is left on the field after corn grain harvesting and provides soil quality benefits such as minimization of erosion, provision of nutrients, among others. The recovery of corn stover removes NPK (which must be replaced by mineral NPK) and carbon that would remain in the soil (Wu et al, 2006). However, its removal avoids N_2O emissions that would take place if the stover remained in the field, due to microbial activity for biomass decomposition (Wu et al, 2006). In the USA, corn stover is recovered after a certain period of

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drying in the field. The recovery process includes windrowing, baling, bales transportation to the edge of the field in wagons, and stocking. Such operations employ equipment usually fueled with diesel (Wang et al, 2013; Wu et al, 2006).

4.1.1.3. Sugarcane straw

In Brazil, most of the sugarcane is harvested mechanically and without burning (green cane), with most straw being left in the field (Cavalett et al, 2012, Cardoso et al, 2017). There is a growing interest in recovering such residue to produce either electricity or 2G ethanol (CGEE, 2012). Recently, the use of straw as a fuel has been increasing in view of the efforts undertaken by some sugarcane mills to recover more of this biomass from the field.

Maintaining part of straw in sugarcane fields can bring benefits to the soil (e.g. erosion and moisture control, increase in organic matter content, carbon accumulation, nutrient recycling, and water storage, as well as weed infestation control, among others) (Castioni et al, 2018; Carvalho et al, 2017a; Menandro et al, 2017; SUCRE, 2017). The amount of straw to be left in the field depends on several aspects, such as sugarcane variety, cutting stage and productivity; climate average conditions (moisture and temperature); soil characteristics; soil C/N ratio; agricultural management; ground slope, among others (CGEE, 2012; Magalhães et al, 2012). The sugarcane straw availability can range from 7 to 20 tonnes (dry basis) per hectare (Carvalho et al, 2017a; Magalhães et al, 2012).

Currently, a small amount of straw (tops and leaves) that remains with sugarcane stalks, considered as impurities, is recovered from the field during the harvesting of sugarcane stalks; most of the straw that remains in the field can be collected via bales or together with sugarcane stalks (integral harvest) (Cardoso et al, 2015; 2018, Carvalho et al, 2017b; Hassuani and Macedo, 2005). In the baling system, the straw is recovered around 10 to 15 days after sugarcane harvesting; the process includes the windrowing of straw, baling operation, bales transportation, loading and transportation to the mill (Cardoso et al, 2018).

Table 3 shows the agricultural inputs per tonne of residue (dry basis) for each feedstock and model assessed in this first section.

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Table 3: Agricultural parameters for feedstock recovery

	GHGenius	GREET	New EC	VSB	
Feedstock	**Wheat straw**	**Corn stover**	**Wheat straw**	**Sugarcane straw**	
Recovery	2.58	10.42	-[1]	3.40	t/ha.yr
Location	Canada West	USA	Europe	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[2]					
N_2O	-	-0.17	-	-0.10	kg N_2O/t
NOx	-	-0.07	-	-0.02	kg NOx/t

[1] 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
[2] Avoided emissions due to residue removal

Particularities of each model - residue recovery

- GHGenius and GREET consider additional NPK inputs due to biomass removal, while New EC and VSB do not.
- GREET and VSB consider N_2O and NO_x avoided emissions from the field, due to biomass removal. In GREET, the N_2O avoided emissions are from the N in corn stover. When N fertilizer is applied after stover removal, N_2O emissions are caused from the applied N fertilizer. This is internal in GREET calculation.
- GHGenius and New EC consider no credit or debit for soil carbon changes, neither avoided emissions (N_2O) due to biomass removal. In GHGenius, the additional N added is equal to the N removed hence the N_2O emissions are essentially the same.
- No emissions in the field are considered by the New EC model, since straw is on the list of residues and wastes (JRC, 2017). The model considers CH_4 and N_2O emissions from baling operation explicitly. In GREET, CH_4 and N_2O emissions are included from the diesel fuel used during stover harvesting and baling, this is internal in the model calculations.
- VSB and GHGenius consider emissions related to agricultural machinery. In GREET, such emissions are optional and can be selected by the user.
- VSB considers the recovery of 50% of sugarcane straw (sugarcane tops and leaves left on the field) recovered from the field in bales.

4.1.2. Integrated 1G2G ethanol production: the case of VSB model

The sugar-energy value chain has been a consolidated sector of the Brazilian economy for many years (UNICA, 2018). Sugar, ethanol and electricity are produced in several mill configurations, mostly in so called “annexed” (distilleries annexed to sugar mills) (Cavalett et al, 2012). Recently, the use of straw as fuel has been increasing since some sugarcane mills are making efforts to recover more straw from the field, to increase the amount of surplus electricity sold to the grid.

For the integrated 1G2G ethanol production, the VSB model considers a combination of lignocellulosic biomass, namely bagasse and straw. Bagasse is the lignocellulosic fraction of sugarcane stalks (obtained after crushing in mill tandems) and it is the main fuel for the co-generation of electricity and process steam in sugarcane plants (UNICA, 2018). As mentioned in the last session, the default straw recovery in the VSB model is of 50%. Table 4 presents the inputs per tonne of sugarcane produced (wet basis).

Table 4: Agricultural parameters for sugarcane production and straw recovery

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

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4.1.3. Standalone 2G ethanol production: Corn stover

The comparison of the corn stover recovery between GHGenius and GREET models are presented (Table 5). The inputs are given per tonne of corn stover (dry basis).

Table 5: Agricultural parameters for corn stover recovery

	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 NO_x/t

[1] avoided emissions due to residue removal

Particularities of each model – corn stover recovery

GHGenius: No credit or debit for carbon changes are considered, neither avoided emissions (N_2O) due to biomass removal.

GREET: The model considers N_2O and NO_x avoided emissions on the field, due to biomass removal.

4.1.4. Standalone 2G ethanol production: Forest residues

Whole-tree harvesting is the most common method for harnessing forest resources in the United States. In this system, whole trees are cut down and gathered by feller bunchers, then hauled by skidders to the landing area for delimbing and stocking. In the storage area, forest

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residues can be left in the field or chipped/grinded to be transported to the final destination (Wang et al, 2013). After pre-processing, forest residues are usually transported to ethanol plants by truck (Wang et al, 2013, Wu et al, 2006). Differently from agricultural residues, the recovery of forest residues in the USA demands more energy, and fuel consumption varies depending on the type of wood (Wu et al, 2006).

There are around 2.3 million hectares of forests planted for industrial purposes in Brazil. Most of wood crops are eucalyptus, used in the pulp and paper industry. The harvesting operation occurs every seven years, with an average yield of 44 m³ (or 22.5 tonnes, wet basis) of wood per hectare per year. Forest residues are composed by leaves, fine wood and bark, accounting for around 10 tonnes per hectare per year (BRACELPA, 2014; IPEF, 1979). In Brazil, trees are mechanically harvested and processed in the field by specific forestry machinery, and the set of harvest operations is the most expensive part of the total eucalyptus production cost (BRACELPA, 2012; Agrianual, 2012; Wilcken et al., 2008; IPEF, 2006; IPEF, 1979). The inputs for forest residues recovery considered in the three assessed models are presented in Table 6. The inputs are given per tonne of forest residues (dry basis).

Table 6: Agricultural parameters for forest residues recovery

	GHGenius	**GREET**	**VSB**	
Feedstock	Forest residues	Forest residues	Forest residues	
Recovery yield	9.19	7.85	6.64	t/ha.yr
Location	20% Canada East. 50% Canada Central, 30% Canada West	USA	Brazil	
Energy inputs for residue recovery				
Diesel	-	4.29	0.41	L/t

Particularities of each model – forest residues recovery

GHGenius: This model has three different options of woody residues: short rotation crops, mill residues and standing timber. In this study, mill residues were considered as the default input. The model does not include any collection or transportation operations for this specific feedstock.

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GREET: The model has a higher fuel consumption since it includes operations such as stumpage and harvesting. Total energy consumption of field operations (harvesting, collection, extraction of residues, milling and chipping) are allocated to forest residues. Besides forest residues, GREET includes short rotation woody crops such as willow trees and hybrid poplars.

VSB: Considers low energy inputs for residue recovery (mainly chipping). In the VSB model, it is considered commercial plantings with 1,667 trees per hectare, seven years between harvests (three cuts in a 21-year cycle), with average productivity of 323 m^3/ha per cut (BRACELPA, 2012; Agrianual, 2012; Wilcken et al., 2008; IPEF, 2006; IPEF, 1979).

4.2. Description of 2G ethanol production systems

Second generation ethanol can be produced either by thermochemical or biochemical pathways (SCOPE, 2015). In this study, the most common route (biochemical conversion) is considered.

