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Greenhouse Gas Analysis of Biomass-based Ethyl Levulinate for Residential Heating

Summary Report

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LCA Study Commissioners:

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Biofine Developments Northeast Inc.

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1 Introduction

Residential heating in the northeastern United States is an essential need that consumes a non-negligible amount of fossil energy and produces a non-negligible amount of greenhouse gas emissions. Biofine has developed an advanced biofuel derived from lignocellulosic biomass, ethyl levulinate, that has potential application as a low-Carbon heating fuel. This study was conducted by EarthShift Global for the National Oilheat Research Alliance and Biofine Development Northeast. This study and report were prepared according to ISO (2005; 2006) guidelines for a screening level LCA to provide information for discussions with regulators and municipal planners. The study focuses only on Greenhouse Gas emissions (a single impact category), does not involve a comparative assessment and has been conducted for public disclosure, thus has been critically reviewed.

This life cycle Greenhouse gas (GHG) assessment focuses on the average well-to-heat (in this case, at the residential burner tip) emissions associated with the production and use of Biofine's ethyl levulinate (EL) fuel for heat in the northeastern US, specifically Maine and surrounding states. The primary study objectives are to quantify the life cycle GHG impacts for EL. A secondary objective is to evaluate potential impact on GHG emission reductions in both pilot and commercial scale manufacturing facilities from regionally available lignocellulosic residue/waste materials in a regionally relevant context.

2 Goal and Scope

The first phase of an LCA is to define the goal and scope of the study. According to ISO 14044, the goal of the study should clearly specify the following: the intended application; reasons for carrying out the study; the intended audience; and whether the results are intended to be disclosed to the public. The scope of the study describes the most important aspects of the study including: the functional unit; system boundaries; any allocation or cut-off criteria; impact assessment method and modelling information.

2.1 Objective

The primary objective of this study is to evaluate the life cycle Greenhouse gas emissions associated with the production and use of Biofine's ethyl levulinate (EL) bioproduct, from softwood forest residues (FR) or post-consumer waste paper (cardboard and paper, PCW or "Waste Paper"), to deliver heat to the home, including production of feedstock (biomaterial or petroleum), feedstock transportation, fuel production, distribution, and combustion to heat in a residential oil-fired heating system (described here as Well-to-Burner Tip, WTBt).

The secondary objective of this study was to assess the emissions from EL produced at two different scales (100 and 1,000 dry tonnes biomass daily, tbd) and from two different waste/residue feedstocks (forest residues and post-consumer waste paper), and with a variety of north eastern US electric grids, to estimate GHG emission reductions from both pilot and commercial scale manufacturing facilities from regionally available lignocellulosic materials in a regionally relevant context.

The analysis is intended help understand the GHG impacts of the lignocellulosic EL fuel and its potential for reducing overall GHG impacts relative to other options. The results of this study are intended to be used in a discussion document to be shared with regulators and for the public. This work is proposed to be used for public disclosure.

2.2 Function & Functional Unit

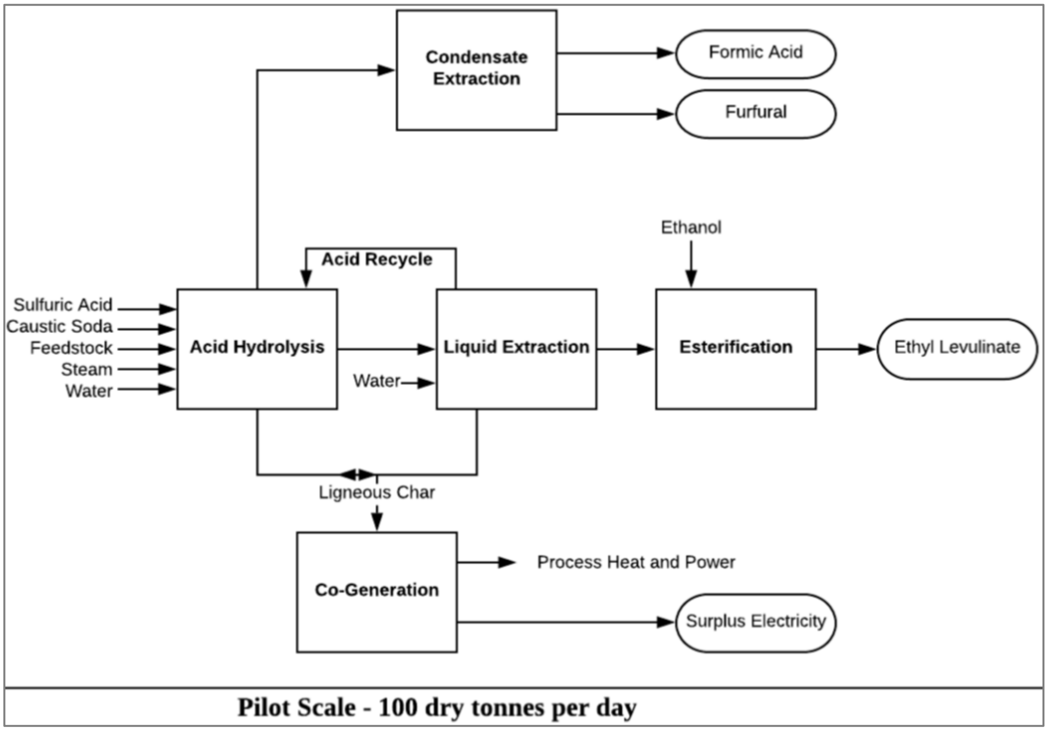
A functional unit identifies the primary “function(s)” of a system based on which alternative systems are considered “functionally equivalent” (ISO, 2006b). A functional unit is defined as the quantified performance of a product system for use as a reference unit (ISO, 2006b). This facilitates the determination of reference flows for the system being studied, which enables the comparison of two or more systems.

The primary function of the system studied (EL) is the provision of residential heat. The functional unit for this study is defined as the delivery of 1 MMBTU of heat at the residential burner tip (post-combustion). The Well-to-Burner tip environmental flows were therefore referenced to this functional unit (per MMBTU of heating fuel used) of comparison.

2.3 System Description & System Boundaries

2.3.1 System Description

Biofine’s ethyl levulinate (EL) fuel is a biobased hydrocarbon produced via acid catalyzed hydrolysis of lignocellulosic biomass and subsequent esterification with ethanol in the proprietary Biofine process (Hayes *et al.*, 2005). The process can use a variety of lignocellulosic materials and produces a high yield of EL, electricity and chemical coproducts (Figure 2-1). The mix and ratio of co-products depends on the facility scale and the feedstock composition. This study considers production of EL from softwood forest residues and post-consumer waste paper, primarily cardboard, in a pilot scale (100 tonnes (dry mass) feedstock daily) and commercial scale (1,000 tonnes (dry mass) feedstock daily) facilities.



Pilot Scale - 100 dry tonnes per day

Figure 2-1: Process flow for EL production from lignocellulosic biomass at scale (100 tpd).

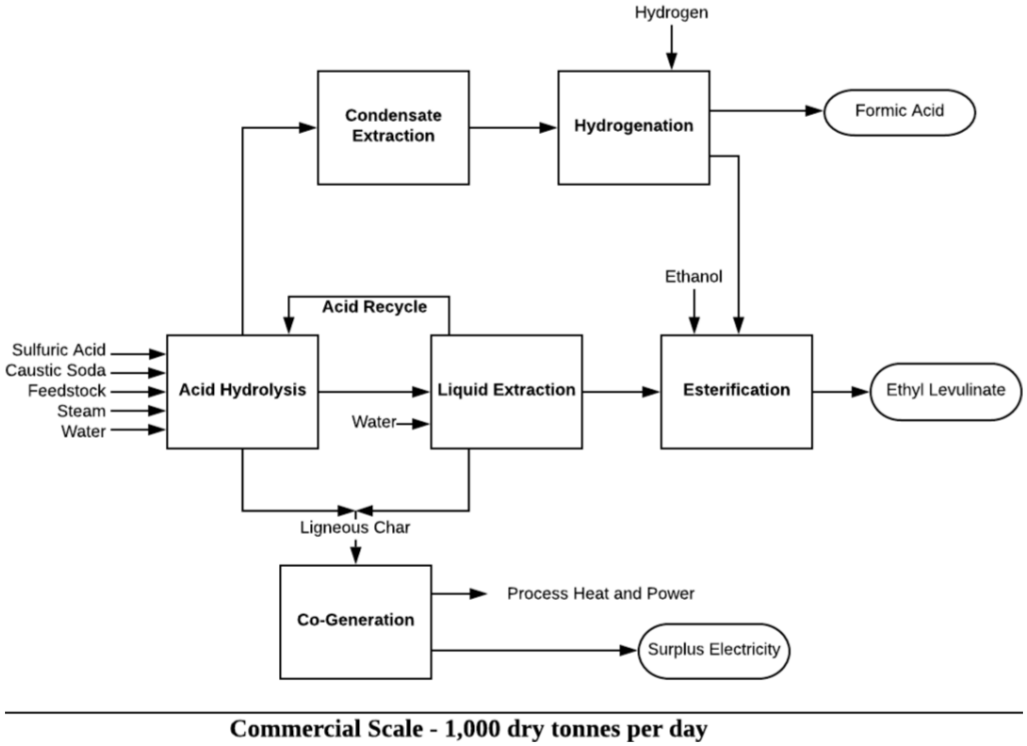


Figure 2-2: Process flow for EL from lignocellulosic biomass at commercial scale (1,000 tpd).

The location of the EL production facility is modeled in mid-coast Maine, however, the only differences for other locations using the ISO New England grid will be feedstock transport distance. For the waste paper, these are likely to be smaller in other areas of New England.

2.3.2 System Boundaries

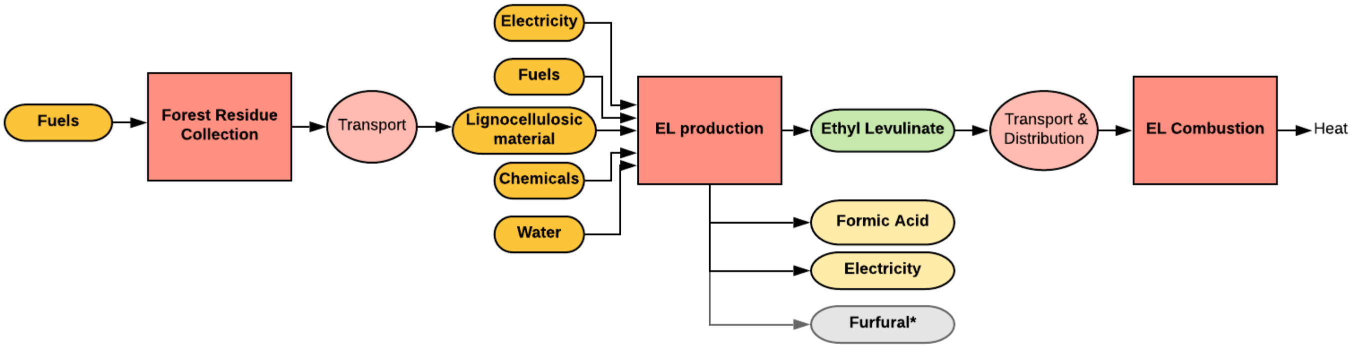
System boundaries are established in LCA to include the significant life cycle stages and unit processes, as well as the associated environmental flows in the analysis. This lays the groundwork for a meaningful assessment where all important life cycle stages and the flows associated with each alternative are considered and allows for consistent and meaningful comparisons.

