ENVIRONMENTAL ASSESSMENT OF BIOREFINERY CO-PRODUCTS

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AC	activated carbon
ATA	Airlines for America
ATJ	alcohol-to-jet fuel
EG	ethylene glycol
EISA	Energy Independence and Security Act
EO	executive order
ETS	emissions trading system
EU	European Union
FCEA	Food, Conservation and Energy Act
FU	functional unit
GAMS	General Algebraic Modeling System
GHG	greenhouse gasses
GWP	global warming potential (CO2 equivalents)
IATA	International Aviation and Transportation Association
IBA	isobutanol
ICAO	International Aviation and Transportation Association
IPCC	International Panel on Climate Change
IPK	iso-paraffinic kerosene
Kg	kilogram
LCA	life cycle assessment
LCIA	life cycle impact assessment
LS	lignosulfonate
MC	moisture content
NARA	Northwest Advanced Renewables Alliance
PET	polyethylene terephthalate
PM2.5	particulate matter <2.5 microns
PTA	purified terephthalate acid
PX	paraxylene
RFS	Renewable Fuels Standard (2)
RIN	Renewable Identification Number
RSB	Roundtable for Sustainable Biomaterials
SSL	spent sulfite liquor
USDA	United States Department of Agriculture
USLCI	United States Life Cycle Inventory

TASK 1: BIO-PRODUCT ENVIRONMENTAL PERFORMANCE AND PREFERABILITY

Objective
The objective was to identify the drivers for bio-product environmental performance and criteria for environmental preferability. This task was formally named EPP-5 under assigned tasks for the NARA EPP team.

Overview
A thorough review of the literature has been completed. Specifically, key governmental policy drivers (RFS2/EISA 2007, FCEA 2008, EO 13514 and 13423, EU Emissions Trading System, etc.), voluntary initiatives and standards (USDA Biopreferred, RSB, IATA, ATA, etc.) and aviation biofuel LCAs were reviewed. Our review also confirmed the continued integration of life cycle approaches in current and anticipated public policies aimed at stimulating fossil fuel/product substitution. Based on current and future policy developments, we recommend a variety of impact allocation methods be explored to assess biofuel and bio-product environmental performance and preferability. The review also suggested overwhelming evidence toward the importance of flexible and scalable life cycle assessment approaches to accommodate the speed of innovation and increased process complexity associated with advanced biorefineries. Consequently, we recommend life cycle assessments be conducted in a modular format to allow for different pathway combinations. Such a structure has been used in subsequent assessments of the NARA biorefinery. The fuel and product standards that influence the environmental preferability of the alcohol-to-jet fuel production process is shown in Figure BCP-1.1.

Renewable Fuels Standard
The Renewable Fuels Standard requires annually increasing volumes of biofuels that meet specific greenhouse gas (GHG) reduction criteria to be blended with fossil-based fuels. Biofuels that meet the GHG reduction targets qualify for the additional sale of RIN credits, which can create substantial economic benefits for biorefinery producers. Jet fuel that can be demonstrated to reduce GHGs relative to their fossil-kerosene counterparts can also qualify for the sale of RINs although it is not directly covered under the RFS.

While four categories of biofuel exist under the RFS, the forest residue biorefinery fuel outputs could qualify for either the cellulosic or advanced biofuel categories, due to the nested nature of the RFS requirements. To qualify for the cellulosic biofuel category, the biofuel must reduce life cycle GHG emissions by 60% relative to the 2005 fossil kerosene baseline emissions. The advanced biofuel category requires a 50% reduction in baseline GHG emissions. To assess performance and compliance, a ‘well to wheels’ life cycle assessment will need to be conducted.

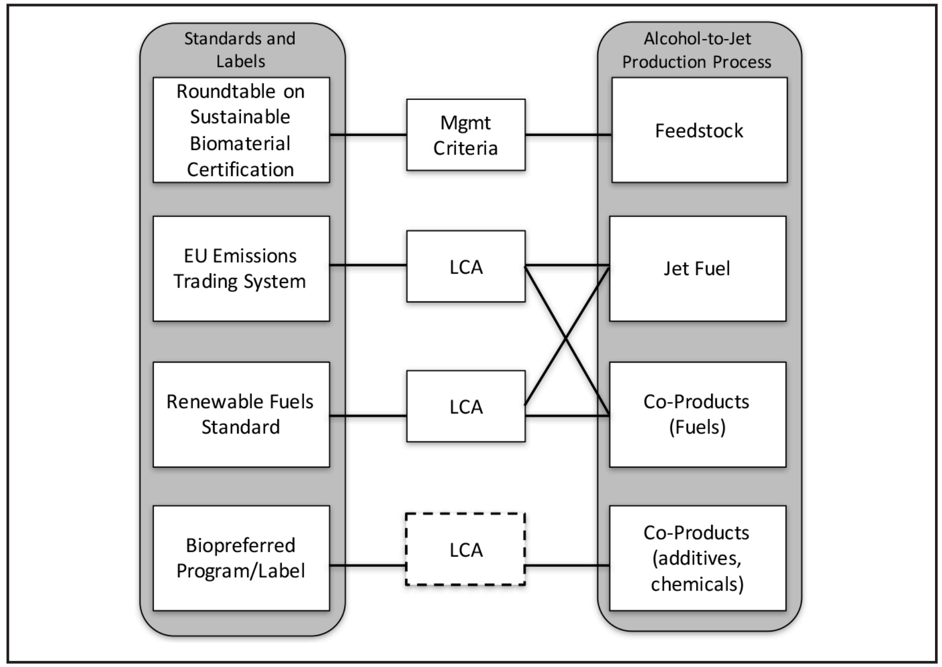

Figure BCP-1.1. Fuel and product standards influence Environmental Preferability of the alcohol-to-jet fuel production process. Dotted line refers to USDA’s request for bio-product producers to voluntarily supply LCA information, and the potential for LCA information to be required in future revisions to the BioPreferred Program and label. Solid lines and boxes reflect the influence of the standards/labels on different components of the biorefinery, and the mechanism by which compliance is measured.

EU Emissions Trading Scheme (ETS)
Since 2012, emissions to or from the EU are required to participate in the EU ETS, which provide airlines tradeable emissions permits that allow a certain level of GHG emissions per year from airline flights. Those that are unable to reach the emissions targets are required to purchase additional emissions permits from the ETS market. It is expected that much of the reductions in GHG emissions will come from using renewably sourced bio-based jet fuels. The International Civil Aviation Organization (ICAO) has further agreed to develop an international market-based system to address aviation emissions by 2020. A truncated LCA, occurring in the use phase, is required to measure emissions and compliance.

BioPreferred Program

The BioPreferred program, which qualifies bio-based products for federal environmentally preferred purchasing, affects non-fuel co-products of the biorefinery. The BioPreferred program was established by the Farm Security and Rural Investment Act of 2002, and strengthened by Executive Orders 13514 and 13423, which mandate federal agencies to give preference to products with the greatest biobased content, given that products are available, performance attributes are similar, and are equally priced. The program currently covers over 100 product categories, certifying over 10,000 products for Federal Preferred Purchasing and over 800 products for the USDA Certified Biobased Label, which signals to consumers the bio-based nature of products.

The Food, Conservation and Energy Act of 2008 expanded the BioPreferred designation to include intermediate products, ingredients or feedstocks used to produce other products. This allows products that require multiple feedstocks or product components to be designated for federally preferable procurement. Final products that contain 50% or more biobased intermediates are automatically designated as BioPreferred.

The USDA originally required LCAs for all biobased products. Due to stakeholder comments, however, the USDA decided such a requirement was not appropriate at this time and amended the program. Because bio-products are not required to measure associated GHG emissions, GHG displacement credits can be given to biofuel outputs without issues of double counting. However, if bio-products are similarly regulated for reduced GHG emissions, alternative allocation methods must be used to distribute impacts of co-production processes, in order to avoid issues of double counting. This change in life cycle GHG accounting may affect the environmental performance of the biofuel outputs, and perhaps, affect its ability to meet the RFS GHG reduction criteria. It is, therefore, important that a sensitivity analysis around allocation methods is conducted.

Roundtable on Sustainable Biomaterials

The Round Table on Sustainable Biomaterials has developed a certification program that producers of biomaterials can voluntarily participate in to certify that renewable feedstocks are sustainably sourced. With regard to the NARA feedstock, forest residues and milling residues are considered non-merchantable byproducts of existing productive operations, and therefore, have minimal direct environmental impact (depending on allocation methods used). Most of the milling residues (approximately 95%) are expected to be unavailable for biofuels production due to their current use to generate electricity and heat for plant operations (Yoder 2010). Therefore, most of the residues are likely to come from forestry operations. The amount of residues removed from forestland can negatively affect water quality as well as soil erosion if it exceeds recommended removal rates. However, there exists significant variability in sustainable removal rate estimates ranging from 20-50% depending on the study and location. Exceeding the recommended removal rates could result in soil degradation due to compaction of the soil during removal, as well as the depletion of nutrients that come from the organic matter. The EPA has designated forest residues to have negligible land use change impact, since residues are a secondary product of dedicated forest harvesting operations.

Other Voluntary Initiatives

Several organizations have voluntarily pledged to reduce GHG emissions and commit to using alternative, renewable fuels, products, and technologies. Regarding biojet fuels, the Sustainable Aviation Fuel Users group, which consists of 23 major airlines, is one among many organizations that have committed to using sustainable, renewable fuels. The aviation industries motivations for pursuing alternative fuels such as biojet fuel is primarily to decrease dependence on foreign oil and its associated price volatility (fuel is the biggest expense for airlines), and to reduce risks associated with current and future environmental regulation.