Independently from the lignocellulosic material type, it is mainly composed of cellulose, lignin and hemicellulose in different proportions (Baeyens et al, 2015; Zhao et al, 2018). Differently from 1G ethanol, 2G ethanol production processes depend on a series of unit operations for the release of sugars contained in the biomass (namely pretreatment and hydrolysis) prior to fermentation (Baeyens et al, 2015; Gaurav et al, 2017; Zabed et al, 2017; Zhao et al, 2018). The main objective of the pretreatment step is to remove mineral impurities from the biomass (mainly soil particles) and to make sugars more accessible for the subsequent hydrolysis step. Through physical, physicochemical, chemical and biological pathways, this operation increases the surface area of the biomass, removes lignin and hemicellulose from the lignocellulosic matrix and decreases crystallinity of cellulose (Baeyens et al, 2015; Manochio et al, 2018; Wang et al, 2012; Zabed et al, 2017; Zhao et al, 2018). It is the most complex and costly step in the conversion of biomass into ethanol (Gaurav et al, 2017; Zabed et al, 2017) and its efficiency varies according to equipment design and feedstock type (Gaurav et al, 2017; Manochio et al, 2018). The most common methods include steam explosion and dilute acid pre-hydrolysis.

Afterwards, the released cellulose and hemicellulose molecules from the pretreatment step are then hydrolyzed into soluble sugars via chemical or enzymatic method – the latter being the most commonly used one (Zabed et al, 2017; Zhao et al, 2018). The hydrolysis step converts glucan and xylan into glucose and xylose, respectively, which are transferred to fermentation vessels (Zhao et al, 2018). There is the possibility of a simultaneous saccharification and fermentation (SSF) operation; a co-fermentation, in which genetically modified organisms convert both glucose and xylose; simultaneous saccharification and co fermentation (SSCF); and separate fermentation of xylose stream (Baeyens et al, 2015). C6 sugars can be easily converted into ethanol during microbial fermentation (Zabed et al, 2017), while the yeast, commonly used for ethanol production (*S. cerevisiae*), cannot metabolize xylose (Baeyens et al, 2015). The selection, isolation and genetic engineering of other yeasts, bacteria and fungi for the conversion of C5 sugars into ethanol (either separately or in conjunction with C6 sugars) is a subject widely researched globally (Baeyens et al, 2015).

After ethanol fermentation, the process is virtually the same for both 1G and 2G ethanol. Regarding the generation of heat and power, the only observation is that residual cellulignin from the 2G process can be sent to boilers for combustion and, depending on the amount of residue from the process, the 2G plant can be energetically auto-sufficient and excess electricity can be sold/exported to the grid (Baeyens et al, 2015; SCOPE, 2015; Wang et al, 2012). Figure 2 presents a simplified flow chart of the 2G ethanol production.

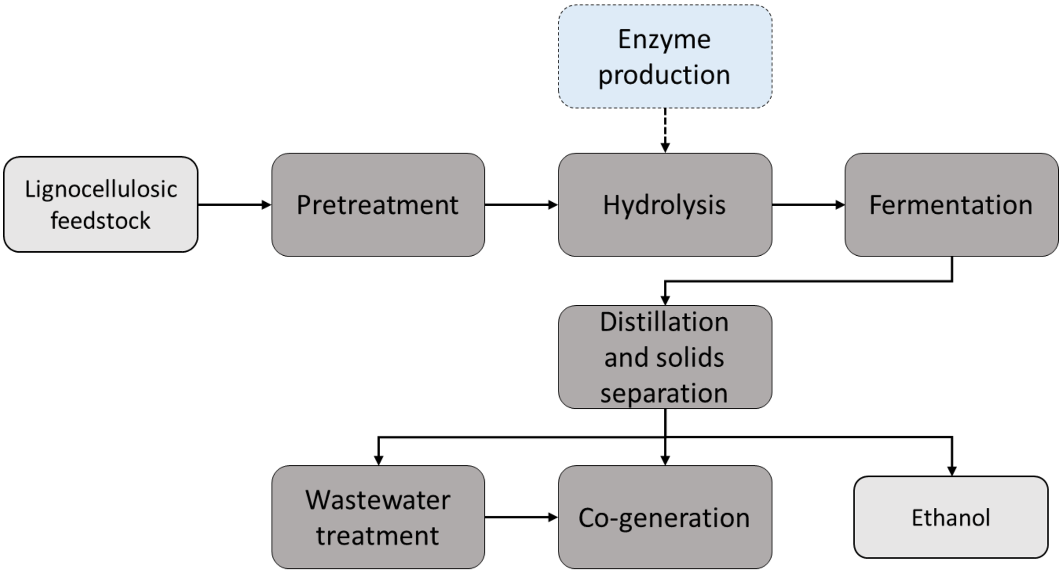

Figure 2: Simplified flow chart of 2G ethanol production

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Enzyme production can happen on-site and/or integrated to the ethanol plant, or it can be purchased, depending on the model assumptions. Another aspect that varies among models is the separation of lignin from the sugary stream, that can either occur before or after fermentation.

Particularities of each model - second generation ethanol production

GHGenius: This model considers the parameters from NREL (2011) report related to a cellulosic ethanol plant. For instance, the pretreatment considered is that of diluted sulfuric acid, followed by enzymatic hydrolysis. Fermentation is carried out with simultaneous SSCF using the microorganism *Zymomonas mobilis* (five days of sequential enzymatic hydrolysis and fermentation). Residual lignin is separated after biochemical conversion and sent to the Combined Heat and Power (CHP) unit. Adsorption with molecular sieves is used for ethanol purification. The wastewater is treated with both anaerobic and aerobic processes. The plant is self-sufficient in terms of steam and electricity and exports the surplus to the grid. The CHP system uses lignin as feedstock. The enzyme used in the process is produced on-site using corn syrup as the carbon source.

GREET: The lignocellulosic material is pretreated and hydrolyzed using enzymes (Wang et al, 2012) produced on-site. Lignin is separated after biochemical conversion and sent to the CHP system (Wu et al, 2006). Except for the case of forest residues ethanol plant, where there is natural gas input for drying and preparing the feedstock, the plant is self-sufficient in steam and electricity production and exports the surplus to the grid, using lignin as feedstock (Wang et al, 2012; Wu et al, 2006). The system also includes wastewater treatment (Wu et al, 2006).

New EC: Enzymes production is integrated to the ethanol plant, and the same pretreated cellulosic feedstock is used for both cellulase and ethanol. The model considers lignin for combined heat and power generation, and it is energetically self-sufficient.

VSB: This model considers steam explosion for lignocellulosic pretreatment, followed by enzymatic hydrolysis. C5 and C6 sugar streams are fermented separately. Differently from the other models, VSB considers cells recycle for fermentation and lignin separation before the biochemical conversion (fermentation) both for the standalone and integrated plant. The

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plants are energetically self-sufficient and export the surplus electricity to the grid, using lignin as feedstock in the case of the standalone plant, and bagasse, straw and lignin in the integrated plant.

4.2.1. Standalone 2G ethanol production

Table 7 presents the industrial inputs per MJ of ethanol produced for each model and the respective biomass considered.

Table 7: Industrial inputs per MJ of 2G ethanol

	GHGenius	GREET	New EC	VSB	
	Wheat straw	Corn stover	Wheat straw	Sugarcane straw	
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
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

[1]GREET considers corn steep liquor

Table 8 shows the industrial emissions for ethanol production and the amount of electricity co-produced.

Table 8: Biomass boiler emissions and output of electricity per MJ of 2G ethanol

	GHGenius	GREET	New EC	VSB	
VOC	-	8.69	-	3.45	mg/MJ EtOH
PM10	72.44	10.63	-	56.04	mg/MJ EtOH
PM2.5	61.99	1.81	-	28.04	mg/MJ EtOH
CO	607.74	130.38	-	49.71	mg/MJ EtOH
NOx	229.73	136.59	-	49.43	mg/MJ EtOH
N_2O	13.53	-	-	2.73	mg/MJ EtOH
SOx	218.59	55.88	-	2.65	mg/MJ EtOH
CH_4 biogenic	70.43	-	-	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

Particularities of each model – ethanol production inputs and emissions

GHGenius: It has high energy inputs for industrial process due to a large list of process chemicals and the use of diesel for operations with wheeled loader. The model also presents the highest emissions.

GREET: The diesel input is relatively low for industrial process, and it used for non-road applications. Besides, the model considers avoided LUC emissions for 2G ethanol production when replacing 1G ethanol.

New EC: There is no external input of enzymes, since their production is integrated to the ethanol plant in a cellulose-fed system that also depends on the CHP system to supply its

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energy requirements (Johnson et al, 2016). This model considers an electricity output considerably higher than the other models.

VSB: The model considers emissions related to zeolite inputs and infrastructure material (e.g. steel, concrete).

Both New EC and VSB models consider no diesel input for the industrial step of ethanol production. Table 9 presents the main transportation parameters for each model.