For the provision of heat, the general system boundary includes production of the refining feedstock, transport of that input feedstock to the conversion facility, conversion of the feedstock to heating fuel and any associated co-products, distribution of the heating fuel in the local/regional residential market, and combustion of the fuel in air to produce heat and combustion emissions, as well as any input chemicals and energy.

Figure 2-3 illustrates the general system boundary for production of ethyl levulinate from lignocellulosic material – either forest residues or post-consumer waste paper used for heat. Detailed process flows for the technology are presented in the next section.

The system boundary for this study does not include the GHG emissions related to infrastructure processes, such as construction of the manufacturing facility and capital equipment.

System I: Heat from forest residue-based EL



System II: Heat from post-consumer waste paper-based EL

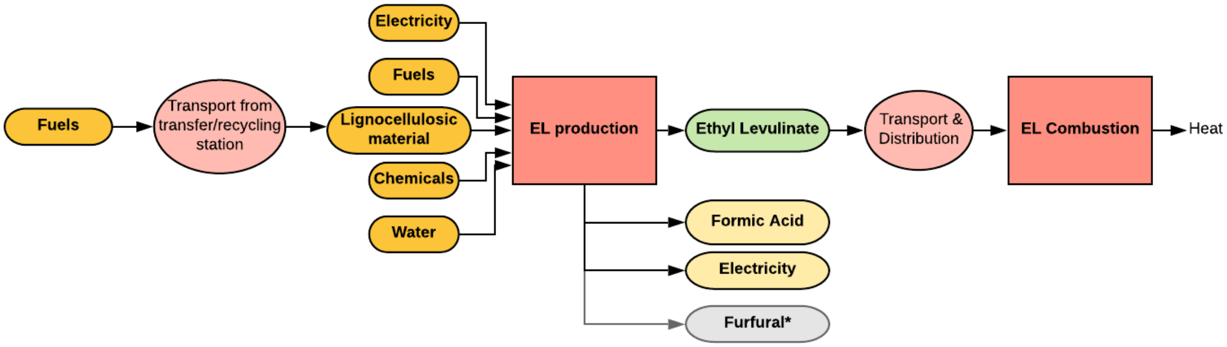


Figure 2-3: System boundaries of the Well-to-Burner tip production and use of EL from softwood forest residues (System I, top) and post-consumer waste paper (System II, bottom) for heat. Both the pilot and commercial scale facilities produce formic acid and surplus electricity co-products. The co-product furfural is only produced in the pilot scale (100 tpd) facility.

2.3.2.1 Heat produced from EL made from lignocellulosic biomass

The system boundaries for the Well-to-Burner tip analysis of EL (Figure 2-3) included the following stages:

- Production of chemicals
- Production (collection) of feedstock, if relevant. The forest residue process includes collection of the residue; the post-consumer waste paper is already collected as part of the municipal services and is not included. Carbon uptake by the trees during growth is included in the biogenic carbon calculations.
- Transportation of feedstock to the manufacturing facility
- Production of EL
- Transportation and distribution of EL
- Combustion of EL in a residential heater

2.4 Data requirements and validation of data

2.4.1 Data quality requirements

Primary measured, metered or calculated data are required and have been used for the pilot scale EL production process. Biofine provided expert projects based on engineering models for the commercial scale process which is appropriate for projections. As US-based government organizations represent one of the primary audiences for the study, secondary data from Argonne National Laboratories GREET 2021 model are required and have been used (Michael Wang, Amgad

Elgowainy, *et al.*, 2018). The GREET model is also a familiar model for heating oil industry, another key audience for the study.

2.4.2 Treatment of missing data

Every effort has been made to include all data. The transportation of post-consumer waste paper to the recycling center is omitted from this study and is considered as a municipal service. A zero-burden approach is applied beginning from the collection at recycling center). The use phase of the heat delivery to residents is also excluded as it is beyond the scope of the study and depends on consumer behavior. The underlying GREET data have not been reviewed for completeness.

2.5 Cut off criteria

Cut-off criteria are often used in LCA practice for the selection of processes or flows to be included in the system boundary. The processes or flows below these cut-offs or thresholds may be excluded from the study. Several criteria are used in LCA practice to decide which inputs are to be considered, including mass, energy, and environmental relevance.

For this study, every effort was made to include all the flows associated with the processes studied. During the interpretation phase, a 1% of environmental relevance criterion, as calculated by the impact assessment method, was used to test the sensitivity of the results to assumptions and data substitutions made. No change was made to the underlying GREET data except as noted.

2.6 Co-Product Allocation

As shown in Figure 2-1 and 2, in addition to ethyl levulinate, the EL manufacturing process yields additional co-products: surplus electricity, formic acid, and – for the smaller scale system – furfural. In a multifunctional (multiproduct) system, the environmental burdens must be attributed appropriately across the functions (products).

Co-product allocation is the calculation step in which the environmental burdens of the overall production system are attributed to the primary product and each of the co-products according to some form of relationship. According to ISO 14044, allocation of the process inputs should be avoided by using the system boundary expansion approach where possible. If allocation cannot be avoided, an allocation method – based on physical causality (mass or energy content for example) or a relationship such as economic value – should be used (ISO, 2006a).

System expansion, the ISO-preferred approach, is a method of avoiding allocation whereby an alternative process (route) for manufacturing the coproducts is subtracted from the system. In this study, the system expansion approach was used wherever possible, and physical allocation was used where system expansion could not be applied and to provide a secondary check on the modelling. Impacts for the input corn ethanol used in the process were calculated in GREET 2021 with its default allocation assumptions for the US average corn ethanol pathway.[1]

2.6.1 Electricity

The energy-dense ligneous char produced during hydrolysis and liquid extraction is used internally as a fuel source (heat and power co-generation) for the EL manufacturing process. The char created from the process produces sufficient electricity and steam to power the entire EL manufacturing process, with some excess electricity available to feed back to the grid. System expansion was used

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[1] System expansion in the absence of a corn oil coproduct and marginal to account for the corn oil coproduct, https://greet.es.anl.gov/files/greet-2021-summary

to credit the electricity being sent to the grid as per other GREET models, with the EL-related surplus electricity offsetting the equivalent amount from the selected grid (see Section 3.3 for grids included in the study).

2.6.2 Chemical co-products

The EL production technology also produces formic acid at either scale. Data for alternative formic acid manufacturing processes was obtained from the ecoinvent 3.8 library (Wernet, 2016) for several routes. The market process for non-European production,[2] is used for the base case. A sensitivity analysis was carried out to evaluate the effect of these assumptions.

The smaller scale system produces furfural as an additional coproduct. However, there remains no alternative manufacturing process in the commercially available LCI databases, nor are robust estimates for the production impacts available in the literature.[3] This study used two approaches: system expansion to account for formic acid coproduction, followed by allocation based on energy content for the remaining EL and furfural products; and a coarse estimate calculated with both energy-based and mass-based physical allocation procedures. The latter is used for guiding the sensitivity analysis carried out to evaluate the effect of these assumptions.

2.6.3 Other allocation

Impacts were also allocated on the basis of both mass and energy as a check on the results and as a means to bound the furfural range. Lower heating values of EL, formic acid and furfural were used to calculate energy-based allocation values (Table 2-1). The lower heating values were obtained from a report prepared by Shell Global Solutions (Louis, J, 2005) and from PubChem, the NIH Open Chemistry Database[4]. The energy and mass allocation factors for each scenario are shown in Table 2-1. The 1,000 dry tonne/day capacity plant converts all the furfural into EL, therefore the only allocation approach used was system expansion, with mass and energy-based allocation used as a check for sensitivity analyses.

Table 2-1: Energy and mass-based allocation for each EL plant type

Scale (tpd)	*Commercial (1,000 tpd)*				*Pilot (100 tpd)*					
Feedstock	Forest Residue		Post-Consumer Waste Paper		Forest Residue			Post-Consumer Waste Paper		
Allocation Scheme	Energy	Mass	Energy	Mass	Energy	Mass	Energy on EL/ furfural	Energy	Mass	Energy on EL/ furfural
EL	91%	83%	88%	78%	66%	58%	74%	81%	71%	93%
Formic Acid	9%	17%	12%	22%	11%	19%		13%	23%	
Furfural					23%	23%	26%	6%	6%	7%

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[2] Ecoinvent 3.8: Formic acid {RoW}| market for | Cut-off, U

[3] A few published LCA studies involve production of furfural as a coproduct in novel biorefinery systems, generally from less common feedstocks. Given the lack of a robust value, we have elected to calculate the value by multiple means to provide a range.

[4] https://pubchem.ncbi.nlm.nih.gov

2.7 Impact Assessment Method and Modelling Tool

Impact assessment methods are used to convert Life Cycle Inventory (LCI) data (environmental emissions and raw material extractions) into a set of environmental impacts. For this Greenhouse Gas assessment, 100-year global warming potentials from the IPCC 100 impact assessment method in GREET 2021, AR5 (see Table 2-2) (IPCC, 2013) without climate-carbon feedbacks. The AR5 base values are the most widely used in the US oil heat industry as of the time of writing and have been chosen for consistency with current expectation.

Table 2-2: Global warming potentials of Greenhouse gases – IPCC100y 2013

Greenhouse gases considered	**Characterization factors (IPCC 100)**
Total CO_2 (with C from VOCs and CO)	1
Methane (CH_4)	30
Nitrous oxide (N_2O)	265

Note that the potential for fossil methane is used as GREET calculates both biogenic carbon uptake and emissions.

Modeling in this study is carried out in the widely-used Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) life cycle assessment model developed by Argonne National Laboratory (Michael Wang, Amgad Elgowainy, *et al.*, 2021). GREET consists of two pieces that together span the full life cycle of a transportation fuel: GREET1 (fuel life cycle) and GREET2 (vehicle life cycle). GREET1 allows analysis of complete life cycles of a range of conventional, biobased and advanced fuels from their extraction (or production of feedstock), transportation, manufacturing and distribution, to combustion in a motor vehicle based on connection to GREET2. For this study, the final use phase GHG emissions for combustion to heat in several different boiler or furnace types (summarized below) were calculated and integrated into a modified GREET1.