With regard to bio-products, environmentally preferable procurement practices and criteria are increasingly being implemented in commercial, institutional and industrial organizations. Currently, these organizations typically use general signals of environmental preference, such as the Biopreferred label, however, as methods for analysis become more accessible to these organizations and the level of sophistication grows, information on the relative environmental impacts of bio-products will likely be requested, as increasingly its recognized that not all bio-products necessarily lead to lower environmental burden.

TASK 2: CO-PRODUCT ENVIRONMENTAL ASSESSMENT

Objective

In general, bio-refinery co-products can significantly effect the net GHG emissions of regulated biofuel products. The objective, therefore, was to assess the environmental performance of the NARA biorefinery co-products, including the production of activated carbon, lignosulfonate cement dispersant, and bio-paraxylene. The results of these assessments are integrated into the life cycle assessment results of the IPK biofuel through close collaboration with the LCA team.

In addition, a case study examining the utilization of bio-paraxylene in the production of Bio-PET bottles was undertaken to assess the relative benefits and environmental preferability of NARA paraxylene compared to other Bio-PET feedstock compositions. As such, a comparative life cycle assessment of 12 PET production scenarios is provided. This task was formally named EPP-1.7 under assigned tasks for the NARA EPP team.

Method

A life cycle inventory was developed for each co-product using Aspen Plus process-flow diagrams developed by the NARA TEA team. Where transparency into unit processes was low, values were augmented based on literature and conversations with industry collaborators to provide the information necessary for appropriately allocating impacts for multi-output processes.

Life cycle impacts were calculated in the GaBi ThinkStep LCA software, and were determined based on a combination of USLCI, EcoInvent and PE LCI databases for process inputs and outputs. Datasets established on a European industry background were altered to fit the context of the U.S. industry, primarily with regard to electricity inputs.

Allocation

Following the IPCC and RFS allocation hierarchy, the displacement method is the primary method of choice used to distribute biorefinery impacts of non-fuel co-products. The displacement method subtracts the life cycle GHG emissions of the displaced conventional product from the non-fuel co-product production emissions, which results in a net decrease or increase in emissions that are then attributed to the main biofuel product. Activated carbon made from NARA fermentation residual solids displaces conventional activated carbon made from hard coal. Bio-paraxylene made from NARA isobutanol displaces conventional paraxylene refined from petroleum feedstocks. A review of the literature for lignosulfonates (LS), however, indicated that there exists a well-established low to medium-grade cement dispersant market for LS feedstock, so the production of LS for this market will not likely replace other feedstocks but rather add to the existing market of cement dispersants. For this reason, we recommend a mass allocation approach be used to allocate impacts to LS. Approximately 34% of the emissions from pretreatment and upstream harvesting emissions and 27% of the fermentation emissions could be allocated to the LS outputs, based on a relative dry mass basis. An alternative approach would be to allocate emissions from fermentation and upstream processes to only IBA, since the residues may be considered a secondary byproduct of dedicated fermentation operations.

Activated Carbon

Tables BCP- 2.1-2.2 show the calculated material and energy inputs and outputs of the carbonization and activation processes. Energy inputs used for drying processes, including belt press, centrifugation and rotary drying, were estimated through literature and included in the carbonization inventory. Energy inputs per hour for direct carbonization and activation were assumed to be equal due to similarities in operating temperatures and residence times.

Figure BCP- 2.1 results show biorefinery activated carbon production impacts are approximately 712 kg per ton of lignin AC produced, the emissions for which are primarily driven by the natural gas input requirements. Impacts do not include upstream biorefinery process emissions, as these can stay with the primary product stream used to produce the main biofuel products (i.e. IBA). Compared to conventional activated carbon produced from hard coal, and considering carbon storage credits, lignin activated carbon production results in approximately 6,514 kg CO_2e displaced per ton of lignin AC produced (Figure BCP-2.2).

Table BCP-2.1. Activation material and energy inputs and outputs

Inputs/Outputs	Units/Ton Activated Carbon	Inventory Value
Inputs		
Char	Tons	1.82
Steam	Klb	.42
Electricity	Mwh	.0033
Natural Gas	M3	108.28
CO2	Tons	.8
Outputs		
Activated Carbon	Tons	1
CO2	Tons	.35

Table BCP-2.2. Carbonization (including drying) material and energy inputs and outputs

Inputs/Outputs	Units/Ton Char	Inventory Value
Inputs		
Fermentation Residual Solids Stillage	Tons	35.69
Steam	Klb	2.51
Electricity	Mwh	.00184
Natural Gas	M3	59.55
N2	Tons	1.76
Outputs		
Char	Tons	1
Pyrolysis Gas	Tons	1.31
Wastewater	Tons	30.63

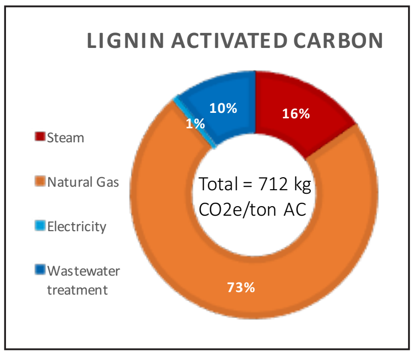

Figure BCP-2.1. NARA lignin activated carbon total greenhouse gas emissions and impact driver assessment. Emissions Includes drying processes (belt press, centrifugal and rotary drying). Note that zero upstream emissions are attributed to FRS inputs.

Paraxylene

Table BCP- 2.3 shows the calculated material and energy inputs and outputs of the paraxylene production process. Inputs were estimated through literature, Aspen plus process-flow diagrams, and thermo-chemical relationships.

Figure BCP- 2.3 results show paraxylene production impacts are approximately 643 kg CO_2e per ton of PX produced, the emissions for which are primarily driven by electricity and hydrogen input requirements. Impacts do not include upstream impacts from upstream biorefinery processes, as these can stay with the primary product stream used to produce the main biofuel products when the displacement method is used. Figure BCP- 2.4 shows that, compared to conventional paraxylene produced from petroleum refining, and considering carbon storage credits (due to the assumption of recycling), bio-paraxylene results in approximately 4,887 kg CO_2e displaced per ton of paraxylene produced.

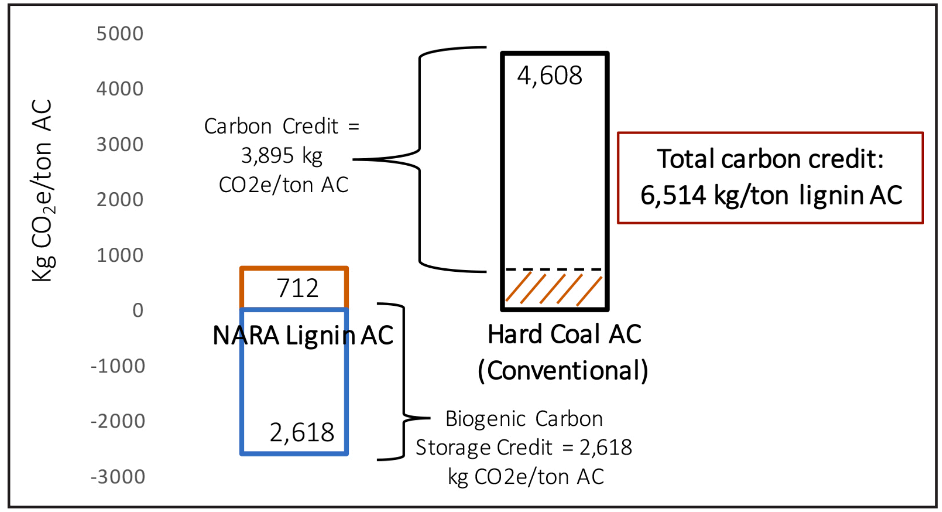

Figure BCP-2.2. NARA lignin activated carbon GHG emission comparison with conventional coal based activated carbon emissions. NARA lignin AC displaces coal AC, resulting in a carbon equivalent credit (reduction) of 6,514 kg CO2e/ton lignin AC produced and attributed to IPK (i.e. 712-4,608 -2,618 = -6514 kg CO2e/ton lignin AC produced)

Table BCP-2.3. Paraxylene production material and energy inputs and outputs.

Inputs/Outputs	Units/Ton Lignosulfonate (60% MC)	Inventory Value
Inputs		
Isobutanol	Tons	2.65
Steam	Klb	1.08
Electricity	Mwh	.812
Hydrogen	Tons	.023
Water	Tons	.065
Outputs		
Paraxylene	Tons	1

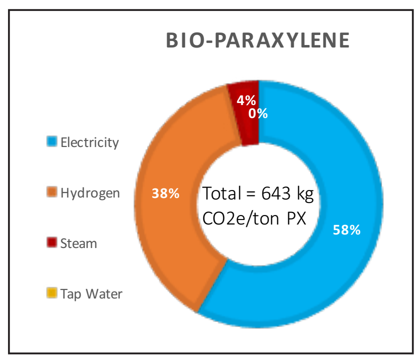

Figure BCP-2.3. Bio-paraxylene total greenhouse gas emissions and impact driver assessment. Isobutanol production emissions are excluded but could be combined with IBA emissions if an allocation approach is undertaken. However, because bio-paraxylene displaces conventional paraxylene, it is appropriate to maintain IBA and upstream production emissions with the main biofuel stream and attributing a displacement credit/debit to the main biofuel based on relative performance of bio-paraxylene compared to conventional paraxylene.