Table 9: Transportation parameters of 2G ethanol

	GHGenius	GREET	New EC	VSB	
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

Particularities of each model – distribution emissions

GHGenius: In this model, the distribution parameters consider the distances between potential feedstock locations and consumer markets in Canada.

GREET: There is no ocean transportation for ethanol distribution (only local consumption of the biofuel within the US for 2G ethanol).

New EC: The model considers partial ocean transportation of ethanol for its distribution.

VSB: As in GREET, no ocean transportation of ethanol is considered (local consumption only).

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4.2.2. Integrated 1G2G ethanol production: the case of VSB model

In this case, the 2G ethanol plant integrated to a 1G ethanol plant. The VSB model (the only one that includes the integrated plant) considers that pretreatment is carried out with steam explosion of both bagasse and straw. There is a separate fermentation for C6 and C5 sugars and considers cell recycling in the fermentation step. The lignocellulosic material (sugarcane bagasse and straw) is splitted for 2G ethanol production and used in CHP units. The feedstock for CHP is the *in natura* lignocellulosic material of sugarcane (bagasse and straw) in addition to the residual cellulignin from the 2G ethanol production. The plant is self-sufficient in terms of energy and exports surplus electricity to the grid. Figure 3 presents a simplified flow chart of the 2G ethanol production in the VSB model and Table 10 presents the inputs for ethanol production per MJ of total ethanol produced.

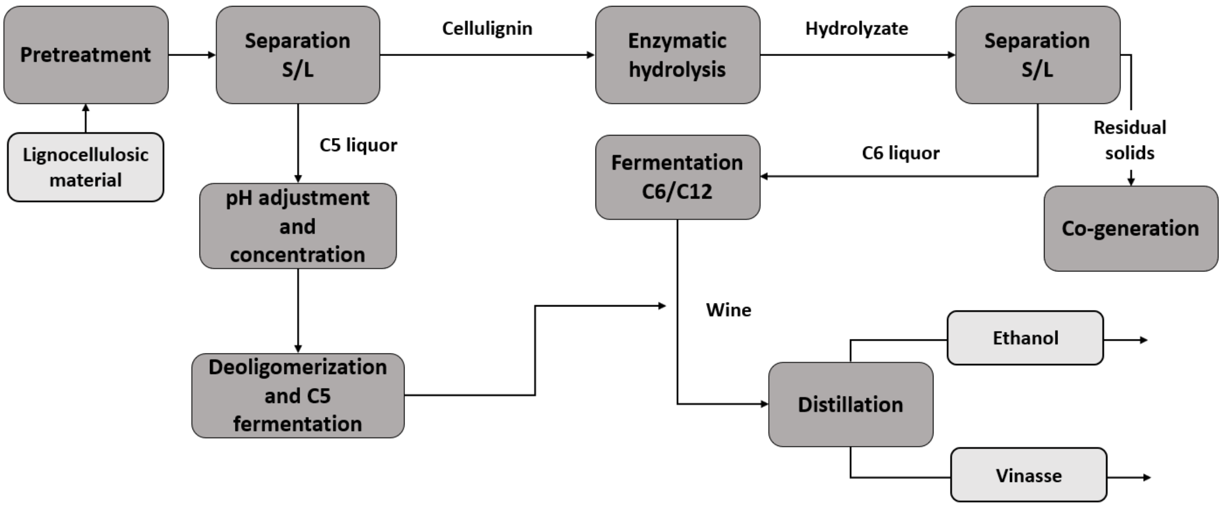

Figure 3: Simplified flow chart of integrated 1G2G ethanol production in the VSB model

In Table 11 the industrial emissions and electricity output per MJ of ethanol are presented, and Table 12 presents the transportation parameters.

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Table 10: Industrial inputs per MJ of total sugarcane ethanol produced

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

[1]per tonne of sugarcane

Table 11: Industrial emissions and electricity output per MJ of sugarcane 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

Table 12: Transportation parameters of sugarcane ethanol

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

4.2.3. Standalone 2G ethanol production: Corn stover

Table 13 indicates the industrial inputs per MJ of corn stover ethanol produced in GHGenius and GREET models.

Table 13: Industrial inputs per MJ of corn stover ethanol

	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

Table 14 presents the industrial emissions and electricity output per MJ of corn stover ethanol produced in GHGenius and GREET models.

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Table 14: Biomass boiler emissions and electricity output per MJ of corn stover ethanol

	GHGenius	GREET	
VOC	-	8.69	mg/MJ EtOH
PM10	71.85	10.63	mg/MJ EtOH
PM2.5	61.49	1.81	mg/MJ EtOH
CO	602.81	130.38	mg/MJ EtOH
NOx	227.87	136.59	mg/MJ EtOH
SOx	216.81	55.88	mg/MJ EtOH
CO_2 LUC	-	-622.96	mg/MJ EtOH
CH_4 biogenic	69.86	-	mg/MJ EtOH
Output			
Electricity	0.08	0.11	MJ/MJ EtOH

Particularities of each model – ethanol production inputs and emissions

GHGenius: It has high energy inputs for industrial process due to a large list of process chemicals and the highest emissions. The model has no enzyme (cellulase) input, because it considers on-site cellulase production.

GREET: The model has low energy input compared to GHGenius. It considers avoided LUC emissions for 2G ethanol production when replacing 1G ethanol.

In Table 15 the transportation parameters of corn stover ethanol produced in GHGenius and GREET models are presented.

Table 15: Transportation parameters of corn stover ethanol

	GHGenius	GREET	
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

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Particularities of each model – distribution emissions

Both models consider local consumption of the ethanol produced, however, GREET has an additional transportation modal that is barge.

4.2.4. Standalone 2G ethanol production: Forest residues

In Table 16 the industrial inputs per MJ of forest residues ethanol produced in GHGenius, GREET and VSB models are presented.

Table 16: Industrial inputs per MJ of forest residues ethanol

	GHGenius	GREET	VSB	
Feedstock	0.14	0.13	0.15	kg/MJ EtOH
Diesel	13.64	4.42	-	10^{-3} MJ/MJ EtOH
Natural gas	-	42.39	-	10^{-3} MJ/MJ EtOH
Ammonia	2.03	0.52	1.35	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	0.06	g/MJ EtOH
Sulphuric acid	3.40	4.30	0.12	g/MJ EtOH
Yeast	0.19	0.00	-	g/MJ EtOH
Cellulase	-	-	0.70	g/MJ EtOH
Urea	-	0.26	-	g/MJ EtOH
Zeolite	-	-	0.01	g/MJ EtOH
Steel	-	-	0.17	g/MJ EtOH
Chromium steel	-	-	10.04	g/MJ EtOH
Concrete	-	-	0.23	cm^3/MJ EtOH
Building hall	-	-	0.05	cm^2/MJ EtOH

[1]GREET considers corn steep liquor

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Table 17 presents the industrial emissions and electricity output per MJ of forest residues ethanol produced in GHGenius, GREET and VSB models.

Table 17: Biomass boiler emissions and electricity output per MJ of forest residues ethanol

	GHGenius	GREET	VSB	
VOC	-	8.69	3.61	mg/MJ EtOH
PM10	76.67	10.63	58.63	mg/MJ EtOH
PM2.5	65.61	1.81	29.34	mg/MJ EtOH
CO	643.20	130.38	52.01	mg/MJ EtOH
NO_x	231.34	136.59	51.72	mg/MJ EtOH
N_2O	14.32	-	2.86	mg/MJ EtOH
SO_x	231.34	55.88	2.78	mg/MJ EtOH
CH_4 biogenic	74.54	-	21.43	mg/MJ EtOH
		Output		
Electricity	0.08	0.11	0.19	MJ/MJ EtOH

Particularities of each model – ethanol inputs and emissions

GHGenius: The model considers no urea input, differently from GREET and VSB.

GREET: In GREET the energy inputs are high compared to the two other models. The natural gas input is primarily for drying and preparing the feedstocks (i.e. grinding).

VSB: The only model to consider zeolite and infrastructure material (e.g. steel, concrete). There are no external energy inputs for the industrial step of ethanol production, and low inputs of sugar and sulfuric acid compared to the other models.

In Table 18 the transportation parameters of forest residues ethanol produced in GHGenius, GREET and VSB models are presented.

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Table 18: Transportation parameters of forest residues ethanol

	GHGenius	GREET	VSB	
Residue transportation				
Truck	-	144.84 (HHD)	100	km
Ethanol distribution				
Barge	-	836.86 (13.2%)	-	km
Train	700	1287.48 (78.9%)	-	km
Truck	225.26	128.75 (7.9%) (HHD)	400	km
Truck	-	48.28	-	km

HHD: heavy-heavy-duty truck

Particularities of each model – ethanol distribution emissions

In the three models, there is only local consumption and no ocean transportation. GREET model also considers barge modal of transportation.