Data unavailable in GREET were augmented with data from ecoinvent 3.8 (Morenal Ruiz E., et al., 2017) and the US EI ('DATASMART LCI Package', 2021) data libraries.

While GREET calculates the fuel-cycle energy consumption, greenhouse gas emissions and emissions of five criteria pollutants: VOCs, CO, NOX, SOX and PM10, this study is concerned only with the GHG emissions, and only contributions to the GHG emissions for EL were considered.

3 Life Cycle Inventory

Life cycle inventory (LCI) data contains the details of the resources flowing into a process and the emissions flowing from a process to air, soil and water.

3.1 Process Details

As depicted above (Figure 2-1), the Biofine process uses acid hydrolysis and esterification to produce EL and co-products from a variety of different waste biomass sources such as wood, straw, waste paper, household waste etc. Along with the primary product, EL, the manufacturing process yields other coproducts – formic acid, and at the pilot scale, furfural (at commercial scale, this is used to produce additional EL). The lignin-rich char is used within the system to produce process heat and power and surplus electricity.

In this study, two sources of biomass are used: 1) softwood forest residue which comes from forest slash (approximately 50% moisture content, 50.3%w/w C); and 2) post-consumer waste paper and cardboard (denoted “PCW” and “post-consumer waste paper,” here) (approximately 10% moisture content, 39.1%w/w C). Two production scales are also used, pilot and commercial, as described in Section 2, with daily feedstock throughput of 100 dry tonnes and 1,000 dry tonnes, respectively. Table 3-1 summarizes the process inputs and outputs for each system.

Table 3-1: Daily process inputs and outputs for plant type (scale + feedstock)

	Pilot Scale		*Commercial Scale*		
	Forest Residue	Waste Paper	Forest Residue	Waste Paper	
Process Inputs					
Feedstock, dry mass	100	100	1000	1000	tonne
Feedstock, water	138	10	1380	100	tonne
Feedstock Moisture Content	58%	9%	58%	9%	
Sulfuric Acid	0.014	5	1.4	50	tonne
Caustic Soda (50%)	0.17	0.5	1.5	0.5	tonne
Ethanol (corn based)	10	14.9	160	167.9	tonne
Hydrogen (natural gas-sourced)	n/a	n/a	2.75	0.8	tonne
Water	50	50	524	7.5	tonne
HP Steam (from CHP using ligneous char)	200	200	2000	2000	tonne
Electricity (from CHP)	2.5	1.3	9.1	20	MW
Electricity (from grid)	0	1	0	0	MW
Key Intermediates					
Ligneous char (ash-free)	52.5	36.5	525	365	tonne
Outputs					
EL	31	46.6	494	525.5	tonne
Formic Acid	10	15	100	150	tonne
Furfural	12.5	4	n/a	n/a	tonne
Electricity (to grid)	0.3	0	20.0	0	MW
Wastewater (low BOD)	342	165.8	3442	2080	Tonne

3.2 Data Quality, Sources and Assumptions

The primary data associated with the production of EL was provided by Biofine Developments Northeast (the emissions were determined based on stoichiometric calculations). Heating system, combustion, and final distribution data were provided by National OilHeat Research Alliance (NORA), Exergy Partners or modeled directly; sources are identified below. For all other unit processes, the data provided within the GREET model were used, supplemented where necessary with library data from ecoinvent 3.8 (Wernet, 2016) for caustic soda (50%), and transportation[5] of

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[5] Transportation emissions in GREET are given per MMBTU of fuel transported and are not easily backcalculated to tonne-miles or other units readily usable for these raw materials. Since their contribution is small, the ecoinvent library process is used.

these to the Maine manufacturing facility. The ecoinvent process was also used for formic acid. A target year of 2023 was used for simulations except for the 2040 projection.

3.2.1 Production of chemicals

The EL conversion process involves three or four input chemicals depending on scale: sulfuric acid, caustic soda, ethanol, and hydrogen gas for the commercial scale process.

GHG emissions for sulfuric acid and hydrogen gas were calculated in GREET 2021 (Michael Wang, Amgad Elgowainy, *et al.*, 2018) with the US Average electricity grid to reflect the uncertainty in production location. Emissions for steam production (CHP) as part of a biomass conversion process are embedded in the GREET calculation and were used unchanged. GHG emissions for corn-based ethanol production were calculated in GREET with the SERC (Midwest and Southeast) electricity grid and then reused in the EL model[6]. The default assumptions for US average corn ethanol in the model were used without modification.[7]

50% caustic soda was added using the ecoinvent library process.[8] The ecoinvent processes used here included the “cradle to gate”[9] life cycle emissions associated with manufacturing of caustic soda. While the available ecoinvent data includes emissions from infrastructure related processes, these processes were excluded in order to be consistent with GREET, which does not include infrastructure processes.

3.2.2 Production of Feedstock

Both feedstocks considered in the current study are essentially waste products. Neither the forest residue nor post-consumer waste paper feedstock production processes use any chemicals (as is already the case in GREET for the forest residue system), the production of chemicals is therefore excluded for both forest residue and post-consumer waste paper. The default system boundaries for production of forest residue provided in GREET were used for this study. Post-consumer waste paper is assumed to go to landfill if not used here, so no burdens were assigned to it (a zero-burden approach or cut-off approach). The cut-off approach to waste paper was chosen since a significant portion of paper that could be used in the EL process is unrecyclable and because there is a limited market for waste paper.

3.2.3 Transportation of Feedstock and inputs to the manufacturing facility

3.2.3.1 Forest Residue:

A catchment radius of 50-75 miles (base case 50 mi) was used for transportation of forest residues from the forest field to the facility used, based on woody biomass availability analyses for Maine.[10]

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[6] Changing the grid mix as appropriate for EL changed the grid mix used for the ethanol, sulfuric acid and hydrogen, so the impacts for these were calculated in a separate instance of GREET.

[7] 10% wet mill (process energy mix 72.5% natural gas, rest coal), 90% dry mill (process energy mix 99.6% natural gas, rest coal), no capture of fermentation CO2 emissions.

[8] ecoinvent 3.4 - Sodium hydroxide, without water, in 50% solution state {RER/RoW}| chlor-alkali electrolysis, this was not updated to the newer version as its impacts were below the environmental cut off.

[9] Cradle to gate emissions include the raw material extraction phase, transportation and manufacturing; the emissions from the use and disposal are not included.

[10] (Maine, 2018), (Mullaney, et al, 2018), (Briedis et al., 2011).

3.2.3.2 Post-consumer waste paper (PCW):

For PCW, the material is already gathered at the local transfer/recycling center before delivery to the conversion facility. A baseline delivery distance of 5 miles was used based on distances to the transfer center in Augusta, ME and Buckston, ME; other collection distances were assessed via sensitivity analysis.

3.2.3.3 Input Chemicals

For ethanol, the default transportation process and distance (520 miles by barge, 600 miles by pipeline, 800 miles by rail and 80 miles by truck) for the transportation of corn-based feedstock to manufacturing facility, given in GREET was used. It is assumed that a comparable transportation distance would be involved for transportation of ethanol to Biofine's facility. The ecoinvent transportation process was used for other inputs. Transportation distances from the chemical manufacturing plant in Illinois to the EL manufacturing facility in Maine 1400 miles, in a 16-32 tonne truck, as previously indicated by Biofine and in keeping with GREET, were used. Transportation parameters for hydrogen were based on available regional suppliers; an average distance of 100 miles was used in place of the GREET default of 30 miles.

3.2.4 Production of EL (100 and 1,000 dry t/day plant size)

The EL production process involves steam injection acid catalyzed hydrolysis of lignocellulosic material at high temperature. Process inputs for the manufacturing of EL include sulfuric acid to hydrolyze the forest residue, caustic soda (50%), ethanol, hydrogen (in the commercial scale system), steam, and electricity which is produced from lignin-rich process residues. They are covered in Sections 3.1 3.2.1, and 3.2.3. The process flows are shown in Figure 2-1, and detailed process parameters supplied by Biofine are provided in Section Process Details, Table 3-1.

The emissions from combustion of biomass to generate steam and electricity in biomass co-generation facilities is already incorporated in the GREET biomass processes. The combustion emissions were isolated out so that they can be correctly addressed. Surplus electricity from combustion of the lignin/char stream is sent to the grid; the grid emissions are calculated in GREET based on the technology type and year. The 2023 and 2040 GREET values were used. Attribution of carbon uptake and emissions from biomass were modified to align with the ISO 14067 reporting requirements.

3.2.5 Distribution EL and other heating fuels

Transportation and distribution for EL as heating fuel are very likely to be comparable to other heating oils. Correspondingly, industry-elicited values for average delivery sizes and distances were used to determine effective transport distances per gallon. The transport emissions associated with those fuel deliveries were calculated using GREET's embedded transportation processes.

Table 3-2: Transport and distribution estimates for oil heat. Values in italics are calculated. [11]

	Delivery size gallons oil	# Deliveries	Total Distance miles	Average distance miles per delivery
Industry Average	185			
Urban Boston		40,000		2
Urban New York		179,690	581,424	*3.2357*

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[11] Data from three dealers on number of deliveries per mile of travel, solicited and provided by J Huber, NORA, February 2019.

Rural	196,224	961,334	*4.8992*
	Weighted average distance per delivery		*3.9017 mi*

3.3 Grids

The regional electricity grid in which the EL plant operates plays an important role in determining EL GHG emissions. Electricity surplus from generating process heat and power is fed into the grid to displace other production. This excess electricity can be as a valuable coproduct for the forest residue cases, in particular. Where it is necessary to consume grid electricity, as in the pilot scale waste paper system, the impacts respond to the characteristics of the grid mix.

There are two particularly relevant grids for regional EL production currently under consideration, both part of the Northeast Power Coordinating Council (NPCC): ISO New England (ISO NE) and ISO New York (NYISO). These grids are shown in Figure 3-1.

The other additional grid is the projected future grid (2040). The current grid mixes for each are used in the study: NPCC, used in this study for the base case, and the US Average included in GREET (based on the EIA 2018 Annual Energy Outlook (USEIA 2018)). SERC was used for the corn ethanol and the U.S. average grid is used for other input materials.