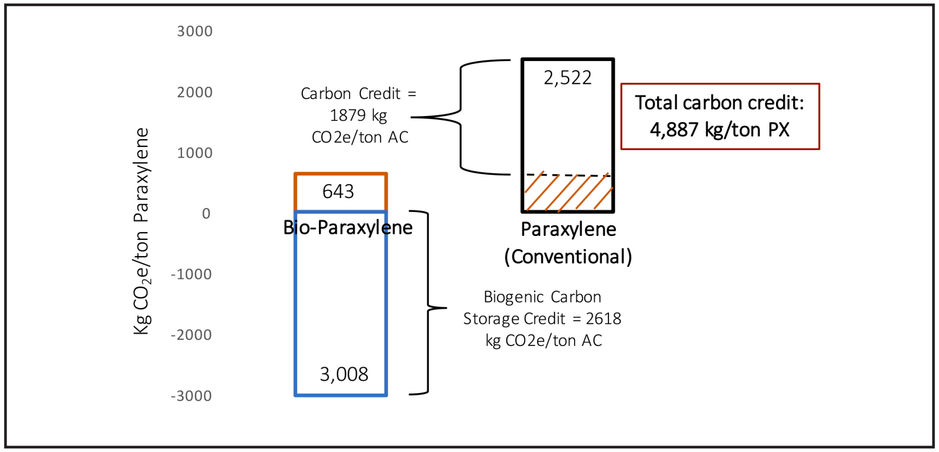

Figure BCP-2.4. NARA Paraxylene GHG emission comparison with conventional paraxylene emissions. NARA PX displaces petroleum-based PX, resulting in a carbon equivalent credit (reduction) of 4,887 kg/ton PX produced attributed to IPK (i.e. 643-2522 -3008 = -4887 kg/ton PX produced)

Lignosulfonate Cement Dispersant

Tables BCP-2.4 and 2.5 show the calculated material and energy inputs and outputs of lignosulfonate cement dispersant production, which involves sending the spent sulfite liquor (SSL) stillage through a series of drying processes. Vapor recompression evaporation dries the lignosulfonate to approximately 60% moisture content. The LS can then either be sold directly or dried further prior to sale to approximately 7% moisture through spray drying. Inputs were estimated through literature, process-flow diagrams, and hydro-thermal relationships.

Figure BCP- 2.5 and 2.6 results show drying impacts for cement dispersant production are approximately 135 kg CO_2e and 699 kg CO_2e per ton of 60% MC and 7% MC lignosulfonate produced, respectively. Upstream emissions from pretreatment and fermentation can be additionally included based on the previously mentioned mass allocation factors, thus further reducing impacts of biofuel. Impacts of vapor recompression evaporation are driven by electricity inputs, whereas impacts of spray drying are driven by natural gas inputs and the upstream impacts of vapor recompression evaporation.

Table BCP-2.4. Vapor recompression evaporation material and energy inputs and outputs.

Inputs/Outputs	Units/Ton Lignosulfonate (60% MC)	Inventory Value
Inputs		
SSL Stillage	Tons	3.62
Steam	Klb	111.14
Electricity	Mwh	.19
Calcium Hydroxide	Tons	.013
Outputs		
Lignosulfonate (60% MC)	Tons	1
Wastewater	Tons	3.06
Solid Waste	Tons	3.04e-5

Table BCP-2.5. Spray drying material and energy inputs and outputs.

Inputs/Outputs	Units/Ton Lignosulfonate (7% MC)	Inventory Value
Inputs		
Lignosulfonate (60% MC)	Tons	2.25
Natural Gas	M3	159.83
Electricity	Mwh	.019
Compressed air	M3	.0078
Outputs		
Lignosulfonate (7% MC)	Tons	1
Wastewater	Tons	1.25
Solid Waste	Tons	1.44e-5

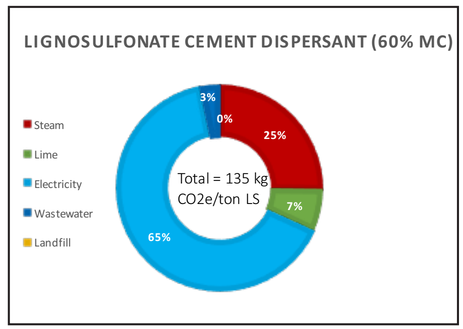

Figure BCP-2.5. Total GHG emissions of lignosulfonate cement dispersant at 60% MC and impact driver assessment. Includes emissions from vapor recompression evaporation drying process. Currently includes zero upstream emissions for SSL stillage inputs, but can be combined with mass allocation of pretreatment and fermentation emissions.

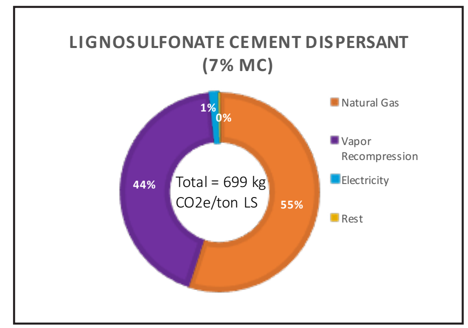

Figure BCP-2.6. Total GHG emissions of lignosulfonate cement dispersant at 7% moisture content, and impact driver assessment. Includes emissions from spray drying inputs and upstream vapor recompression evaporation processes. Currently includes zero upstream emissions for SSL stillage inputs, but can be combined with mass allocation of pretreatment and fermentation emissions.

TASK 3: CASE STUDY: A COMPARATIVE ASSESSMENT OF FOREST RESIDUE BIO-PET

Objective

A case study examining the utilization of bio-paraxylene in the production of Bio-PET bottles was undertaken to assess the relative benefits and environmental preferability of NARA paraxylene compared to other Bio-PET feedstock compositions. As such, a comparative life cycle assessment of 12 PET production scenarios is provided to explore the system-wide advantages or limitations of fully bio-based PET bottle production scenarios over partially bio-based and fossil-derived PET bottles.

Methods and Results

Given that upstream processes (feedstock extraction, component production and product manufacturing) of PET bottle life cycles are what primarily differentiates bio-based PET from fossil PET, a cradle-to-factory-gate approach was applied. The consumer use phase and the end-of-life phase (disposal or recycling) are excluded from the analysis, given the complexity of possible options available to adequately handle bioplastics in the current waste streams and that consumer use impacts will be identical between scenarios; however, end-of-life impacts are worth further exploration in future work. Figure BCP- 3.1 illustrates the process flow diagrams for producing fully bio-based PET bottles, which represents the system boundary of the study. Scenarios of fossil-based and bio-based PET Bottles are shown in Table BCP-3.1.

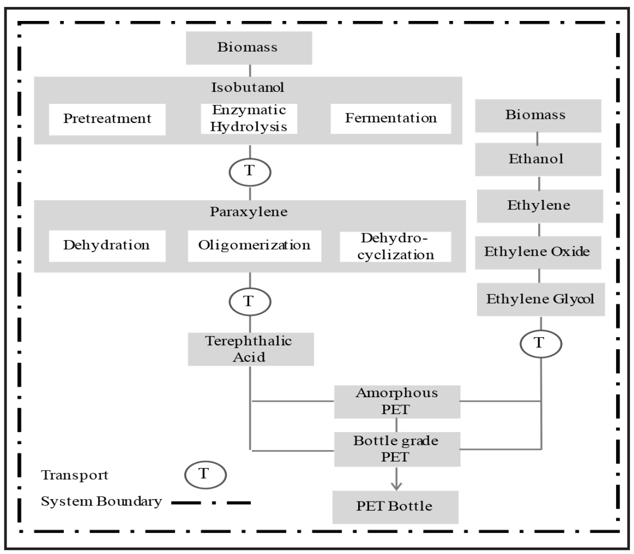

Figure BCP-3.1. Cradle-to-Gate system boundary for 100% bio-based PET bottles. Grey boxes represent the product output flow of each intermediate production process. White boxes indicate the more detailed account of the novel wood-based IBA and paraxylene production processes and life cycle inventories that are a primary focus in this study.

For the functional unit (FU), the environmental impact per 1 kg of PET bottles was investigated. This equals the weight of approximately 100 bottles with 0.5-liter capacity, and is kept consistent for all compared scenarios in order to yield meaningful comparative results.

Life cycle models were developed in the thinkstep GaBi software, and Ecoinvent was the primary database applied in this study, with supplementary information retrieved from literature, PlasticsEurope database, and the U.S. Life Cycle Inventory database. Datasets established on a European industry background were altered to fit the context of the U.S. industry.

Table BCP-3.1. Scenarios of Fossil-based and Bio-based PET Bottles

Scenario	Feedstock of PTA	Feedstock of EG	% of Biomass	Scenario	Feedstock of PTA	Feedstock of EG	% of Biomass
1[a]	Fossil	Fossil	0	7	Wood	Switchgrass	100
2	Fossil	Corn	30	8	Wood	Wheat Straw	100
3	Fossil	Switchgrass	30	9	Corn Stover	Fossil	70
4	Fossil	Wheat Straw	30	10	Corn Stover	Corn	100
5	Wood	Fossil	70	11	Corn Stover	Switchgrass	100
6	Wood	Corn	100	12	Corn Stover	Wheat Straw	100

The comparative LCIA results are illustrated in Figure BCP-3.2. Solid color bars refer to impacts without including displacement credits, indicating that in almost all categories, bio-PET bottles (both partial and fully bio-based ones) have worse performance than their 100% fossil-based counterparts. However, if avoided impacts are counted (depicted as impact offsets by the hashed sections on bars), bottles made from woody biomass purified terephthalic acid (PTA) show significant advantage over fossil PTA and corn stover PTA bottles. Figure BCP-3.3 gives a more detailed profile of impacts from each unit process along the 12-scenario life cycles, with no avoided impacts included. Each bar refers to the impacts generated from producing PTA and ethylene glycol (EG) for each scenario and does not include PET bottle manufacturing processes because these processes are identical throughout all scenarios (esterification/polymerization, solid state poly-condensation, and injection stretch blow molding). Each color block indicates the impacts derived from a specific unit process; for example, block 'PX' shows emissions from upgrading IBA to PX.