4.3. Emission factors

The related Table 19 and Table 20 contain the retrieved emission factors for the default inputs of both agricultural and industrial phases in the four models of the study. Despite the fact that the models report emission factors associated to several other compounds, these are not presented in the cited tables since they are not employed as default inputs in the analyzed pathways.

Table 19: Emissions factors for the 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	-	2,799	g CO_2eq/kg
K_2O	426	686	-	545	g CO_2eq/kg
P_2O_5	2,012	1,807	-	1,468	g CO_2eq/kg
High density polyethylene	-	1,565	-	3,505	g CO_2eq/kg

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Table 20: Emissions factors for the industrial phase

	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	848	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
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

In GHGenius a set of indirect emissions such as the ones from manufacture and maintenance of farm tractor are considered as part of diesel emission factor, that is why it is higher than the other models. It is worthwhile mentioning that in GHGenius the emissions factors for most of chemicals vary with the region due to different electricity emission factors, and nitrogen emission factors varies with region depending on the mix of N fertilizer used in that region.

The emissions factors for NPK in the VSB are used only in the case of 1G2G ethanol production where there is the sugarcane production.

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5. Harmonization between LCA models

For this study, the harmonization for two routes were performed:

- Corn stover ethanol: GHGenius and GREET models
- Forest residues ethanol: GHGenius, GREET and VSB models

For the first case, data and parameters were retrieved from the GREET database and inserted on GHGenius for harmonization purposes.

For the second case, data and parameters were retrieved from the VSB database and inserted on GHGenius and GREET models.

The new JRC model (New EC) was not included in the harmonization since the calculation tool is proprietary and, therefore, not publicly available to users, although all inputs, outputs and other assumptions are publically available, allowing replication of the calculation as carried out in this work.

With this approach, it was possible, for each scenario, to identify the main differences and to check the possibility of reaching similar impacts from different LCA models considering the same production system. Besides, this approach helps understanding if the LCA models are consistent regarding their methodology and system boundaries.

These analyzes of climate change impact were performed for the corn stover and forest residues ethanol, considering a cradle-to-gate approach (ethanol distribution was not harmonized).

The following list of items was taken into account in the corn stover ethanol harmonization:

- Avoided N_2O emissions
- Diesel
- Avoided LUC emissions
- Industrial yield
- Co-product credit
- N_2O from boiler emissions

The following list of items was considered in the harmonization of forest residues ethanol:

- Allocation procedure: substitution method was replaced by economic allocation
- Recovery inputs
- Industrial energy inputs
- Industrial inputs: ammonia, sugar, cellulase and sulfuric acid inputs

6. Results: comparison of LCA models

6.1. Standalone 2G ethanol production

The main objective of this section is to present a comparison between the emissions of 2G ethanol production from different feedstocks (wheat straw, corn stover, sugarcane straw and bagasse, and forest residues) in the compared LCA models and identification of the particularities leading to different outcomes.

6.1.1. Cradle-to-gate

The emissions of ethanol production in the cradle-to-gate approach include:

- Residue recovery;
- Residue transportation to ethanol plant;
- Industrial process;
- Emissions displaced by co-products (if that is the case).

In Table 21 and Figure 4, the emissions are presented in grams of CO_2eq per MJ of ethanol, according to the allocation or substitution method of each model.

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Table 21: Cradle-to-gate emissions associated with 2G ethanol production, in g CO_2eq/MJ ethanol, by phase of production

	GHGenius	GREET	New EC	VSB
Feedstock	**Wheat straw**	**Corn stover**	**Wheat straw**	**Sugarcane straw**
Recovery of residues	5.13	3.98	1.78	-1.11
Transport	2.33	2.65	5.45	1.14
Industrial processing	21.56	14.07	4.85	4.92
Emissions displaced by co-products (electricity)	-12.27	-14.38	-	-
Total	16.74	6.32	12.08	4.95

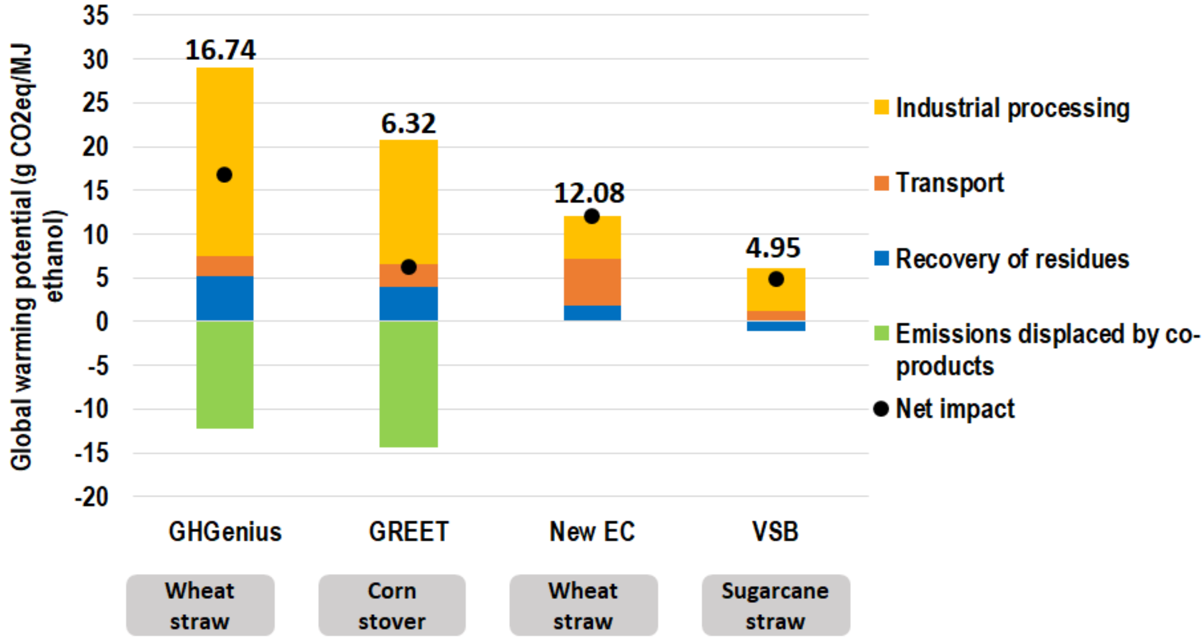

Figure 4: Cradle-to-gate emissions of standalone 2G ethanol production

The net impact of each model varies significantly, even when comparing GHGenius and New EC (both consider ethanol from wheat straw in this analysis).

In general, the differences are justified by the different input values and emissions factors. Besides, two models consider substitution procedure (GHGenius and GREET), while New EC considers energetic allocation among products, and the VSB considers economy allocation.

In the pathway for residues recovery, both GHGenius and GREET have the highest emissions, these two models consider replacement of NPK due to residue removal, however, GREET considers N_2O and NO_x avoided emissions, which decreases the impacts in the emissions.

Despite considering CH_4 and N_2O emissions from baling, the New EC model has no NPK inputs. Finally, the VSB model considers no NPK inputs, but rather considers N_2O and NO_x avoided emissions due to straw recovery. VSB presents the lowest emissions compared to the other models.

The New EC model presents the highest transportation emissions; this can be justified because the considered transportation distance is higher than in the 3 other models.

Neither the New EC model nor the VSB model consider energy inputs for the industrial processing. GREET and GHGenius, on the other hand, consider diesel inputs. The higher emissions derived from the industrial pathway in GHGenius can be justified by the high diesel input.

6.1.2. Cradle-to-pump

Using cradle-to-pump boundaries, emissions from ethanol production include those previously reported in the cradle-to-gate analysis plus the emissions from fuel storage and distribution:

- Residue recovery;
- Residue transportation to ethanol plant;
- Industrial process;
- Emissions displaced by co-products (if that is the case).
- Ethanol storage and distribution

Emissions are presented in g of CO_2eq per MJ of ethanol in Table 22 and Figure 5, according to the allocation method of each model.