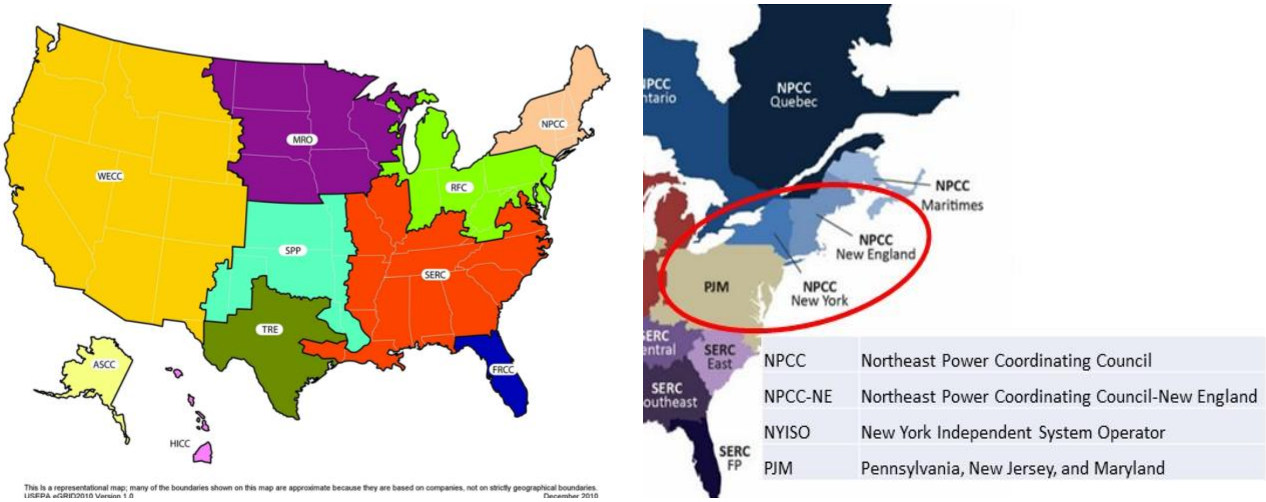

Figure 3-1: U.S. electric grid regions in North American Electric Reliability Corporation (NERC) (left) and the more granular NERC assessment regions relevant for EL plant siting and electricity offset impacts included in the study (right). (figures from the 2020 NERC Summer Reliability Assessment).

The mixes used are shown in Table 3-3, along with per kilowatt-hour life cycle GHG emissions as calculated in GREET.

Table 3-3: Electricity grid mixes used in the current study

	ISO New England	*NYISO Average*	*NYISO Upstate*	*SERC*	*NPCC*	*PJM*	*ISO New England 2040*
Oil	0.2%	0.2%	7.0%	0.2%	0.2%	0.3%	-
Natural gas	53.0%	42.6%	0.7%	41.5%	45.7%	27.1%	-
Coal	0.5%	0.1%	0.2%	17.0%	0.1%	31.8%	-
Nuclear power	27.0%	29.2%	41.2%	33.9%	29.7%	35.6%	3.9%

	ISO New England	*NYISO Average*	*NYISO Upstate*	*SERC*	*NPCC*	*PJM*	*ISO New England 2040*
Biomass	2.0%	-	-	0.6%	1.3%	-	0.4%
Hydroelectric	7.0%	22.9%	43.2%	4.7%	16.5%	-	8.9%
Geothermal	-	-	-	-	-	-	11.7%
Wind	4.0%	3.2%	6.5%	0.0%	3.7%	4.8%	35.5%
Solar PV	3.0%	-	-	1.9%	1.1%	0.3%	33.8%
Other Renewables	3.4%	1.7%	1.2%	0.2%	1.8%	0.1%	5.7%
Other	0.1%	-	-	-	-	-	-
Source	ISO NE, 2022	NYISO, 2021	NYISO, 2021	Han et al, 2021	Wang et al, 2021	PJM, 2018	ISO NE, 2022
Life Cycle GHGs, g CO2 eq/MMBTU							
100 year	86,407	68,196	24,592	73,931	120,878	147,938	3,411
20 year	98,761	77,963	26,154	84,704	134,983	162,935	3,428

3.4 Combustion of EL in residential heater (boiler or furnace)

A variety of oil-fired heating systems with a range of efficiencies are used in assessing the total Well-to-Burner Tip emissions of producing an MMBTU of heat at that burner tip. Table 3-4 shows the systems included in the study. The non-condensing boiler is used for the base case analyses.

Table 3-4: Energy-to-heat conversion efficiencies of current and emerging oil-fired heating systems.[12]

Equipment Type	*Conversion Efficiency, %*
Non-condensing boiler	92.
Condensing boiler	97.
Non-condensing furnace	88.6
Condensing furnace	95.8
Air-source absorption heat pump (DOE test data)	140.

The emissions from combustion of EL to heat were modeled by using 100% EL combusted in excess air. Because the only source of Carbon in the EL product is biomass based, these combustion biogenic emissions are 100% non-fossil Carbon.

4 Modeling EL in GREET

GREET default parameters were used as wherever possible. However, certain input parameters were changed to accommodate EL production and use. Physical properties for EL were added to the “Fuel_Specs” worksheet: lower heating value (LHV) 96,227 Btu/gal, density 3,845 grams/gal and Carbon ratio (weight percent Carbon) 58.3%. Transport and distribution processes for EL and general heating fuels were added to the T&D sheet.

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[12] Efficiencies provided by Dr. T Butcher, Brookhaven National Laboratory, Jan 2019.

The pre-existing production process for ethanol from forest residue was duplicated and modified to create a production process for EL appropriate for both the forest residue and post-consumer waste paper processes at either the 100 tpd and 1,000 tpd scales on an EL-specific sheet. An additional input and results sheet specific for the heating analysis was added to facilitate this and other scenario variations.

The modified EL process was structured to accommodate both forest residue and post-consumer waste paper, as the former includes the residue collection process while the latter includes only the transportation of the collected feedstock to the conversion facility. The feedstock transportation distances in the EL process were altered to take input from the new input sheet. New EL transportation and distribution processes were added within GREET (*i.e.*, to pump, here to fuel supplier) to use input for transport of EL to storage and the final distribution distance was calculated from the delivery statistics supplied by NORA.

Mass-weighted GHG emissions associated with sulfuric acid, ethanol and hydrogen (in the case of the 1,000 t/day plant) were added as fixed values on the EL sheet using values calculated in GREET under the conditions described in §3.2.1 and 3.2.3 or, for caustic soda, the ecoinvent library process. Avoided emissions from coproducts were incorporated under the non-combustion emissions in the new EL process. Additionally, fuel distribution and use (combustion) modeling was incorporated on the new inputs and results sheet.

5 Results – Well-to-Burner Tip GHG emissions

Base case parameters are shown in Table 5-1.

Table 5-1: Base case parameters for EL production scenarios

Parameter	Value
Forest residue collection radius	50 mi
Post-consumer waste paper collection radius	5 mi
Electricity Grid	ISO New England
Heating system	Non-condensing boiler
Co-product Allocation	Formic Acid: system expansion Furfural (in 100 tpd cases): energy basis
Life cycle GHG emissions for Formic Acid (from ecoinvent)	2,898 g CO_2eq per kg

5.1 EL production scenarios

Table 5-2 shows the Well-to-Burner Tip GHG emissions for EL used to supply 1 MMBTU of heat in a non-condensing boiler for all four EL systems using base case values. Figure 5-1 shows the fossil and biogenic contributions to the GHG impacts for each of the life cycle stages. Figure 5-2 breaks down the contributions to the conversion process impacts in further detail.

Both forest residue base case scenarios result in Carbon negative heat, due to the export of electricity to the grid that displaces higher-carbon intensity electricity and the co-production of formic acid and, in the pilot scale, furfural. Conversely, the waste paper process at either scale results in positive GHG emissions because neither produces excess electricity and, indeed, the pilot scale waste paper case is able to meet only about 56% of the process's electricity demand and must meet the remainder with grid electricity (see Table 3-1). When biogenic emissions are included, all four scenarios result in negative GHG emissions as a result of storing a portion on the biomass C in uncombusted coproducts.

Table 5-2: Well-to-Burner tip GHG (100y) emissions to produce heat with EL broken down by life cycle stage, kg CO_2e/MMBTU heat, non-condensing boiler.

	Pilot Scale		*Commercial Scale*	
	Forest Residue	Waste Paper	Forest Residue	Waste Paper
Feedstock production/collection and transport	3.75	0.09	3.19	0.09
Conversion excl. biogenic	21.63	45.80	31.09	40.95
Electricity offset (exported excess electricity)	-2.09	0.00	-11.82	0.00
Co-product offset (avoided products)	-30.00	-37.68	-25.48	-35.93
Distribution	0.02	0.02	0.02	0.02
Use (Combustion at burner tip)	0	0	0	0
Total excluding biogenic CO_2	**-6.68**	**8.23**	**-3.00**	**5.13**
Biogenic CO_2 emissions				
Feedstock	-262.54	-184.61	-214.23	-173.26
Processing to fuel	114.84	57.50	104.57	56.70
Use (Combustion at burner tip) - biogenic	92.84	92.84	92.84	92.84
Total including biogenic CO_2	**-21.98**	**-5.65**	**-11.41**	**-6.73**
CO_2 stored as C in non-combusted coproducts	*39.55*	*20.38*	*8.41*	*11.86*

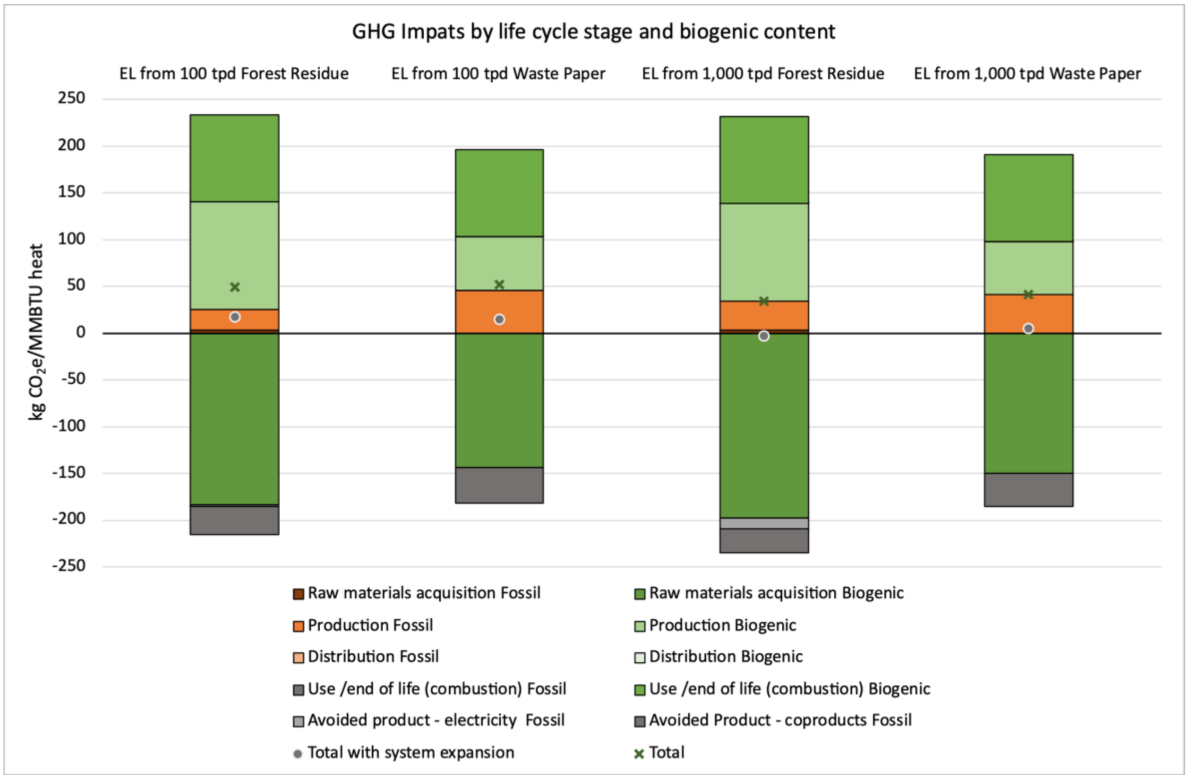

Figure 5-1: Fossil and biogenic Well-to-Burner tip GHG (100y) emissions by lifecycle stage for the production of 1 MMBTU of heat from ethyl levulinate in a non-condensing boiler on the ISO New England electrical grid.