Climate change impacts (Global Warming Potentials, GWPs) of forest residue-derived bottles is about 4.14 to 4.92 kg CO_2-equivalent per kg PET bottles. This results in 27% lower CO_2-eq than those produced from corn stover PTA bottles (~5.49 to 6.48 kg CO_2-eq/kg PET bottles) and 21% lower than those from fossil PTA bottles (~4.74 to 6.36 kg CO_2-eq/kg PET bottles) on average. Regarding the fossil fuel consumption category, bio-PET bottles intuitively consume less fossil energy than fossil PET bottles (Figure BCP-3.2b). Producing wood PTA bottles with displacement credits (~8.10 to 10.41 MJ surplus energy/kg PET bottles) required even fewer fossil fuels (22% and 9% lower than the fossil PTA and corn stover PTA groups, respectively). The corn stover PTA group has the greatest acidification impact, followed by wood and fossil PTA groups (Figure BCP-3.2c). Avoiding slash pile burning results in approximately 0.014 kg SO_2 equivalent/kg bottles of impact offsets for forest residue PTA bottles but still results in 27% higher acidification impact than their fossil-based counterpart. For eutrophication impacts on terrestrial ecosystems, wood PTA bottles have a similar performance to fossil PTA bottles. The corn stover PTA group, however, generated significantly higher eutrophying emissions, equaling approximately 5 times the eutrophying impacts of those driven by fossil and wood PTA groups on average. Human Health Particulate emissions are interpreted in kg PM2.5 equivalent per kg PET bottles, shown in Figure BCP-3.2e. On average, forest residue PTA bottles with displacement credits have the lowest impacts (~ -0.043 to -0.041 kg PM2.5-eq/kg PET bottles), but were comparable to other scenarios without avoided impacts incorporated (~ 0.0037 to 0.0059 kg PM2.5-eq/kg PET bottles). The majority of eco-toxicity potential impacts are due to bio-EGs and bio-PTAs. With regard to smog effects, compared to corn stover and fossil counterparts, bio-PTA bottles have higher emissions than fossil PTA bottles. Similarly, just as with eco-toxicity and human health particulates, smog impacts increased greatly with the extraction of agricultural feedstocks due to the fuel combustion from operating agricultural machinery (for tillage, grinding, drying and bailing).

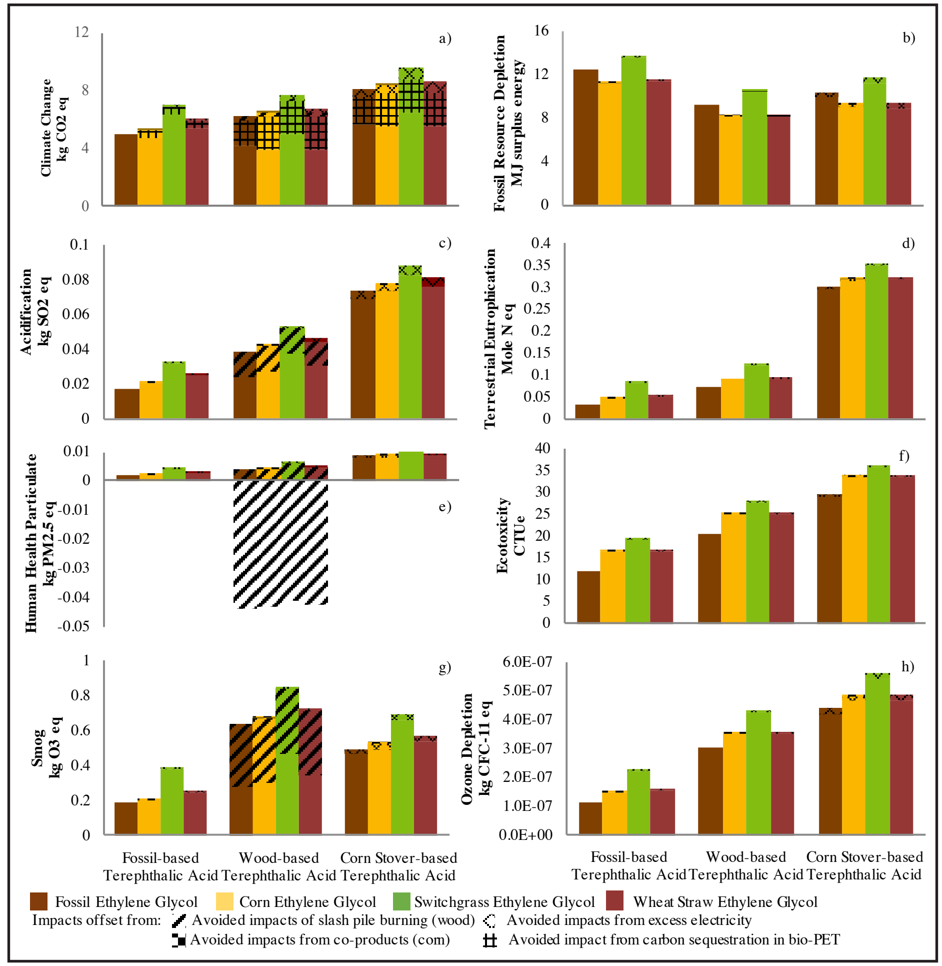

Figure BCP-3.2. Life Cycle Impact Assessment results for 12 PET bottle production scenarios (per kg PET bottles).

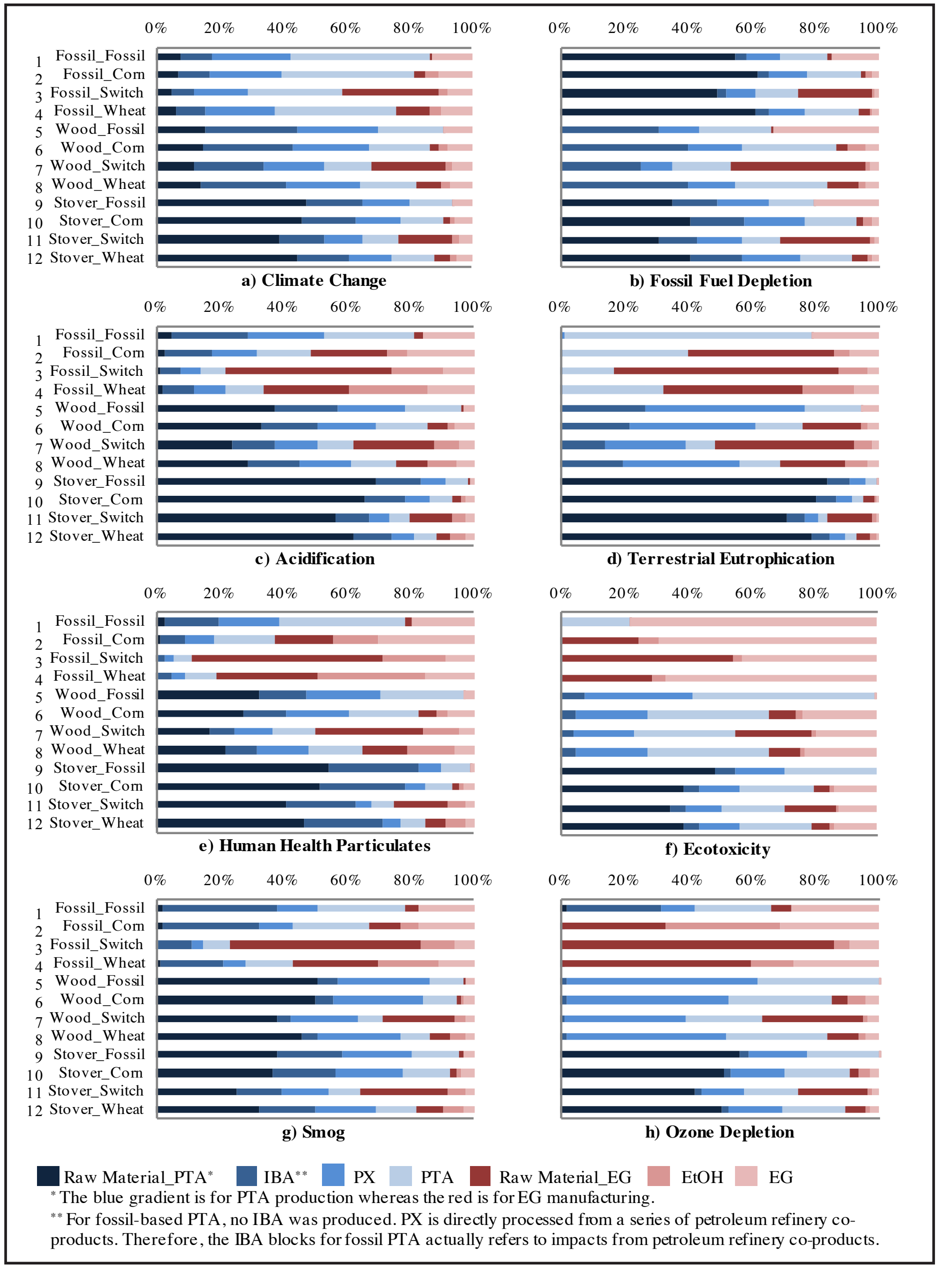

Figure BCP-3.3. Unit process impacts for 12 different PET bottle production scenarios.