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Table 22: Cradle-to-pump emissions associated with 2G ethanol production, in g CO_2eq/MJ ethanol, by phase of production

	GHGenius	GREET	New EC	VSB
Recovery of residues	5.13	3.98	1.78	-1.11
Transport	2.33	2.65	5.45	1.14
Industrial processing	21.56	14.07	4.85	4.92
Ethanol distribution and storage	1.79	1.00	1.60	2.24
Emissions displaced by co-products (electricity)	-12.27	-14.38	-	-
Net impact	18.53	7.32	13.68	7.18

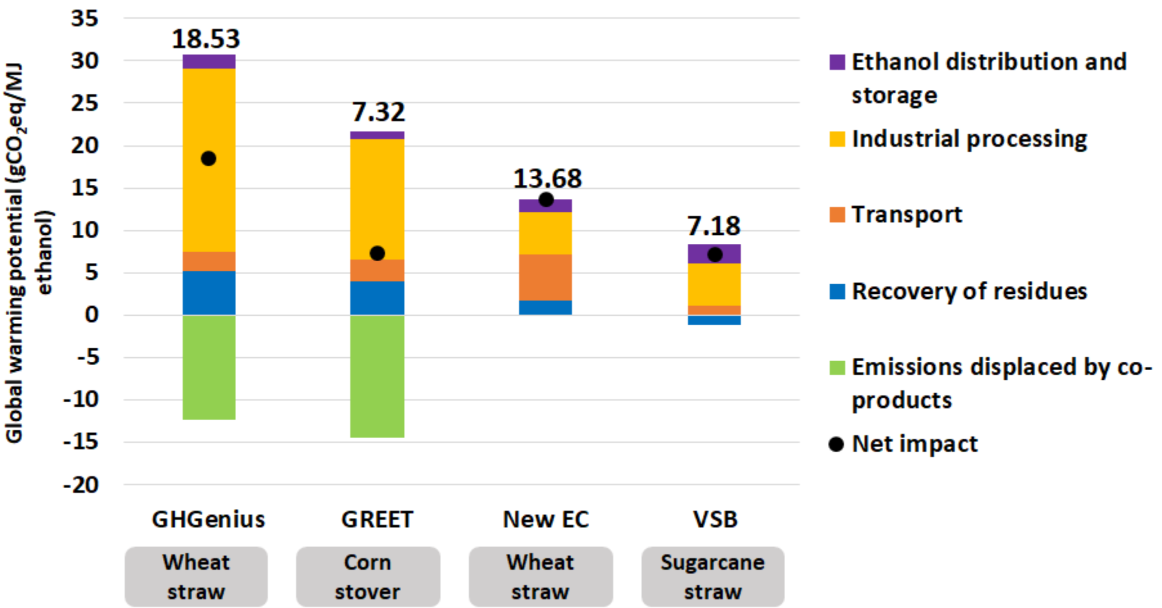

Figure 5: Cradle-to-pump emissions of standalone 2G ethanol production

VSB has higher distribution emissions compared to the other models, and this can be justified because the model considers only truck modal, and the distance considered is the largest among the models.

6.2. Integrated 1G2G ethanol production: the case of VSB model

In this section, the main objective is to present the emissions of the 1G2G integrated ethanol plant in the VSB model considering sugarcane bagasse and straw as feedstock for 2G ethanol

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production. Afterwards a comparison between the 1G2G integrated ethanol plant with the 2G standalone plant, that considers only sugarcane straw as feedstock is presented.

6.2.1. Cradle-to-gate

For the comparison among the integrated 1G2G ethanol plant with the standalone 2G plant in the VSB model, emissions are presented in grams of CO_2eq per MJ of ethanol in Table 23 and Figure 6:

Table 23: Comparison of cradle-to-gate emissions from standalone 2G ethanol and integrated 1G2G ethanol, in g CO_2eq/MJ ethanol, by phase of production using the VSB model

	Standalone 2G	Integrated 1G2G
Fertilizer and agricultural residues emissions	-4.19	7.06
NPK (production)	-	1.95
Other agricultural processes	3.07	3.11
Transport	1.14	2.22
Industrial processing	4.92	2.87
Total	7.18	19.45

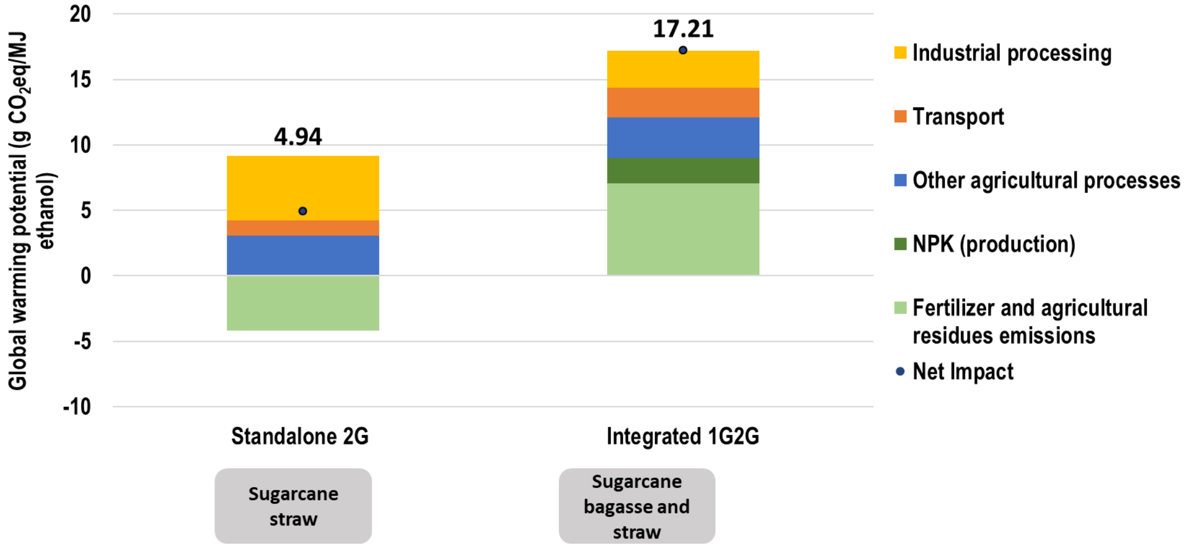

Figure 6: Comparison of cradle-to-gate emissions associated with standalone 2G ethanol and integrated 1G2G ethanol

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6.2.2. Cradle-to-pump

In Table 24 and Figure 7 and, the emissions are presented in grams of CO_2eq per MJ of ethanol, according to the allocation or substitution method of each model.

Table 24: Comparison of cradle-to-pump emissions from standalone 2G ethanol and integrated 1G2G ethanol, in g CO_2eq/MJ ethanol, by phase of production using the VSB model

	Standalone 2G	Integrated 1G2G
Fertilizer and agricultural residues emissions	-4.19	7.06
NPK (production)	-	1.95
Other agricultural processes	3.07	3.11
Transport	1.14	2.22
Industrial processing	4.92	2.87
Ethanol distribution and storage	2.24	2.24
Total	7.18	19.45

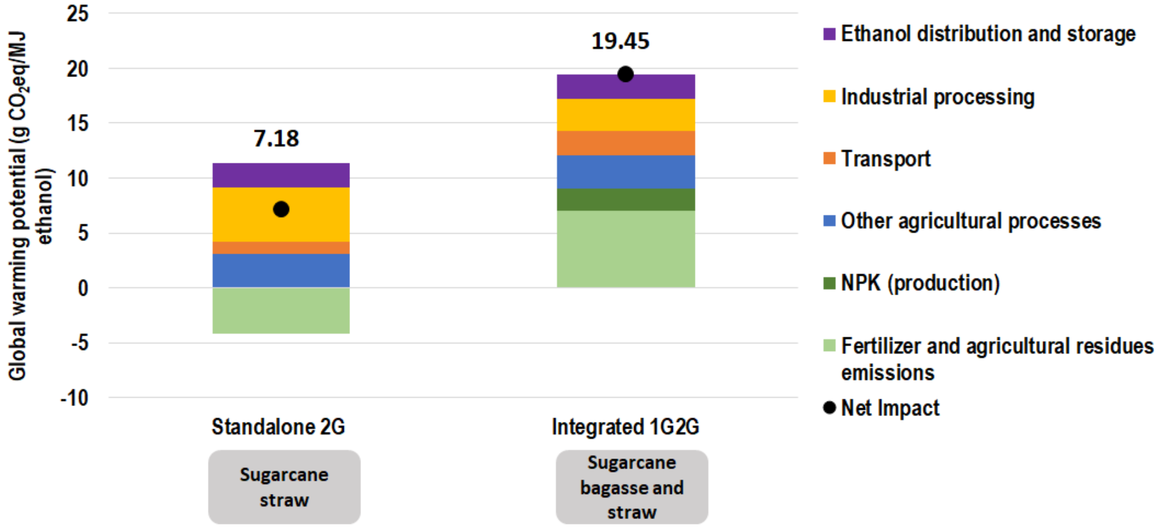

Figure 7: Comparison of cradle-to-pump emissions associated with standalone 2G ethanol and integrated 1G2G ethanol

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The final emissions in the integrated ethanol plant are higher than the standalone plant because the final emissions "carry" the impacts of sugarcane production.

It is worthwhile mentioning that the integrated plant presents lower emissions than a first generation ethanol plant. It can be justified since more ethanol is produced without the need of extra sugarcane cultivation. For instance, the carbon intensity of 1G sugarcane ethanol in Brazil is around 21 gCO_2eq/MJ of ethanol produced (Mastuura et al, 2018).

6.3. Standalone 2G ethanol production: Corn Stover

The objective of this section is to present a comparison between the emissions of corn stover ethanol production using the GHGenius and GREET models, and identification of the particularities leading to different outcomes.