Emissions from combustion during use and processing to fuel dominate the GHG emissions for production and use of EL for heat. Combustion of the EL produces significant GHG emissions, however, these emissions are biogenic, arising from the contemporaneous carbon cycle through uptake of the carbon during tree growth. The conversion process is fueled by bio-based materials as well, which are also offset/credited by the plant growth. In addition, the conversion process creates electricity and chemicals which can replace those produced elsewhere and so generate a further credit to the system. Thus, the overall change to the market from the production of EL is expected to be a reduction in GHG emissions. Because both feedstocks are essentially wastes, they contribute relatively little to the Well-to-Burner tip GHG emissions.

The large biogenic CO_2 contribution during processing to fuel arises almost entirely from the use of residual biomass for cogeneration of heat and power to avoid the use of steam and electricity derived from fossil sources to the extent possible. Combustion of fossil fuels release carbon that has been locked up, while burning biomass emits biogenic carbon emissions that are already part of the biogenic carbon cycle. Therefore, the CO_2 that is released from burning of residual biomass is simply returning to the atmosphere the previous carbon that was absorbed by plants in an effectively contemporaneous cycle. Similarly, the displacement of grid electricity with excess power from the lignaceous residue results in decreased emissions as biogenic carbon displaces fossil emissions (the amount depending on the characteristics of the grid mix being displaced). Thus, the bioenergy net greenhouse gas (GHG) emissions cannot be determined by comparing emissions at the point of combustion of EL but need to be compared with the GHG emissions associated with the energy system (heat and power) displaced.[13] This carbon credit becomes more dominant as production of EL and chemical coproducts are increased in preference to electricity generation within a circular economy perspective.

Figure 5-2 shows the various contributions to the GHG emissions for the conversion stage of EL production by life cycle stages. Conversion of feedstock to fuel and coproducts are by far the most significant contributors to impact (in the absence of biogenic carbon).

Feedstock emissions arise from collecting the biomass (forest residue) and delivering the collected biomass to the conversion facility (both forest residue and wastepaper). Because the primary feedstocks used for EL production are generally wastes, the contributions from feedstock collection and transportation are small relative to other elements of the systems. While important, the relative impact of the catchment radius size is a small contribution to the total. Increasing the collection radius for post consumer waste paper adds about 1% to the total impact for every doubling of distance. Increasing the catchment radius for the forest residue cases is more noticeable because the collection radius is already significantly larger for the forest residue cases.

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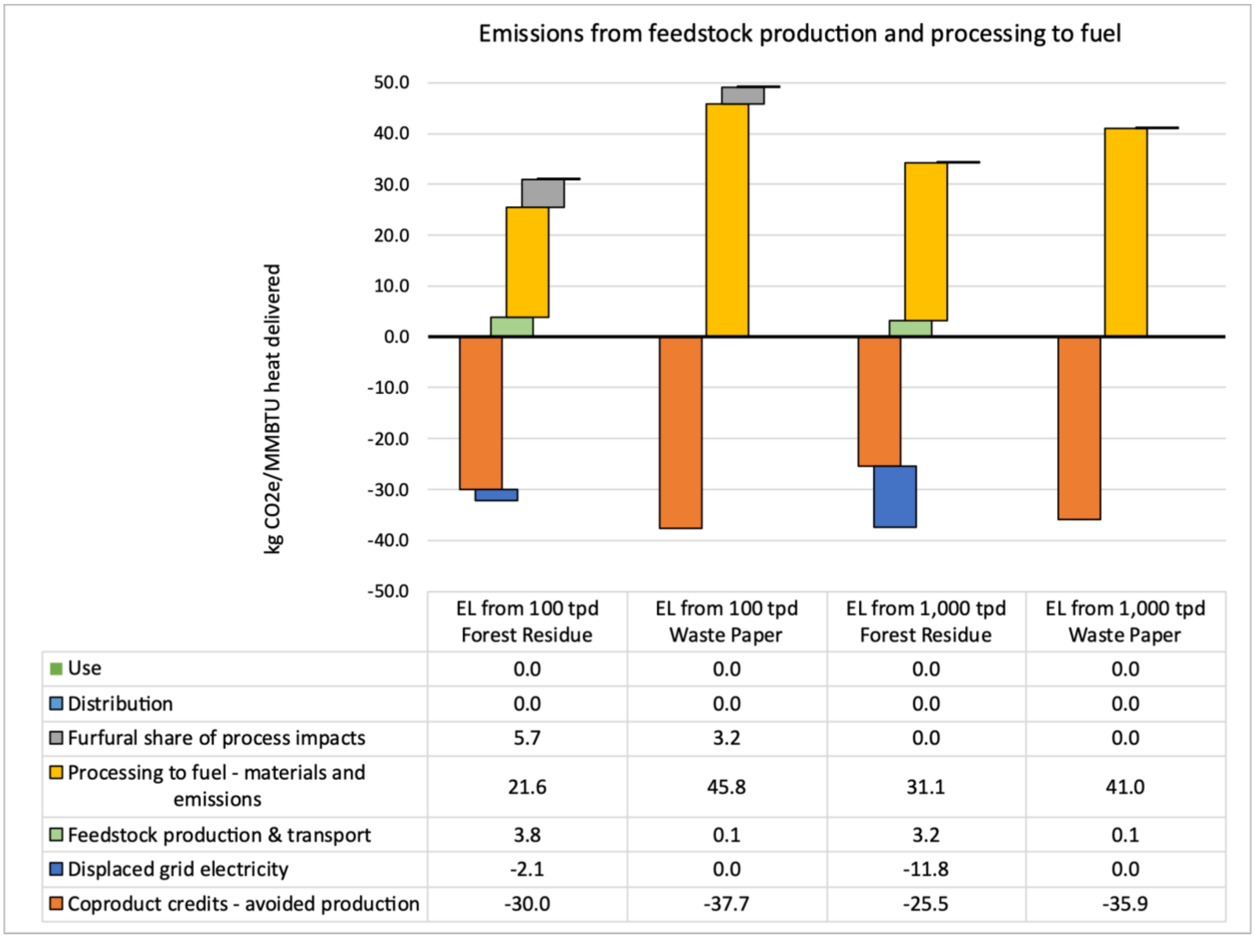
[13] This is described in the GREET cell comment as “This is the amount of CO2 in burnt biomass that is from the atmosphere.” for the conversion process, and – in GREET – is used to subtract out the portion of general combustion CO2 emissions attributable to the biomass from combustion emissions from unspecified fuel in conversion boilers.



	EL from 100 tpd Forest Residue	EL from 100 tpd Waste Paper	EL from 1,000 tpd Forest Residue	EL from 1,000 tpd Waste Paper
🟩 Use	0.0	0.0	0.0	0.0
🟦 Distribution	0.0	0.0	0.0	0.0
▨ Furfural share of process impacts	5.7	3.2	0.0	0.0
🟨 Processing to fuel - materials and emissions	21.6	45.8	31.1	41.0
🟩 Feedstock production & transport	3.8	0.1	3.2	0.1
🟦 Displaced grid electricity	-2.1	0.0	-11.8	0.0
🟧 Coproduct credits - avoided production	-30.0	-37.7	-25.5	-35.9

Figure 5-2: Feedstock and conversion contributions to GHG emissions for EL including credits, kg CO2eq/MMBTU heat.

The balance of coproducts dictates the overall impact. Thus, for the commercial scale (1,000 tpd) forest residue scenario, the shift in coproduct yields decreases the coproduct credits and the avoided emissions from displacing the somewhat higher quantity of electricity are insufficient to offset the loss of other coproduct credits. This is a direct result of the method of dealing with the coproducts by avoiding traditional production, as the ISO New England grid is a strong contributor to this credit and assumptions about the particular production routes being displaced for other coproducts are significant. Sensitivity analysis (sections 5.2.1) was carried out to understand how the results might change with different perspectives and avoided products.

5.2 Results under different scenarios

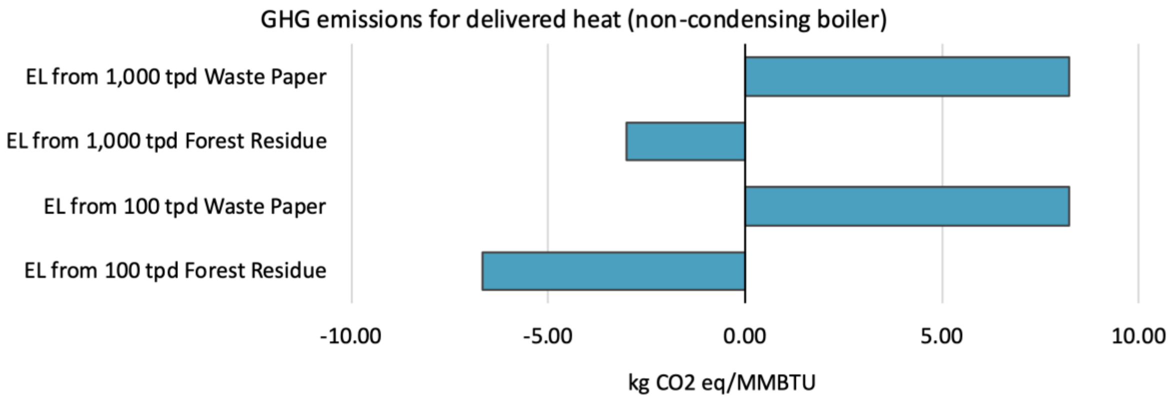


Figure 5-3 shows the Well-to-Burner Tip emissions for 1 MMBTU of delivered heat for each EL scenario. Figure 5-4 shows contributions to the well-to-tip from the primary life cycle stages.