TASK 4: ECONOMIC AND ENVIRONMENTAL CO-PRODUCT OPTIMIZATION

Objective

Co-products play a particularly critical role for generating revenues in biorefineries, paralleling the importance in the generation of profit for petroleum refineries. Several studies have demonstrated the economic benefits associated with flexible polygeneration production systems, allowing production managers to hedge market risks by diversifying product outputs. Consequently, biorefinery product portfolios may change from year to year as production managers adapt to changing market conditions to achieve better economic performance. In doing so, however, the environmental impacts of the regulated biofuel products can also change in significant and highly variable ways. The objective was therefore to assess how changes in market conditions can affect the economic performance of biorefineries and the environmental performance of biofuel and bio-product outputs. This task was formally named EPP-1.7 under assigned tasks for the NARA EPP team.

Method

To assess the potential scope of variability in environmental performance, additional co-product outputs and substitutable inputs are examined as part of the portfolio choice set. Figure BCP-4.1 shows the possible production outputs examined, including IPK, ethanol from SSL, activated carbon, isobutanol, paraxylene, two varieties of cement dispersant, fly ash cement filler, char, and process energy, and the method for which impacts are allocated. A linear programming optimization model was built in the GAMS software utilizing the CPLEX solver to assess optimal production outputs under varying market conditions, with the objective of maximizing gross profits (i.e. revenues – operating expenses).

Table BCP-4.1 shows a tableau of the parameters used in the model, namely, the production activity and input requirements for alternative production processes, as determined through Aspen plus process-flow diagrams, literature, and industry/academic collaborations, baseline costs/prices, and production constraints. A well-to-wheels LCA is conducted on the optimal production output scenarios, utilizing appropriate impact assessment and allocation methods to assess RFS policy compliance under different market conditions.

In addition to the current RFS policy, this study considers an equivalent future policy requirement for other bio-based products to also comply with GHG reduction targets, which may be on the horizon for the U.S. BioPreferred program. Such a policy would affect the choice of allocation methods, thus having potentially significant effects on environmental performance and RFS policy compliance.

Market Scenario Characterization

Market price and cost information for co-product outputs and inputs signal to operations managers what to produce and in what quantities. The modeled baseline price/cost estimates are based on public, proprietary and personal communication sources, and are grounded in at least some historical basis for characterizing price variability. Baseline prices for each biofuel co-product (i.e. IPK, bio-gasoline and ethanol) are based on the average spot prices for their respective fossil fuel counterparts (assuming price competitiveness) and the average cellulosic RIN prices, to reflect the total expected value and market signal to produce each of the biofuel outputs. Bio-paraxylene price is determined based on conventional prices scaled by a price premium of approximately 17.5%, as determined through literature.

To simulate market dynamics and uncertainty in market price conditions, one million market scenarios were generated through randomly selecting price combinations from a set of discrete market prices/costs possibilities for each set of outputs and inputs (see Tables BCP-7.2 and 7.3 for details of baseline input and output prices and variability). Because jet fuel, gasoline, and ethanol prices are well correlated, some combinations of prices may not be representative of those likely to be seen in reality, therefore, we constrain the random pricing selection for these fuel outputs based on the computed maximum dollar quantity that individual fuel prices can exceed the prices for the correlated fuel (see Figure BCP-4.2). A review of the litera-ture revealed that the effect of natural gas prices on electricity prices is statistically weak; as such, we do not constrain the electricity pricing scenarios based on natural gas prices. Additionally, although in previous years, the correlation between natural gas and crude oil prices was more strongly correlated, since 2008, the correlation has been very weak, consequently we do not constrain fuel prices based on natural gas prices or vice versa.

To reflect the overall economic signal and incentive to produce biofuel, RIN prices are added to biofuel prices for each market scenario for consideration in the optimization model. Because of the nested nature of the RFS, it is possible for a biofuel that meets the cellulosic biofuel category target of 60% GHG reduction to also satisfy the advanced biofuel volume obligations, requiring only 50% GHG reduction.

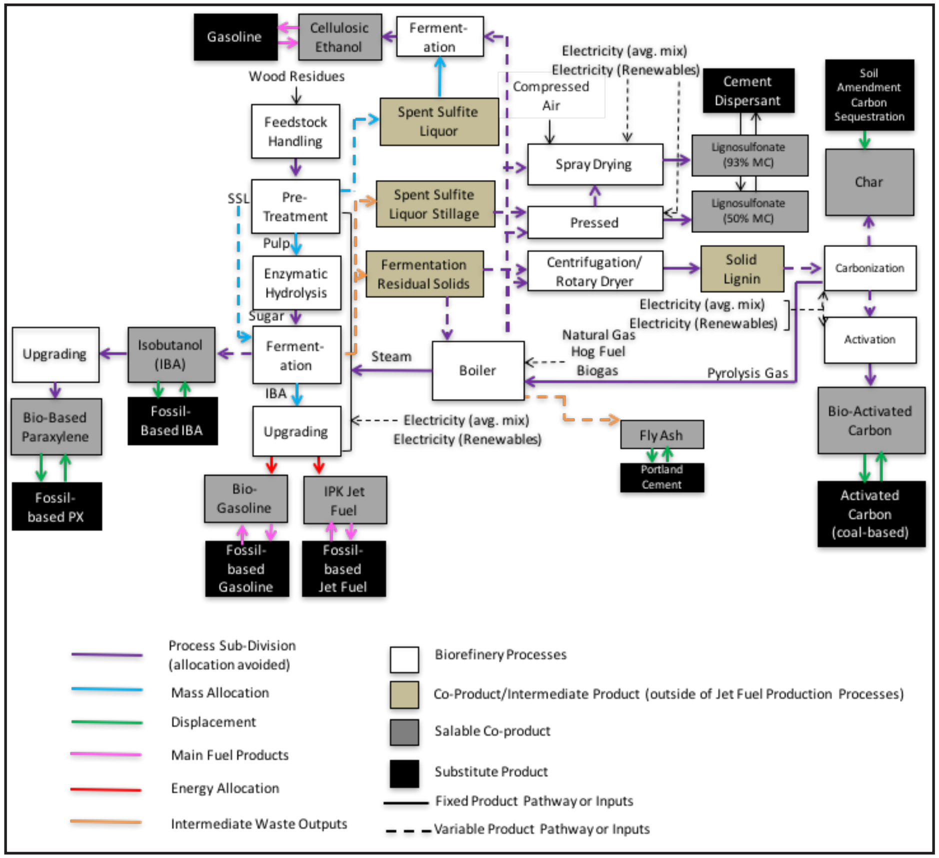

Figure BCP-4.1. Biorefinery Possible Product Portfolio and allocation approach.

Table BCP-4.1. Tableau of optimization model parameters

	Econmic Factors		Output of Direct Sales Activities																				
	Rev - Revenue	C - Cost	IBA	JF	GAS	CH	AC	PX	CD50	CD93	Eth	FA	FHAE	FHGE	PTAE	PTGE	CD50AE	CD50GE	CD93NG	CD93NGGE	CD93BG	CD93BGGE	SSLETHAE
Objective: Maximize Net Revenue	1	-1																					
Products - O																							
SW - sorted wood (tons)													-1.000	-1.000	0.187	0.312							
WR - wood residues (tons)													-0.099	-0.099									
Pp - Pulp (tons)															-0.439	-0.439							
SG - hydrolysate sugar (tons)																							
FRS - fermentation residual solids (tons)																							
SSL - spent sulfite liquor (tons)															-0.561	-0.561							58.973
SSLS - spent sulfite liquor stillage (tons)																	3.624	3.624					
IBA - isobutanol (tons)			1																				
JF - jet fuel (tons)				1																			
GAS - Gasoline					1																		
CH - char (tons)						1																	
AC - Activated Carbon (tons)							1																
PG - Pyrolysis Gas (tons)																							
PX - Paraxylene (tons)								1															
CD50 - cement dispersant 50% MC (tons)									1										2.247	2.247	2.247	2.247	
CD93 - cement dispersant 7% MC (tons)										1									-1.000	-1.000	-1.000	-1.000	
Eth - ethanol (tons)											1												-1.000
Stm - steam (klb)												1			0.237	0.237	1.420	-1.420					11.860
FA - fly ash (tons)																							
WW - wastewater (tons)													-0.297	-0.297	-0.063	-0.063	-2.624	-2.624	-1.247	-1.247	-1.247	-1.247	-54.717
WTL - solid waste to landfill (tons)																	0.000	0.000	0.000	0.000	0.000	0.000	
TW - Treated Wastewater (tons)																							
Inputs - I																							
W - Wood (tons)													1.099	1.099									
NG - Natural Gas (m3)																			159.826	159.826			
HF - Hog Fuel (tons)																							
BG - Biogas (m3)																					337.411	337.411	
CA- Compressed air (m3)																			0.008	0.008	0.008	0.008	
H2 - Hydrogen (tons)																							
AVE - Average Electricity (MWh)													0.035		0.003		0.191		0.019		0.019		0.000
GRE - Green Electricity (MWh)														0.035		0.003		0.191		0.019		0.019	
Price and Cost Scenarios - PSA																							
S1*S1,000,000			1	1	1	1	1	1	1	1	1	1											
Economic Performance Measures			**Dollars per unit of Direct Sales**																				
Rev - Revenue	1		-1341.5	-1264	-1416	-2486	-2623	-1603	-142.5	-650	-1119	-24											
C - Cost		1											0.100	0.100	1.400	1.400	1.290	1.290					543.400
Minimum production runs																							
Run1*Run15				1																			
Jet Fuel Minimum Production Constraints (contracts)																							
Run1																							
Run15																							
Other Constraints on Production																							
TotIBA - IBA max production (tons)			1																				
TotCH - Char maximium production (tons)						1																	
Lower Bound	∞	∞	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Upper Bound	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞

Table BCP-4.1. Tableau of optimization model parameters *(continued)*

	SSLETHGE	HydAE	HydGE	FAEwSSL	FGEwSSL	FAEwoSSL	FGEwoSSL	UpAE	UpGE	UpAEG	UpGEG	CarbAENG	CarbAEBG	CarbGENG	CarbGEBG	ActAENG	ActAEBG	ActGENG	ActGEBG	PXPAE
Objective: Maximize Net Revenue																				
Products - O																				**Intermediate Product C**
SW - sorted wood (tons)																				
WR - wood residues (tons)																				
Pp - Pulp (tons)		0.470	0.470																	
SG - hydrolysate sugar (tons)		-1.000	-1.000	0.555	0.555	0.872	0.872													
FRS - fermentation residual solids (tons)				-0.615	-0.615	-0.966	-0.966					35.690	35.690	35.690	35.690					
SSL - spent sulfite liquor (tons)	58.973			0.377	0.377															
SSLS - spent sulfite liquor stillage (tons)				-0.360	-0.360															
IBA - isobutanol (tons)				-0.026	-0.026	-0.034	-0.034	1.501	1.501	1.501	1.501									2.646
JF - jet fuel (tons)								-1.000	-1.000	-0.500	-0.500									
GAS - Gasoline										-0.500	-0.500									
CH - char (tons)												-1.000	-1.000	-1.000	-1.000	1.818	1.818	1.818	1.818	
AC - Activated Carbon (tons)																-1.000	-1.000	-1.000	-1.000	
PG - Pyrolysis Gas (tons)												-1.309	-1.309	-1.309	-1.309					
PX - Paraxylene (tons)																				
CD50 - cement dispersant 50% MC (tons)																				
CD93 - cement dispersant 7% MC (tons)																				
Eth - ethanol (tons)	-1.000																			
Stm - steam (klb)	11.860	0.002	0.002	0.191	0.191	0.358	0.358	0.614	0.614	0.553	0.553	2.510	2.510	2.510	2.510	0.419	0.419	0.419	0.419	1.082
FA - fly ash (tons)																				
WW - wastewater (tons)	-54.717			-0.309	-0.309	-0.486	-0.486	-0.587	-0.587	-0.587	-0.587	-30.627	-30.627	-30.627	-30.627					
WTL - solid waste to landfill (tons)		-0.009	-0.009																	
TW - Treated Wastewater (tons)																				
Inputs - I																				**Input Requ**
W - Wood (tons)																				
NG - Natural Gas (m3)												59.555		59.555		108.281		108.281		
HF - Hog Fuel (tons)																				
BG - Biogas (m3)													100.581		100.581		182.875		182.875	
CA- Compressed air (m3)																				
H2 - Hydrogen (tons)								0.014	0.014	0.014	0.014									0.023
AVE - Average Electricity (MWh)		0.000		0.025		0.041		0.010		0.137		0.008	0.008			0.003	0.003			0.268
GRE - Green Electricity (MWh)	0.000		0.000		0.025		0.041		0.010		0.137			0.008	0.008			0.003	0.003	
Price and Cost Scenarios - PSA																				
S1*S1,000,000																				
Economic Performance Measures																				**Costs (dollars) per output of processing act**
Rev - Revenue																				
C - Cost	543.400	3.700	3.700	109.450	109.450	114.760	114.760	1.290	1.290	1.290	1.290	-103.700	-103.700	-103.700	-103.700	143.700	143.700	143.700	143.700	
Minimum production runs																				
Run1*Run15																				
Jet Fuel Minimum Production Constraints (contracts)																				
Run1																				
Run15																				
Other Constraints on Production																				
TotIBA - IBA max production (tons)																				
TotCH - Char maximium production (tons)																				
Lower Bound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Upper Bound	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞

Table BCP-4.1. Tableau of optimization model parameters *(continued)*

	Production Processing Acivities																		
	PXPGE	BPGAE	BPGGE	BFRSAAE1	BFRSAAE2	BFRSAGE1	BFRSAGE2	BFRSLAE1	BFRSLAE2	BFRSLGE1	BFRSLGE2	BNGAE	BNGGE	BHFAAE1	BHFAAE2	BHFAGE1	BHFAGE2	BHFLAE1	BHFLAE2
Objective: Maximize Net Revenue																			
Products - O	**Output Requirements per Unit of Processing Activity**																		
SW - sorted wood (tons)																			
WR - wood residues (tons)																			
Pp - Pulp (tons)																			
SG - hydrolysate sugar (tons)																			
FRS - fermentation residual solids (tons)				0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067								
SSL - spent sulfite liquor (tons)																			
SSLS - spent sulfite liquor stillage (tons)																			
IBA - isobutanol (tons)	2.646																		
JF - jet fuel (tons)																			
GAS - Gasoline																			
CH - char (tons)																			
AC - Activated Carbon (tons)																			
PG - Pyrolysis Gas (tons)		0.241	0.241																
PX - Paraxylene (tons)																			
CD50 - cement dispersant 50% MC (tons)																			
CD93 - cement dispersant 7% MC (tons)																			
Eth - ethanol (tons)																			
Stm - steam (klb)	1.082	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000
FA - fly ash (tons)				-0.002	-0.002	-0.002	-0.002							-0.008	-0.008	-0.008	-0.008		
WW - wastewater (tons)				-0.046	-0.046	-0.046	-0.046	-0.046	-0.046	-0.046	-0.046	-0.046	-0.046	-0.046	-0.046	-0.046	-0.046	-0.046	-0.046
WTL - solid waste to landfill (tons)								-0.002	-0.002	-0.002	-0.002							-0.008	-0.008
TW - Treated Wastewater (tons)																			
Inputs - I	**uirements per Unit of Processing Activity Output**																		
W - Wood (tons)																			
NG - Natural Gas (m3)				0.159		0.159		0.159		0.159		34.700	34.700	0.159		0.159		0.159	
HF - Hog Fuel (tons)														0.116	0.116	0.116	0.116	0.116	0.116
BG - Biogas (m3)					0.335		0.335		0.335		0.335				0.335		0.335		0.335
CA- Compressed air (m3)																			
H2 - Hydrogen (tons)	0.023																		
AVE - Average Electricity (MWh)		0.007		0.006	0.006			0.006	0.006			0.007		0.006	0.006			0.006	0.006
GRE - Green Electricity (MWh)	0.268		0.007			0.006	0.006			0.006	0.006		0.007			0.006	0.006		
Price and Cost Scenarios - PSA																			
S1*S1,000,000																			
Economic Performance Measures	**tivity (includes all costs associated with inputs not included as part of choice set)**																		
Rev - Revenue																			
C - Cost		0.936	0.936	180.190	180.190	180.190	180.190	180.190	180.190	180.190	180.190	0.936	0.936	180.190	180.190	180.190	180.190	180.190	180.190
Minimum production runs																			
Run1*Run15																			
Jet Fuel Minimum Production Constraints (contracts)																			
Run1																			
Run15																			
Other Constraints on Production																			
TotIBA - IBA max production (tons)																			
TotCH - Char maximium production (tons)																			
Lower Bound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Upper Bound	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞

Table BCP-4.1. Tableau of optimization model parameters *(continued)*

															Direct In			
	BHFLGE1	BHFLGE2	BWRAAE1	BWRAAE2	BWRLAE1	BWRLAE2	BWRAGE1	BWRAGE2	BWRLGE1	BWRLGE2	BBGAE	BBGGE	WWT	LF	W (tons)	NG (m3)	HF (tons)	BG (m3)
Objective: Maximize Net Revenue																		
Products - O																		
SW - sorted wood (tons)																		
WR - wood residues (tons)			0.116	0.116	0.116	0.116	0.116	0.116	0.116	0.116								
Pp - Pulp (tons)																		
SG - hydrolysate sugar (tons)																		
FRS - fermentation residual solids (tons)																		
SSL - spent sulfite liquor (tons)																		
SSLS - spent sulfite liquor stillage (tons)																		
IBA - isobutanol (tons)																		
JF - jet fuel (tons)																		
GAS - Gasoline																		
CH - char (tons)																		
AC - Activated Carbon (tons)																		
PG - Pyrolysis Gas (tons)																		
PX - Paraxylene (tons)																		
CD50 - cement dispersant 50% MC (tons)																		
CD93 - cement dispersant 7% MC (tons)																		
Eth - ethanol (tons)																		
Stm - steam (klb)	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000						
FA - fly ash (tons)			-0.002	-0.002			-0.002	-0.002										
WW - wastewater (tons)	-0.046	-0.046	-0.046	-0.046	-0.046	-0.046	-0.046	-0.046	-0.046	-0.046	-0.046	-0.046	1.010					
WTL - solid waste to landfill (tons)	-0.008	-0.008			-0.002	-0.002			-0.002	-0.002			-0.010	1.000				
TW - Treated Wastewater (tons)													-1.000					
Inputs - I																		
W - Wood (tons)															-1			
NG - Natural Gas (m3)	0.159		0.159		0.159		0.159		0.159							-1		
HF - Hog Fuel (tons)	0.116	0.116															-1	
BG - Biogas (m3)		0.335		0.335		0.335		0.335		0.335	58.700	58.700						-1
CA- Compressed air (m3)																		
H2 - Hydrogen (tons)																		
AVE - Average Electricity (MWh)			0.006	0.006	0.006	0.006					0.007		0.010					
GRE - Green Electricity (MWh)	0.006	0.006					0.006	0.006	0.006	0.006		0.007						
Price and Cost Scenarios - PSA																		
S1*S1,000,000															1	1	1	1
Economic Performance Measures																	**Baseline Input Costs per**	
Rev - Revenue																		
C - Cost	180.190	180.190	180.190	180.190	180.190	180.190	180.190	180.190	180.190	180.190	0.936	0.936	0.064	47.000	-67.05	-0.155	-45	-0.512
Minimum production runs																		
Run1*Run15																		
Jet Fuel Minimum Production Constraints (contracts)																		
Run1																		
Run15																		
Other Constraints on Production																		
TotIBA - IBA max production (tons)																		
TotCH - Char maximium production (tons)																		
Lower Bound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Upper Bound	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	845000	∞	∞	∞