6.3.1. Cradle-to-gate

The emissions of ethanol production in the cradle-to-gate approach include:

- Residue recovery;
- Residue transportation to ethanol plant;
- Industrial process;
- Emissions displaced by co-products.

In Table 25 and Figure 8, the emissions are presented in grams of CO_2eq per MJ of ethanol for GHGenius and GREET models.

Table 25: Cradle-to-gate emissions associated with corn stover ethanol production, in g CO_2eq/MJ ethanol, by phase of production

	GHGenius	GREET
Recovery of residues	9.58	3.98
Transport	2.31	2.65
Industrial processing	21.52	14.07
Emissions displaced by co-products (electricity)	-12.27	-14.38
Total	21.13	6.32

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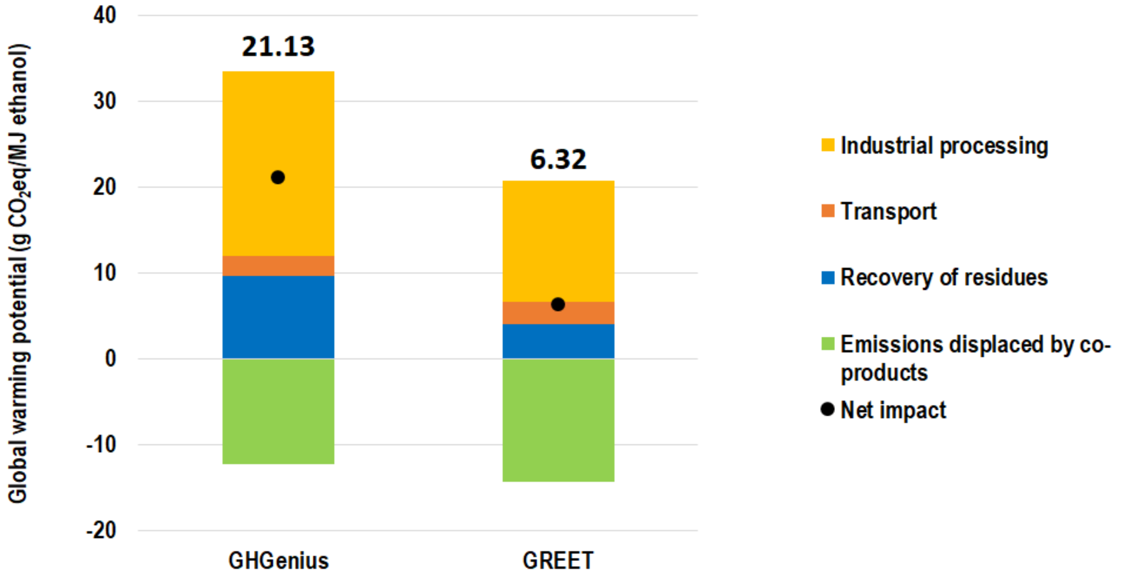

Figure 8: Cradle-to-gate emissions of corn stover ethanol production

The GHGenius model presents higher emissions for 2G ethanol produced from corn stover due to several reasons. For instance, the two models consider emissions displaced due to electricity exportation to the grid; however, the credit considered varies according to each country's electricity matrix and, in this case, the emissions displaced in GREET model are higher than in GHGenius. Besides, GHGenius has no avoided emissions of N_2O and NOx due to corn stover removal, neither avoided LUC emissions, as in GREET. In the industrial processing, GHGenius presents higher energy inputs compared to GREET, plus a larger amount of used chemicals.

6.3.2. Cradle-to-pump

Using cradle-to-pump boundaries, emissions from ethanol production include those previously reported in the cradle-to-gate analysis plus the emissions from fuel storage and distribution:

- Residue recovery;
- Residue transportation to ethanol plant;
- Industrial process;
- Emissions displaced by co-products;
- Ethanol storage and distribution.

Emissions are presented in g of CO_2eq per MJ of ethanol (Table 26 and Figure 9), according to the allocation method of each model.

Table 26: Cradle-to-pump emissions associated with corn stover ethanol production, in g CO_2eq/MJ ethanol, by phase of production

	GHGenius	GREET
Recovery of residues	9.58	3.98
Transport	2.31	2.65
Industrial processing	21.52	14.07
Ethanol distribution and storage	1.79	1.00
Emissions displaced by co-products (electricity)	-12.27	-14.38
Total	22.92	7.32

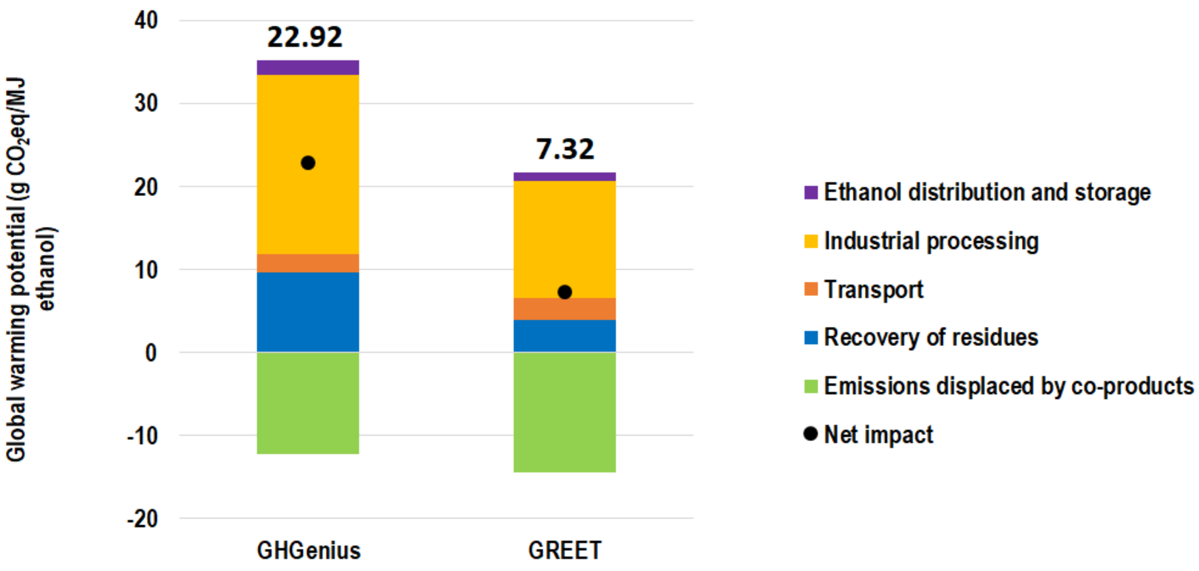

Figure 9: Cradle-to-pump emissions of standalone corn stover ethanol production

The results of the harmonization of these two models are presented in Chapter 7.

6.4. Standalone 2G ethanol production: Forest residue

The objective of this section is to present a comparison between the emissions of forest residues ethanol production in the GHGenius, GREET, and VSB models, as well as the identification of the particularities leading to different outcomes.

6.4.1. Cradle-to-gate

The emissions of ethanol production in the cradle-to-gate approach include:

- Residue recovery;
- Residue transportation to ethanol plant;
- Industrial process;
- Emissions displaced by co-products (if that is the case).

In Table 27 and Figure 10, the emissions are presented in grams of CO_2eq per MJ of ethanol for GHGenius, GREET and VSB models.

Table 27: Cradle-to-gate emissions associated with forest residues ethanol production, in g CO_2eq/MJ ethanol, by phase of production

	GHGenius	**GREET**	**VSB**
Recovery of residues	-	1.33	0.25
Transport	-	3.98	0.10
Industrial processing	21.91	15.10	7.30
Emissions displaced by co-products	-12.27	-14.43	-
Total	9.63	5.97	7.65