EL from forest residues results in a carbon negative heat, while that from post consumer waste paper is positive. The trend difference between forest residue and waste paper pathways is primarily because the forest residue cases produce excess electricity while the waste paper pathways either produce no excess electricity or require the import of grid electricity to meet the energy demand for the conversion process. While the biogenic origin of use phase combustion emissions has the biggest effect, the use of residue lignocellulosic material and credits in conversion also contribute, particularly in driving this trend.

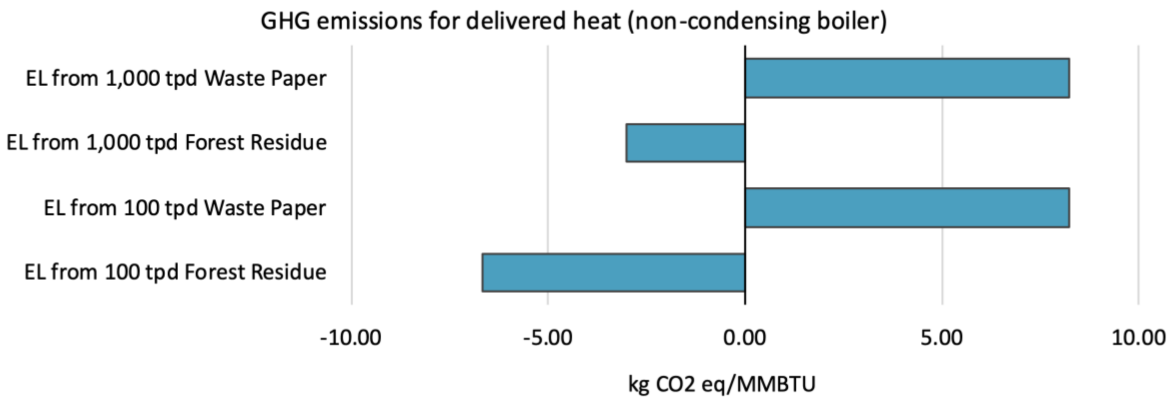


Figure 5-3: Well-to-Burner Tip GHG emissions for heat from EL in the different scenarios, used in a non-condensing boiler, in kg CO2eq/MMBTU.

EL is produced from what is essentially waste matter; forest residue and waste paper come into the process burden free. Combustion emissions are reduced to essentially nothing because they are plant based. Consequently, the major drivers of impact are the use (or displacement) of grid electricity and coproducts that can displace fossil-intensive alternatives.

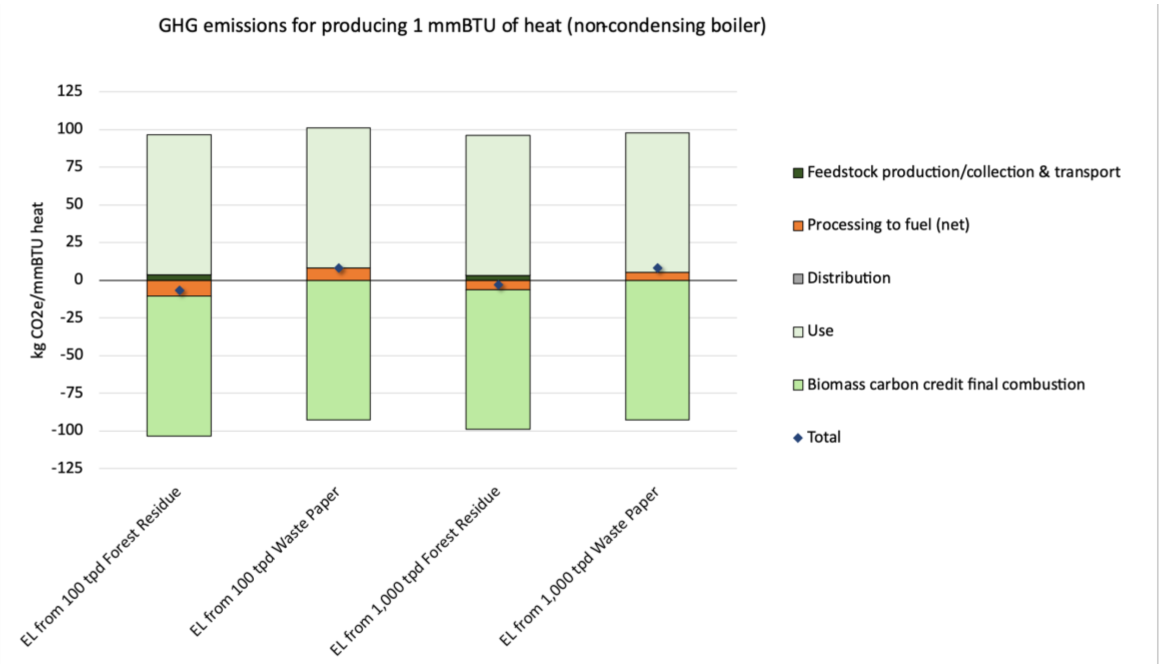


Figure 5-4: Well-to-Burner Tip GHG emissions for provision of 1 MMBTU of heat by fuels in the study, broken down by life cycle stages. Diamonds show the total Well-to-Burner Tip GHG emissions for each. kg CO2eq/MMBTU (GWP 100y).

In the use phase, direct combustion emissions for MMBTU of heat prior to applying the biomass carbon credit are within a few percent of each other. The credit for atmospheric Carbon released from burning bio-based fuel(s) at the combustion stage results in net zero use phase emissions for EL. If the biogenic carbon stored in the non-combusted coproducts from EL production (formic acid and – for PCW-based EL – furfural) is taken into consideration, the production of EL may be carbon negative.

5.2.1 EL heating fuel scenarios under different grids

The electricity produced by combusting lignin-rich char for cogeneration that is not used by the process and is instead returned to the grid is assumed to displace the need for grid electricity production. The credit applied to the production of EL depends upon the mix of sources in the displaced grid electricity. As this is a significant contribution to the calculated negative impacts of EL, alternative grid mixes were considered, as shown in Figure 5-5.

The most benefit comes from offsetting the PJM grid, which has a much higher proportion of coal than the others. Conversely, because the NYISO Upstate grid mix is cleaner, offsetting it provides less of a benefit and in the case of forest residue feedstock at scale, the net benefit from EL production is essentially neutral.

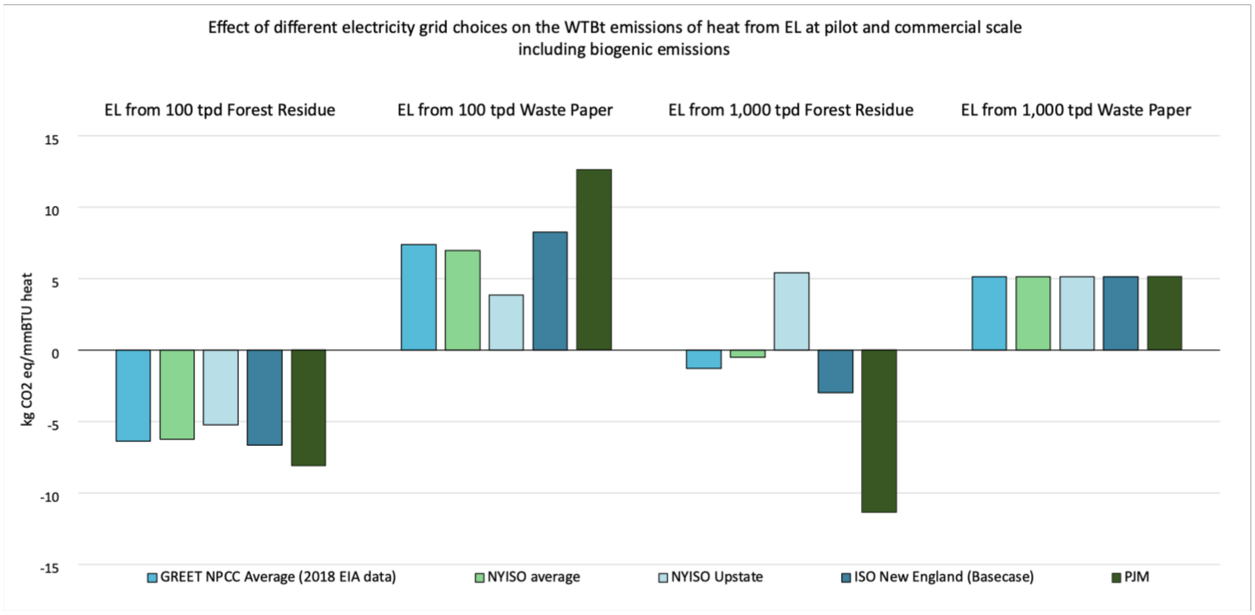


Figure 5-5: Well-to-Burner Tip (WTBt) GHG emissions with different grid mixes. kg CO2 eq/MMBTU.

GHG emissions reductions for EL heat are slightly lower in 2040 because the grid is greener. The NPCC New England grid mix in 2040 has improved efficiencies but is still predominantly natural gas and nuclear. Thus, GHG reductions decrease slightly relative to the baseline, as shown in Figure 5-6.

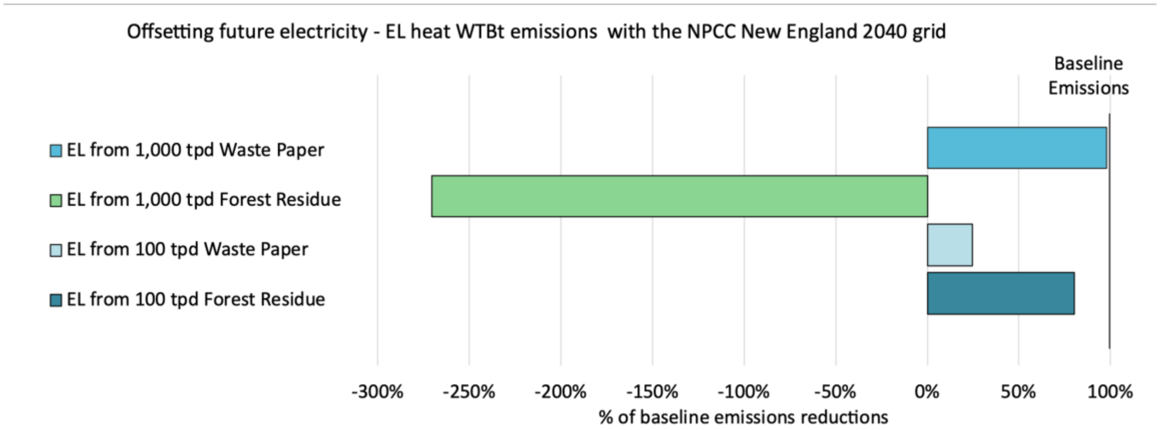


Figure 5-6: Well-to-Burner tip GHG emissions for EL with the 2030 NPCC New England electricity grid.

5.2.2 EL heating fuel scenarios for different heating system technologies

The difference between different heating systems changes the GHG emissions but does not change the scenario trends.