Table BCP-4.1. Tableau of optimization model parameters *(continued)*

	put Purchases				
	CA (m3)	H2 (tons)	AVE (MWh)	GRE (MWh)	RHS
Objective: Maximize Net Revenue					
Products - O					
SW - sorted wood (tons)					0
WR - wood residues (tons)					0
Pp - Pulp (tons)					0
SG - hydrolysate sugar (tons)					0
FRS - fermentation residual solids (tons)					0
SSL - spent sulfite liquor (tons)					0
SSLS - spent sulfite liquor stillage (tons)					0
IBA - isobutanol (tons)					0
JF - jet fuel (tons)					0
GAS - Gasoline					0
CH - char (tons)					0
AC - Activated Carbon (tons)					0
PG - Pyrolysis Gas (tons)					0
PX - Paraxylene (tons)					0
CD50 - cement dispersant 50% MC (tons)					0
CD93 - cement dispersant 7% MC (tons)					0
Eth - ethanol (tons)					0
Stm - steam (klb)					0
FA - fly ash (tons)					0
WW - wastewater (tons)					0
WTL - solid waste to landfill (tons)					0
TW - Treated Wastewater (tons)					0
Inputs - I					
W - Wood (tons)					0
NG - Natural Gas (m3)					0
HF - Hog Fuel (tons)					0
BG - Biogas (m3)					0
CA- Compressed air (m3)	-1				0
H2 - Hydrogen (tons)		-1			0
AVE - Average Electricity (MWh)			-1		0
GRE - Green Electricity (MWh)				-1	0
Price and Cost Scenarios - PSA					
S1*S1,000,000	1	1	1		0
Economic Performance Measures	**· unit of direct input purchases**				
Rev - Revenue					0
C - Cost	-4.51E-05	-3840.11	-90	-103	0
Minimum production runs					
Run1*Run15					0
Jet Fuel Minimum Production Constraints (contracts)					
Run1					0
Run15					118000
Other Constraints on Production					
TotIBA - IBA max production (tons)					148532.5
TotCH - Char maximium production (tons)					827
Lower Bound	0	0	0	0	
Upper Bound	∞	∞	∞	∞	

As such, biofuel prices are combined with the greater of the two RIN prices randomly selected (advanced or cellulosic) in each market scenario to yield total expected biofuel prices for each market scenario.

Tableau Notation

- FHAE = Feedstock handling using average electricity for PNW
- FHGE = Feedstock handling using green electricity for PNW
- PTAE = Pretreatment using average electricity for PNW
- PTGE = Pretreatment using green electricity for PNW
- CD50AE = Vapor recompression evaporation using average electricity for PNW, for cement dispersant at 60% MC
- CD50GE = Vapor recompression evaporation using green electricity for PNW, for cement dispersant at 60% MC
- CD93NG = Spray drying using average electricity for PNW and natural gas, for cement dispersant at 7% MC
- CD93NGGE = Spray drying using green electricity for PNW and natural gas, for cement dispersant at 7% MC
- CD93BG = Spray drying using average electricity for PNW and biogas, for cement dispersant at 7% MC
- CD93BGGE = Spray drying using green electricity for PNW and biogas, for cement dispersant at 7% MC
- SSLETHAE = Ethanol fermentation using SSL and average electricity for PNW
- SSLETHGE = Ethanol fermentation using SSL and green electricity for PNW
- HydAE = Enzymatic hydrolysis using average electricity for PNW
- HydGE = Enzymatic hydrolysis using green electricity for PNW
- FAEwSSL = Isobutanol fermentation using SSL, Pulp and average electricity for PNW
- FGEwSSL = Isobutanol fermentation using SSL, Pulp and green electricity for PNW
- FAEwoSSL = Isobutanol fermentation using Pulp and average electricity for PNW but without SSL
- FGEwoSSL = Isobutanol fermentation using Pulp and green electricity for PNW but without SSL
- UpAE = Upgrading isobutanol to iso-paraffinic kerosene using average electricity for PNW
- UpGE = Upgrading isobutanol to iso-paraffinic kerosene using green electricity for PNW
- UpAEG = Upgrading isobutanol to iso-paraffinic kerosene and bio-gasoline using average electricity for PNW
- UpGEG = Upgrading isobutanol to iso-paraffinic kerosene and bio-gasoline using green electricity for PNW
- CarbAENG = Carbonization of FRS using average electricity for PNW and natural gas
- CarbAEBG = Carbonization of FRS using average electricity for PNW and

biogas

- CarbGENG = Carbonization of FRS using green electricity for PNW and natural gas
- CarbGEBG = Carbonization of FRS using green electricity for PNW and biogas
- ActAENG = Activation of char using average electricity for PNW and natural gas
- ActAEBG = Activation of char using average electricity for PNW and biogas
- ActGENG = Activation of char using green electricity for PNW and natural gas
- ActGEBG = Activation of char using green electricity for PNW and biogas
- PXPAE = Upgrading isobutanol to paraxylene using average electricity for PNW
- PXPGE = Upgrading isobutanol to paraxylene using green electricity for PNW
- BPGAE = Boiler using pyrolysis gas and average electricity for PNW to produce steam
- BPGGE = Boiler using pyrolysis gas and green electricity for PNW to produce steam
- BFRSAAE1 = Boiler using FRS, producing fly ash for sale using average electricity for PNW and natural gas to produce steam
- BFRSAAE2 = Boiler using FRS, producing fly ash for sale using average electricity for PNW and biogas to produce steam
- BFRSAGE1 = Boiler using FRS, producing fly ash for sale using green electricity for PNW and natural gas to produce steam
- BFRSAGE2 = Boiler using FRS, producing fly ash for sale using green electricity for PNW and biogas to produce steam
- BFRSLAE1 = Boiler using FRS, producing landfilled fly ash using average electricity for PNW and natural gas to produce steam
- BFRSLAE2 = Boiler using FRS, producing landfilled fly ash using average electricity for PNW and biogas to produce steam

Preliminary Results

Preliminary results suggest that changes in market price conditions can incentivize alternative production scenarios involving different inputs and production outputs, which can in turn change the environmental performance of the biofuels. Changes to maximum production output constraints also can have a significant effect on environmental performance (see Figures BCP-4.3 and 4.4). In some cases, these changes in performance can result in failure to meet the RFS standard. Consequently, production managers must be aware of various production constraints to ensure continued compliance.

Table BCP-4.2. Input baseline costs and potential market variability. Dynamic market scenarios are created through random selection and combination of discreet costs and prices within the indicated ranges.

Input Choice Set	Baseline Average Price | Year	Price Range	% variation off baseline	Source
Wood (forest residue)	$67/ton | 2013	$17 - $89	-75% to +25%	NARA (2013); ORNL (2011)
Natural Gas	$.155/m^3 | 2014	$.046 - $.496	-70% to +220%	EIA (2016)
Hog Fuel	$45/ton | 2016	$11 - $56	-75% to +25%	Spink and Gao (2016)
Biogas	$.512/m^3 | 2014	$.104 - $.922	-80% to +80%	Dodge (2014)
Compressed Air	$4.51e-5/m^3 | 2006	$2.3e-5 - $5.6e-5	-50% to +25%	Ulrich and Vasudevan (2006)
Hydrogen	$3840/ton | 2016	$1,152 - $12,288	-70% to +220%	Spink and Gao (2016)
Electricity (PNW)	$90/Mwh | 2014	$45 - $112	-50% to +25%	EIA (2016)
Green Electricity (PNW)	$103/Mwh | 2014	$41 -$129	-60% to +25%	EPA (2016)

Table BCP-4.3. Output baseline prices and potential market variability. Dynamic market scenarios are created through random selection and combination of discreet prices and costs within the indicated ranges. Sources are listed in the reference section of this report.