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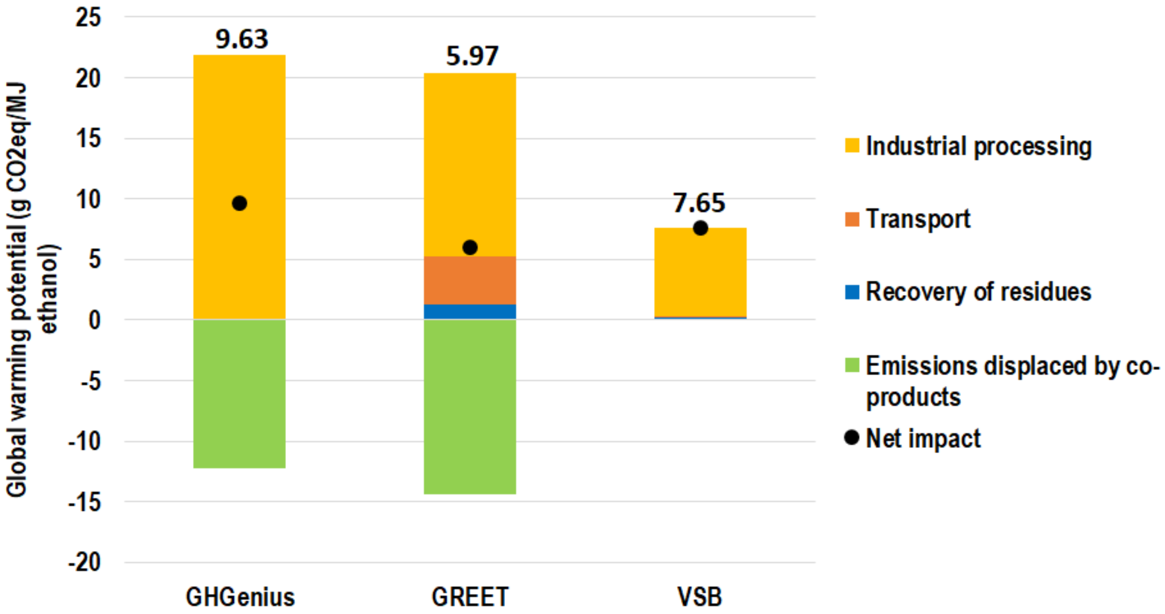

Figure 10: Cradle-to-gate emissions of forest residues ethanol production

Overall, the three models present relatively close results. As mentioned previously, GHGenius has three different options of woody residues. Short rotation crops, mill residues, and standing timber. In this study, we considered the mill residues and no residue collection is included. However, the model considers no transportation of the mill residue to the ethanol plant, which should be considered.

As in the case of corn stover, both GHGenius and GREET models consider emissions displaced due to electricity exportation to the grid. The credit considered varies according to each country's electricity matrix and the emissions displaced in GREET model are higher than in GHGenius. The VSB model considers economy allocation method to share the impacts among the products.

6.4.2. Cradle-to-pump

Using cradle-to-pump boundaries, emissions from ethanol production include those previously reported in the cradle-to-gate analysis plus the emissions from fuel storage and distribution:

- Residue recovery;
- Residue transportation to ethanol plant;
- Industrial process;
- Emissions displaced by co-products (if that is the case);
- Ethanol storage and distribution.

Emissions are presented in g of CO_2eq per MJ of ethanol (Table 28 and Figure 11), according to the allocation method of each model.

Table 28: Cradle-to-pump emissions associated with forest residues ethanol production, in g CO_2eq/MJ ethanol, by phase of production

	GHGenius	GREET	VSB
Recovery of residues	-	1.33	0.25
Transport	-	3.98	0.10
Industrial processing	21.91	15.10	7.30
Ethanol distribution and storage	1.79	1.10	2.24
Emissions displaced by co-products	-12.27	-14.43	-
Total	11.42	7.07	9.88

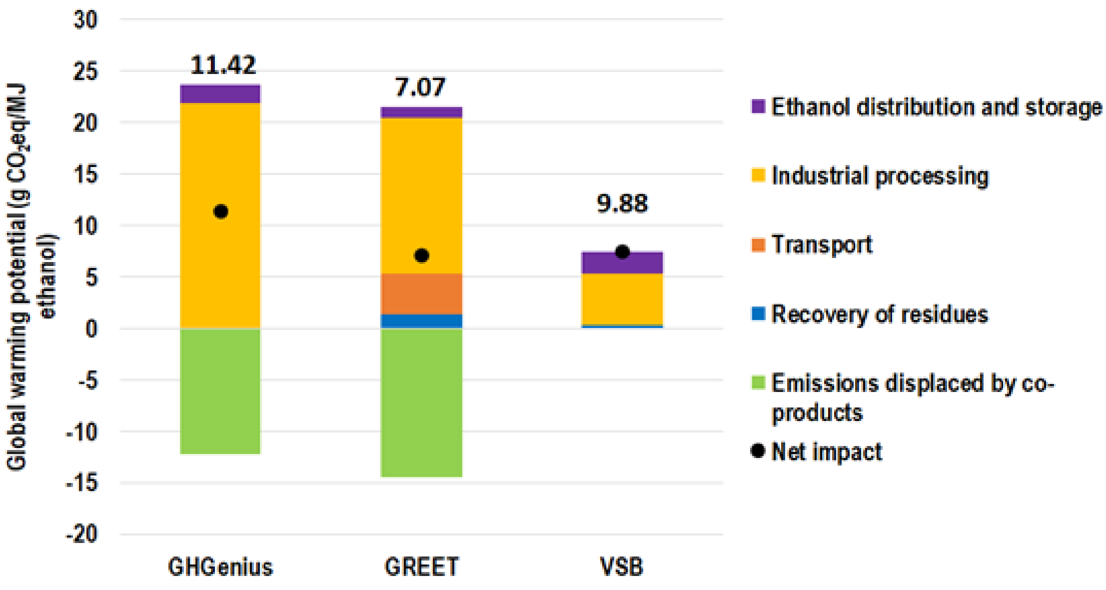

Figure 11: Cradle-to-pump emissions of forest residues ethanol production

In VSB model, the emissions are higher when compared to the other models, because 100% of transportation modal considered is road (trucks) and the distances are quite large.

7. Harmonization of 2G ethanol production

This section presents the results obtained after harmonization of 2G ethanol production from corn stover (GHGenius and GREET) in section 7.1, and forest residues (GHGenius, GREET and VSB) in section 7.2.

It is important to highlight that the New EC was not included in the harmonization procedure: despite the data for several scenarios being available online (and an external user would be able to "rebuild" the calculation structure, if needed), the spreadsheet with the calculation tool is locked for edition by users. This led to the removal of New EC from this specific section of the study since the purpose of a harmonization exercise is not only identifying the differences between assumptions and input data from each model, but also understanding the underlying features of the calculation mechanism itself.

7.1. Harmonization of corn stover ethanol production

In this section, the harmonization of ethanol production using corn stover was performed retrieving data and parameters from GREET and including in GHGenius model, and also retrieving data and parameters from GHGenius and inserting in GREET model.

For the harmonization of corn stover ethanol production among GHGenius and GREET models, the following parameters were selected:

- Avoided N_2O
- Industrial diesel
- Avoided LUC
- Industrial yield
- Co-products credits
- N_2O from boiler emissions

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The selection of these parameters was carried out due to its relevance in the difference among the two models and consequently, in the final results.

Figure 12 presents the results for the harmonization of corn stover ethanol production using GREET data, i.e. considering the USA corn stover production system and industrial conversion data. Figure 13 presents the results using GHGenius data inserted in GREET model.

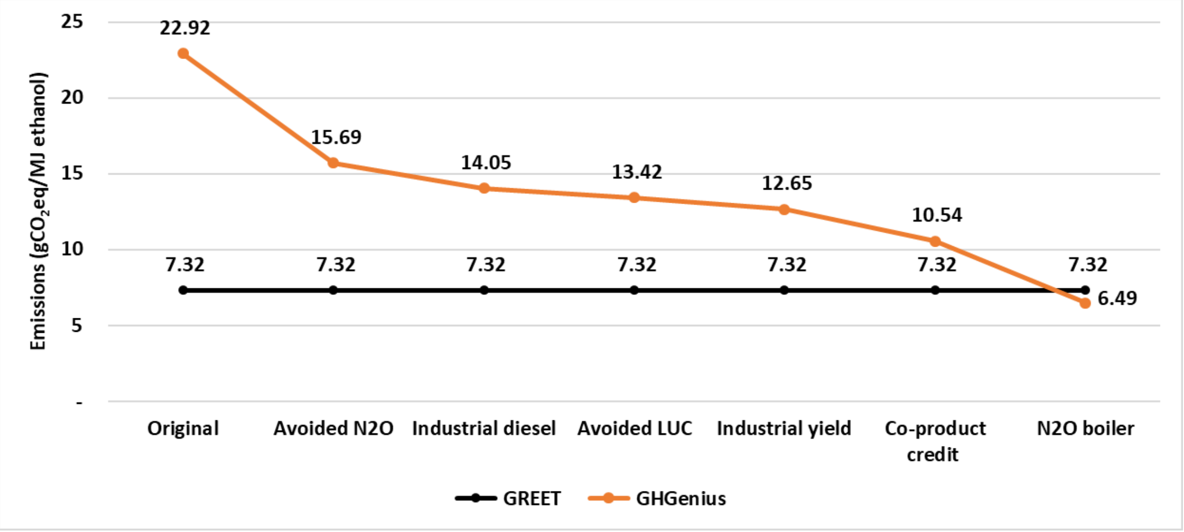

Figure 12: Harmonization of corn stover ethanol emissions – inclusion of GREET values on GHGenius