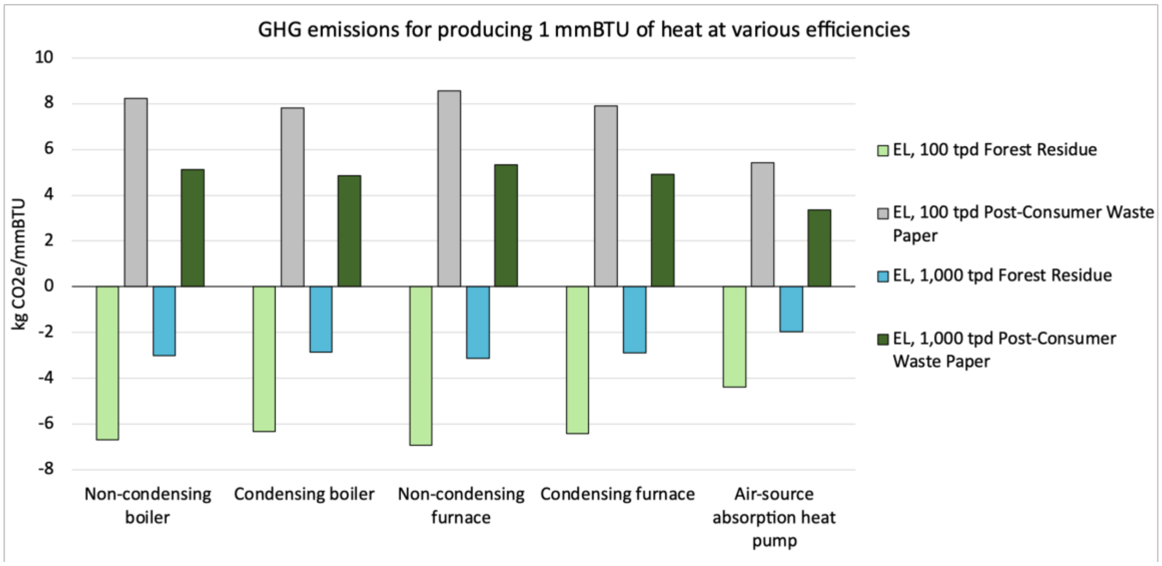


Figure 5-7: Emissions performance for different heating systems, grouped by heating technology (GWP 100y).

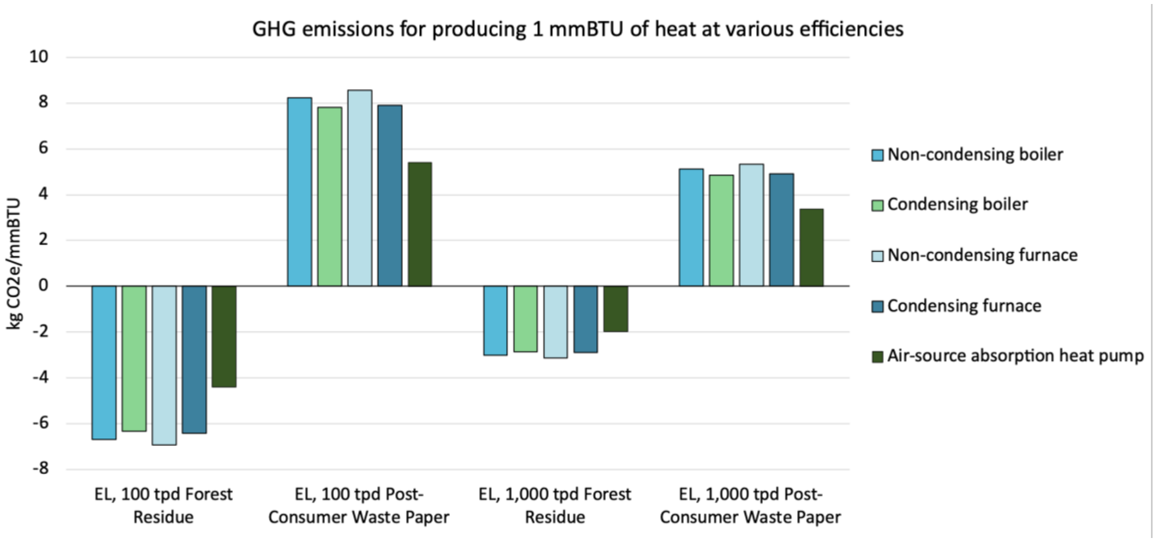


Figure 5-8: Emissions performance for different heating systems, grouped by heating fuel.

5.3 Sensitivity analysis

The GHG emissions for EL are strongly dependent on the allocation approach. ISO 14044 guidance is to expand the system to include the replacement of the coproduct(s) by other means. The results here are strongly dependent on the GHG emissions associated with other production routes for formic acid and, to a lesser extent, furfural.

5.3.1 Sensitivity to avoided co-product emissions for EL

The ecoinvent database contains formic acid production from methyl formate and butane (European and Rest of World production) processes. However, the GHG emissions associated with methyl formate based formic acid are significantly higher than butane based formic acid. For this study, the more general value for formic acid via methyl formate (non-European), 3.4kg CO_2eq/kg formic acid, has been used, since it was not known which type of formic acid is more commonly used in the U.S. However, uncertainty about the production route for formic acid and the wide range in impacts from the different routes (from 0.7 to 3.4 kg CO2eq/kg formic acid), as well as the lack of reported values for the commercial production of furfural, results in high uncertainty about effect of these key values. Consequently, a sensitivity analysis was performed for formic acid production emissions and furfural production emissions. Results of the sensitivity analyses for allocation are presented in Figure 5-9 and Figure 5-10.

Figure 5-9 shows the change in GHG emissions from the conversion phase (left panel) and Well-to-Burner tip (right panel) for three different formic acid options.

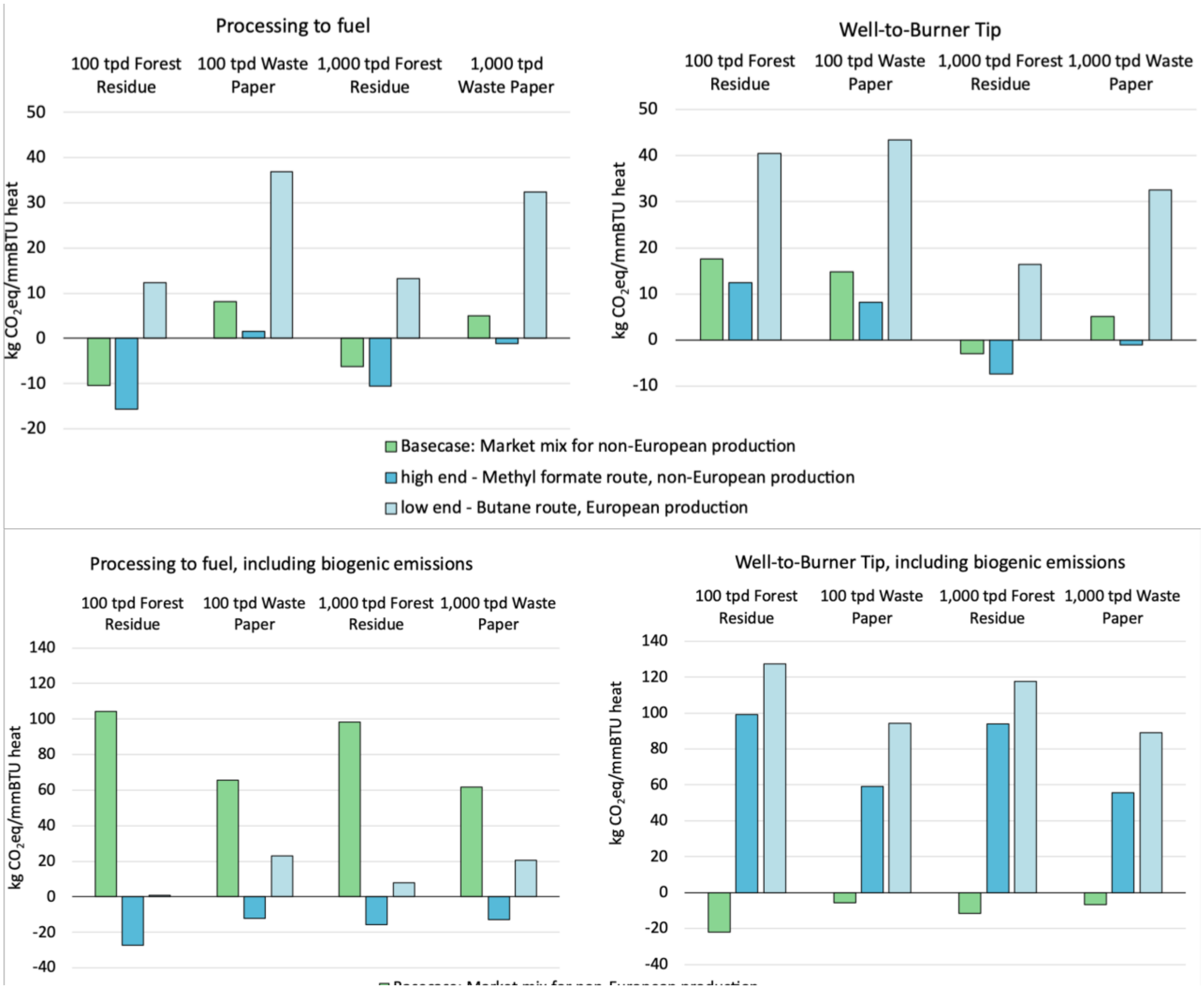


Figure 5-9: Response of EL Well-to-Burner tip emissions to the possible production routes used to produce the avoided formic acid being avoided with the EL formic acid co-product, without biogenic emissions (top) and with (bottom).

The sensitivity analysis used the most general (and highest impact option) in the ecoinvent database for the upper bound and the lowest of the ecoinvent options (butane route, European production) which has only 20% of the impacts of the top end. This is useful for assessing the lower or most conservative case for avoided emissions, despite the fact that it is an extreme case. We also allocated the impacts entirely by mass and energy as a sensitivity check on allocation vs system expansion. The results are shown in Figure 5-10. However, in keeping with the ISO guidance encouraging avoidance of allocation where possible, the basecase scenarios use system expansion for exported electricity and formic acid. When a furfural coproduct is present, the basecase uses energy allocation for it due to the lack of LCA results for furfural in the databases and literature.

Since the GHG emissions from butane based formic acid are lower than methyl formate based formic acid, the coproduct credit reduces when butane based formic acid is used, and hence the overall GHG emissions for EL increase.

The responsiveness of the overall GHG emissions to changes in the co-product avoided emissions is clear in Figure 5-9. Since the European production cases are not reflective of North American cases, a more realistic lower bound is absent. Together with the importance of the co-product/co-generation balance, this reflects a need for more concrete market and production information for co-product alternatives.