Co-Product	Baseline Average Price | Year	Price Range	% variation off baseline	Source
IPK	$704/ton | 2014	$70 - $1,056	-90% to +50%	EIA (2015
Bio-gasoline	$796/ton | 2014	$119 - $1,074	-85% to +40%	EIA (2015)
Ethanol	$712/ton | 2014	$249 - $1,139	-65% to +60%	ERS (2015)
Activated Carbon	$2,623/ton | 2013	$2,098 - $3,147	-20% to +20%	Freedonia (2014)
Char	$2,486/ton | 2013	$0 - $13,051	-100% to +425%	Jirka and Tomlinson (2014)
Isobutanol	$1,341/ton | 2015	$939 - $2,280	-30% to +70%	Sapp (2015)
Paraxylene	$1,603/ton | 2014	$962 - $2,164	-40% to +35%	Platts (2014)
Cement Dispersant (60% MC)	$50/ton | 2016	$42.5 -$57.5	-15% to +15%	Spink (2016)
Cement Dispersant (7% MC)	$100/ton | 2016	$70 - $130	-30% to 30%	Spink (2016)
Fly Ash	$24/ton | 2011	$13 - $42	-45% to 75%	TDF (2011)
IPK RIN[1] (Advanced)	$272/ton | 2012-2016 (avg.)	$136 - $394	-50% to +45%	Argus (2013); Opis (2016)
IPK RIN[1] (Cellulosic)	$560/ton | 2015 - 2016 (avg)	$392 - $728	-30 to +30%	Opis (2016)
Bio-gasoline RIN[2] (Advanced)	$302/ton | 2012-2016 (avg.)	$151 - $438	-50% to +45%	Argus (2013); Opis (2016)
Bio-gasoline RIN[2] (Cellulosic)	$622/ton | 2015 - 2016 (avg)	$435 - $809	-30% to +30%	Opis (2016)
Ethanol RIN[3] (Advanced)	$198/ton | 2012-2016 (avg.)	$99 - $287	-50% to +45%	Argus (2013); Opis (2016)
Ethanol RIN[3] (Cellulosic)	$407/ton | 2015 - 2016 (avg)	$285 - $529	-30% to +30%	Opis (2016)

[1] Equivalence value of IPK (# RIN/gal) is 1.6, and density of 2.84 kg/gal.
[2] Equivalence value for gasoline (# RIN/gal) is 1.447, and density of 2.83 kg/gal.
[3] Equivalence value of ethanol (# RIN/gal) is 1, and density of 2.987 kg/gal.

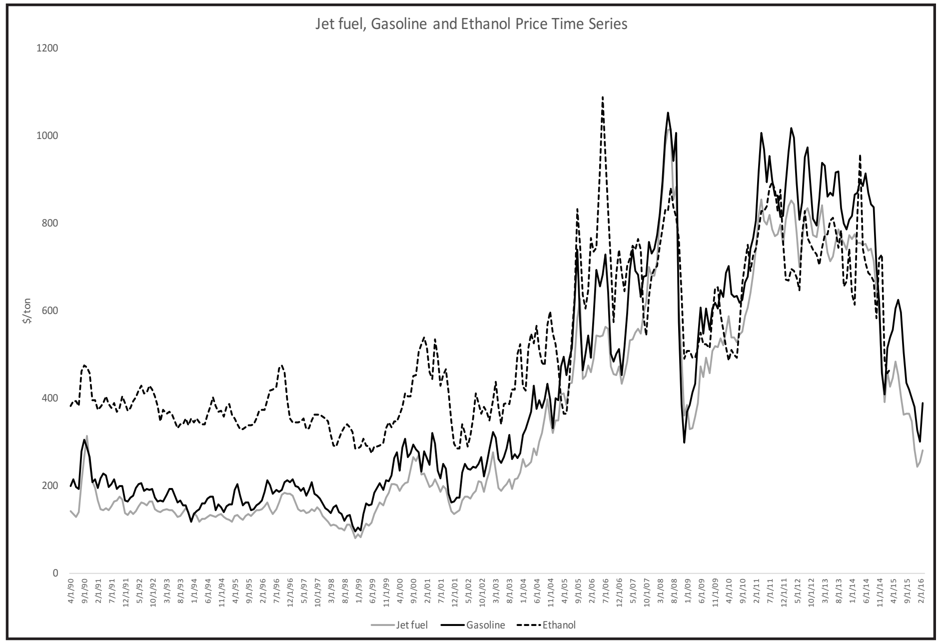

Figure BCP-4.2. Time series of fuel prices for scenario combination. Used to determine the maximum amount of dollars that gasoline prices can exceed jet fuel prices ($149.44), jet fuel prices can exceed gasoline prices ($28.33), gasoline prices can exceed ethanol prices ($186.42), and ethanol prices can exceed gasoline prices ($368.38).

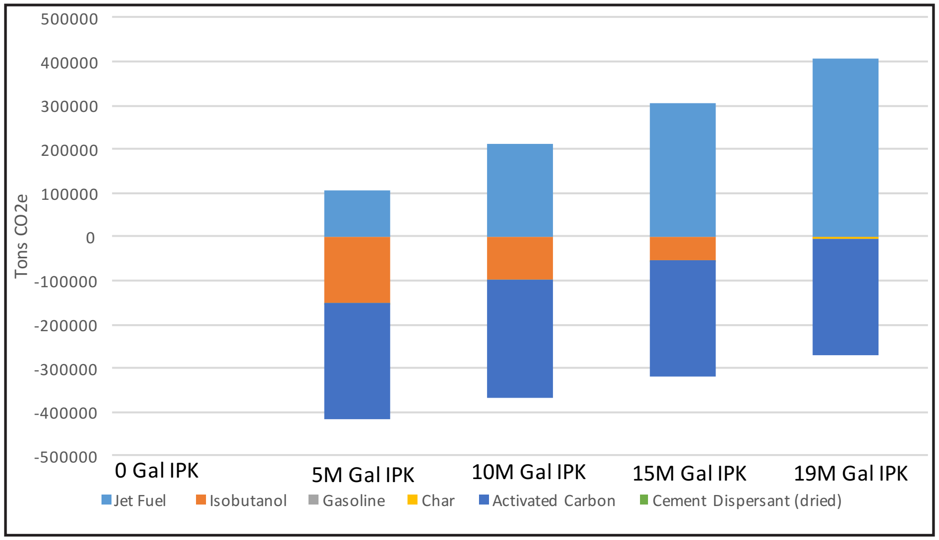

Figure BCP-4.3. Total annual GHG emissions of IPK, incl. co-product displacement credits. Different quantities of minimum jet fuel output constraints result in different quantity and type of co-product GHG displacement credits.

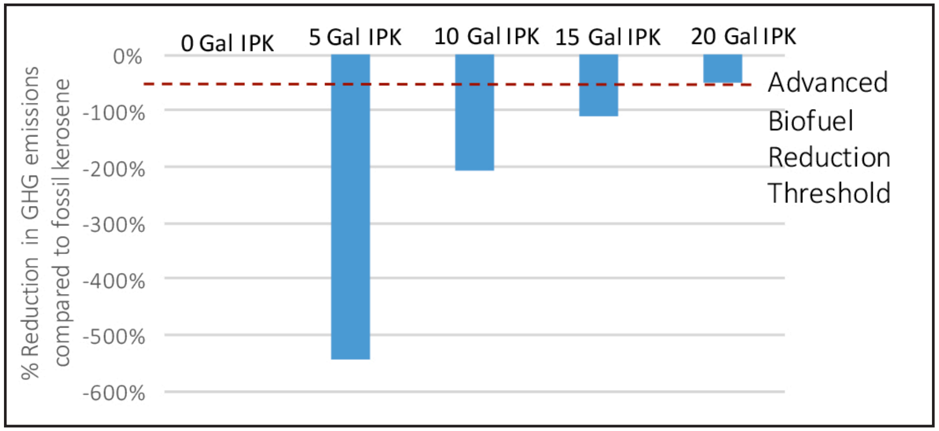

Figure BCP-4.4. IPK percent reduction in GHG emissions compared to fossil kerosene. Different quantities of minimum jet fuel output constraints result in different quantities of co-product outputs, affecting the environmental performance and ability to meet RFS standard GHG reduction thresholds.

NARA OUTPUTS

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NARA OUTCOMES AND FUTURE DEVELOPMENT

The research outlined in Task 1 has clarified the different elements that drive the preference for environmental performance among biofuels and bio-products, which has informed subsequent research pathways, such as the need to delve into methods of allocation to respond to possible future policy environments.

Results of the assessments in Task 2 reveal the significant quantity of co-product credits that can be gained from the production of non-fuel co-products, and the potential implications of alternative allocation methods and assumptions on the overall performance and preferability of biofuel outputs. Results of co-product assessments are used in subsequent optimization analyses and will be integrated with the full biofuel LCA, as calculated by the NARA LCA team, and submitted to the USLCI database, which will be publicly available to inform future research endeavors.

The finalized results of the assessment will provide valuable insights about the optimal operating process configurations for a given set of product prices and input costs, which not only helps production managers determine what to produce, with what inputs, and in what quantities, but also helps shed light on what market developments or policies are required to make certain products attractive to produce. This analysis will also help illuminate policy recommendations regarding methods for allocation under different environmental policy contexts, and the stability of environmental performance under varying market conditions.

Regarding the case study assessment in Task 3, mixed results were found across impact categories when comparing the environmental performances of partially and fully bio-based PET bottles versus fossil-based ones. In most categories, with avoided impact credits considered, forest residues had a better or comparable environmental profile to corn stover when used as feedstock for bio-PET bottles. The conclusion is subject to uncertainty, where variability in avoided burdens could alter the conclusion of environmental rankings for fossil and bio-PET bottles.

Overall, future research should focus on 1) improving the availability and reliability of LCI data; 2) developing more detailed avoided impact/allocation scenarios around co-product output opportunities; 3) optimizing biorefinery processes; 4) determining a sustainable residue collection rate for feedstocks; 5) incorporating economic analyses to deliver a more robust and comprehensive sustainable portfolio of bio-refineries.

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