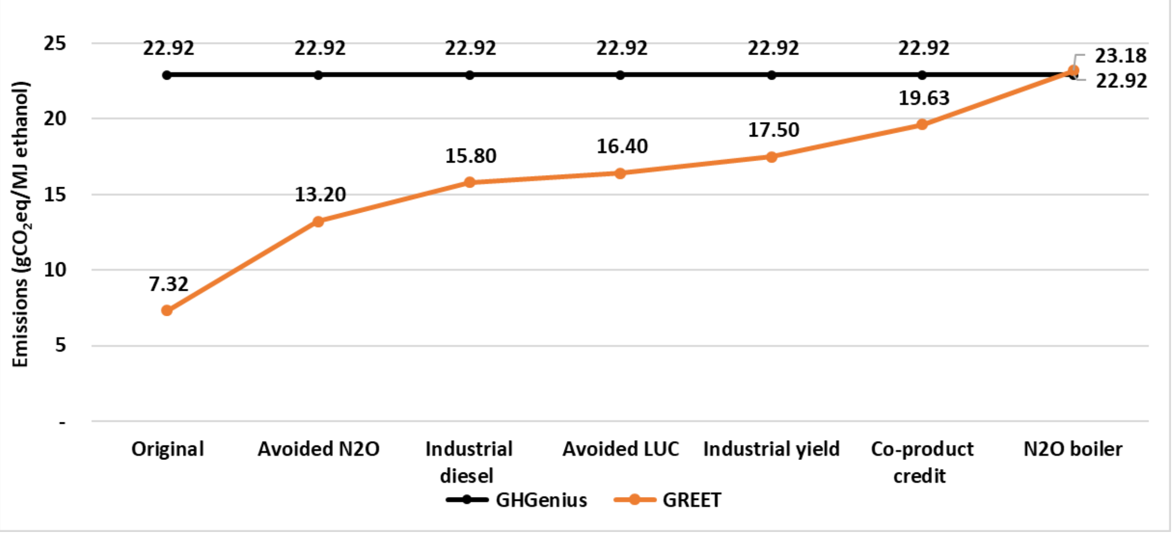

Figure 13: Harmonization of corn stover ethanol emissions – inclusion of GHGenius values on GREET

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Figure 12 and 13 clearly indicates that the differences among the assessed models decrease considerably and they reach similar results after harmonization of a few chosen inputs and parameters. The harmonization of avoided N_2O emissions presents the highest contribution to approximate GREET and GHGenius results.

Major differences after harmonization

The remaining small differences among the results are due to some unharmonized points:

- Other particularities of each model;
- Differences in the calculation procedures from one model to another;
- Emission factors;
- Characterization factors (GWP-100) differ among models (Table 2).

It is worthwhile mentioning that GHGenius allows the user to change the characterization factor, and that would lead to more similar results compared to GREET. However, as mentioned before, this study considered the default pathways for comparison.

Remaining steps that were not harmonized can cumulatively account for the differences found in the final result.

7.2. Harmonization of forest residues ethanol production

The harmonization of ethanol production using forest residues was performed using the VSB dataset and other parameters and including than in GHGenius and GREET models.

For the harmonization of forest residues ethanol production among GHGenius, GREET and VSB models, the following parameters were selected:

- Allocation procedure
- Recovery inputs
- Transportation
- Industrial energy inputs
- Industrial inputs

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Again, the selection of these parameters was carried out due to its relevance in the differences among the models and, consequently, in the final results.

In Figure 14 there are the results for the harmonization of forest residues ethanol production using VSB data.

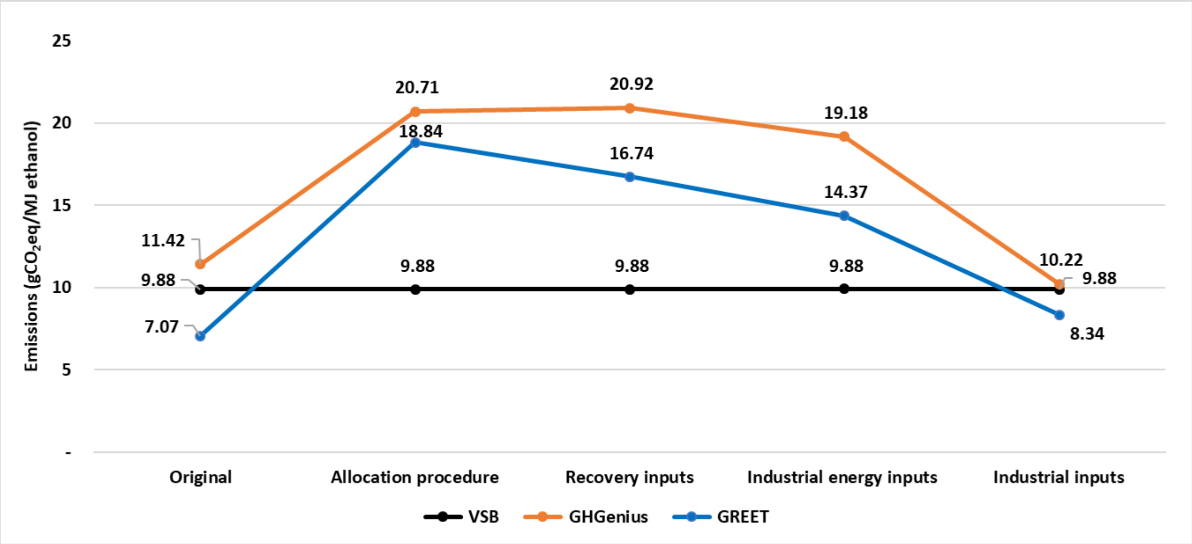

Figure 14: Harmonization of forest residues ethanol emissions – inclusion of VSB values on GHGenius and GREET

The inclusion of recovery and transportation inputs increased GHGenius emissions, since this model does not consider such inputs.

The results from the three models were already similar before harmonization, and despite the differences among the data, parameters and assumptions, after harmonization they reached similar results once more.

The harmonization of transportation parameters led to the largest difference among the models, and the harmonization of industrial inputs had the largest influence to approximate the results.

Major differences after harmonization

The remaining small differences among the results are again due to some unharmonized points:

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- Particularities of each model
- 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
- Characterization factors (GWP-100) differ among models (Table 2).

It is worthwhile mentioning that GHGenius allows the user to change the characterization factor. However, as mentioned before, this study considered the default pathways for comparison. If all pathways are harmonized to IPCC AR5 GWP, this could bring all results to the most recent IPCC GWPs.

8. Conclusions and final remarks

The main differences among the four assessed models and the factors contributing to such differences were quantitatively identified, as well as the parameters impacting the carbon intensity associated to the production and distribution of 2G ethanol using different lignocellulosic feedstocks. In Table 29, there are the results for each assessed feedstock/pathway duo using the studied LCA models.

Table 29: Summary of cradle-to-pump emissions in g CO_2eq/MJ ethanol

	GHGenius	**GREET**	**New EC**	**VSB**	
Wheat straw	18.53	-	13.68	-	gCO_2eq/MJ
Corn stover	22.92	7.32	-	-	gCO_2eq/MJ
Sugarcane straw	-	-	-	7.18	gCO_2eq/MJ
Forest residue	11.42	7.07	-	9.88	gCO_2eq/MJ
Sugarcane 1G2G	-	-	-	19.45	gCO_2eq/MJ

Not all the four models have pathways to all the feedstocks assessed. In the case of wheat straw, GHGenius presents higher emissions than New EC, mostly because of NPK replacement in the field due to straw removal, and higher energy inputs in the industrial phase.

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For corn stover, GHGenius also presents higher emissions than GREET. This is due to higher energy inputs in the industrial phase, lower emissions displaced by co-products, no avoided emissions of N_2O and NOx due to corn stover removal, and no avoided LUC emissions.

In the case of forest residues ethanol, GHGenius presents the highest emissions among the 3 models assessed, GREET presents the lowest emissions and VSB is in between. The emissions in the industrial processes are higher in GHGenius compared to the other models.

Only VSB has sugarcane straw and 1G2G ethanol production from sugarcane. The results for sugarcane straw ethanol are close to the values presented for corn stover and forest residues ethanol in GREET.

The harmonization procedure carried for the corn stover ethanol and forest residues ethanol pathways show it is possible to align the results issued by the models through a series of steps considering only few parameters. The analysis found differences in the input data and methodological choices, some of which could be harmonized, such as the divergences between energy inputs among the studied models, or the considered avoided emissions.

As in the Phase 2 Part 1 (biofuels from oleaginous feedstocks), the industrial phase of each pathway should have similar results in the assessed models, besides the fact that the plant configuration can vary in each model assessed.

We emphasize that there is room for discussion and standardization of models in order to decrease the difference of input data and approaches and thus “pre-harmonize” all models and make them more consistent.

Once more, an effort to build a harmonized data set of input data for the technological pathways and to update the databases of the main models would benefit the community and deliver better GHG emission results and comparisons for the life cycle assessment of biofuels production.

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