Because of the ambiguity around production routes of the avoided products demonstrated in Figure 5-9, above, we also assessed the results using mass and energy allocation. The results of this analysis are shown in Figure 5-10 below. The absence of displaced electricity is the most significant factor for the post consumer waste paper routes. The forest residue cases, however, show more variation. However, despite the variation, the relative ranking of the four cases are almost independent of allocation type; only full energy allocation changes the order between pilot and commercial scale forest residue pathways, visible in Figure 5-10.

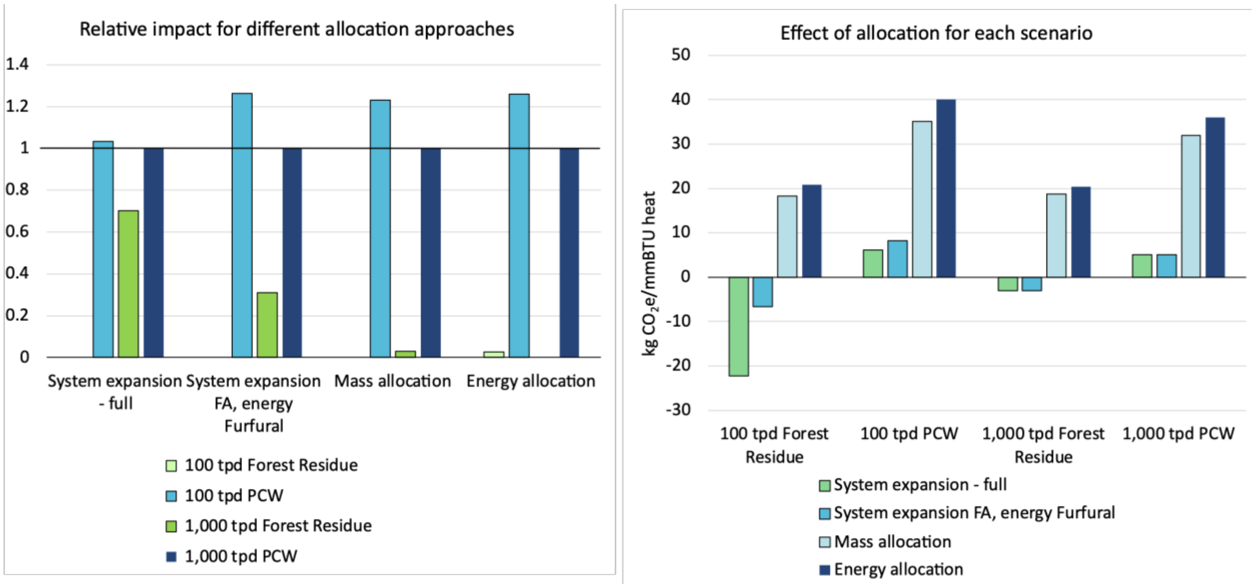


Figure 5-10: Comparison of Well-to-burner tip GHG (100y) emissions (non-biogenic) for the base case using different allocation methods, including system expansion for both formic acid and furfural (if present), allocation by mass, and allocation by energy. The left panel shows values relative to the difference from the result from 1,000 tpd waste paper, the right panel shows the absolute values for each allocation.

Together, Figure 5-9 and Figure 5-10 demonstrate that system expansion depends strongly on both the amount and assumed production route of avoided product, such that the forest residue process that produces the most co-product benefits strongly. On the other hand, mass and energy allocation show no such trend.

5.4 Sensitivity of assumptions to environmental cut off

Impacts for the input corn ethanol used in the process were calculated in GREET 2021 with its default allocation assumptions for the US average corn ethanol pathway.[14] The default assumptions for US average corn ethanol in the model were used without modification.[15]

Data for alternative formic acid manufacturing processes was obtained from the ecoinvent 3.8[16] library (Wernet, 2016) for several routes. The market process for non-European production[17] is used for the base case. A sensitivity analysis was carried out to evaluate the effect of these assumptions (see §5.3.1).

For post consumer waste paper, collection and transport are the only impacts associated with the feedstock, and the collection radius will depend on variable factors such as local population density, so the effect of the collection distance was considered via sensitivity analysis. A baseline delivery distance of 5 miles was used based on distances to the transfer center in Augusta, ME and Buckston, ME. Impacts for 10, 15 and 50 mile collection distances were also assessed.

Doubling the post-consumer waste paper collection radius doubles the feedstock contribution since it must be sourced from farther away, but increases the total Well-to-Burner Tip emissions by only about 1% because the feedstock contribution is so much smaller than the other life cycle stages. At an extreme radius of 50 mi, the feedstock portion contributes about 10% for the total impact. Increasing the Forest Residue catchment radius from 50 to 75 miles increases feedstock emission by 25-30% and increases Well-to-Burner Tip emissions 5-10% but does not change the sign of the overall emissions.

5.5 Data quality assessment

As mentioned in the inventory section, the data for the ethyl levulinate process were obtained from the pilot scale production facility and projected for commercial scale by Biofine experts. These data are as good as they can be and meet the data quality requirements. The secondary data from GREET and Ecoinvent are considered to be good quality and meet the data quality requirements. It should be noted that the GREET data are embedded in a large, difficult to navigate spreadsheet making it difficult to assess any particular piece of data from the model.

5.6 Limitations

The study uses the GREET 2021 model and its data, the most recent version available as of the time of writing. These processes reflect, generally, US average production, which may differ somewhat from the inventories for the materials actually sourced. Additionally, much of the background data in GREET is not updated annually and thus is not entirely current. It is important to note that if this method of EL production expands to the point where it is the dominant source of formic acid, formic acid will need to be treated as a co-product. This change, along with a cleaner grid allowing fewer credits is likely to result in a positive, but still low GHG potential. The results are likely to be

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[14] System expansion in the absence of a corn oil coproduct and marginal to account for the corn oil coproduct, https://greet.es.anl.gov/files/greet-2021-summary

[15] 10% wet mill (process energy mix 72.5% natural gas, rest coal), 90% dry mill (process energy mix 99.6% natural gas, rest coal), no capture of fermentation CO2 emissions.

[17] Ecoinvent 3.8: Formic acid {RoW}| market for | Cut-off, U

valid in areas where there are significant forest residuals, but may not apply where forests are not harvested for other purposes. The inherent limitation of this report lies in focusing on a single impact category (climate change). For quantification and communication purposes, multiple sustainability indicators are recommended. Another limitation relates to methodological assumptions made throughout the study. The presented LCIA results are also relative expressions and do not predict impacts on category endpoints such as human health and ecosystems damage.

6 Conclusions

All four EL scenarios result in overall (Well-to-Burner Tip) negative GHG emissions for the production of heat. This arises from four causes: Carbon emissions removal for the biomass-based Carbon released in the use phase; Carbon emissions reduction after replacing higher intensity grid electricity with the process's surplus electricity; the carbon emissions reduction for biomass-based Carbon released during cogeneration; and avoided emissions from replacing higher GHG intensity co-product alternatives.

Moving to commercial scale EL production shifts the balance of emissions. The process efficiency has increased over the pilot scale, resulting in a higher yield of EL. However, this increase comes at the expense of the formic acid coproduct yield and captures the furfural produced at pilot scale. The share of burden carried by formic acid thus decreases, and process emissions increase with the addition of hydrogen for hydrogenation of furfural going to additional EL. Consequently, the pilot scale emissions are lower than the commercial scale. Because the current version of the process for waste paper to EL does not produce an electricity copropduct and consumes grid electricity in the pilot scale, it is disadvantaged relative to the woody residues, even when those residues are treated as a coproduct of other forest products. Additionally, the decrease in excess electricity to export to the grid greatly decreases an opportunity to decrease forest residue EL's burden, even for the lowest impact grid, NYISO Upstate.

Three key aspects contribute to potential shifts in sign: magnitude of the electricity offset credit (influenced by electricity quantity and grid composition); potential for coproducts to replace higher intensity options (influenced by co-product yield, market, and alternative production technology and distribution); and transportation of inputs. Thus, decreasing waste heat and power to increase the quantity of electricity to the grid may help stabilize EL's Carbon negative performance across scenarios. Decreasing transport emissions for processing inputs can contribute to a lower GHG value; local or regional sourcing of chemical inputs may provide additional benefits in this case. Together with the importance of the co-product/co-generation balance, this suggests that more concrete market and production information for co-product alternatives would be useful.

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8 Appendices

8.1 Impact assessment results using GWP 100y (AR5)

Below are the results of the impact assessment for production of ethyl levulinate for the 100y global warming potential. All use the ISO New England electrical grid and use system expansion to accommodate the formic acid and excess electricity generated during conversion of biomass in the EL. Environmental burdens for furfural have been accounted for using energy allocation after the formic acid and electricity have been accounted for.

Table 8-1: GWP 100y (IPCC2013) results for EL produced from forest residues at a 1,000 tpd plant

1,000 tpd Forest Residue	g CO2e / MMBTU delivered heat				
	Non-condensing boiler	Condensing boiler	Non-condensing furnace	Condensing furnace	Air-source absorption heat pump
CO2 from atmosphere in feedstock	-155,527	-147,510	-161,496	-149,358	-102,204
CO2 from atmosphere in input chemicals -corn ethanol	-41,884	-39,725	-43,491	-40,222	-27,524
Feedstock production/collection and transport	3,189	3,025	3,311	3,062	2,096
Gross Conversion - excl biogenic	31,086	29,484	32,279	29,853	20,428
Conversion - biogenic -CHP combustion, ethanol production	104,567	99,177	108,580	100,420	68,716
Coproduct Credits -avoided product	-25,483	-24,169	-26,460	-24,472	-16,746
Electricity Credit -avoided product	-11,819	-11,210	-12,273	-11,350	-7,767
Distribution	22	21	23	22	15
Use -Combustion at burner tip - Fossil	0	0	0	0	0
Use -Combustion at burner tip - Biogenic	92,844	88,058	96,406	89,161	61,011
Total including biogenic	*-3,004*	*-2,849*	*-3,119*	*-2,885*	*-1,974*
Total without biogenic	*-3,004*	*-2,849*	*-3,119*	*-2,885*	*-1,974*
Net Conversion - excl biogenic	**-6,215**	**-5,895**	**-6,454**	**-5,969**	**-4,084**

Uptake of CO2 from atmosphere ultimately stored in non-combusted co-products	-8,410	-7,976	-8,732	-8,076	-5,526
CO2 stored in non-combusted co-products	8,410	7,976	8,732	8,076	5,526
Total including biogenic	-11,414	-10,825	-11,852	-10,961	-7,500
Total without biogenic	-3,004	-2,849	-3,119	-2,885	-1,974

Table 8-2: GWP 100y (IPCC2013) results for EL produced from forest residues at a 100 tpd plant

1,000 tpd Forest Residue	g CO2e / MMBTU delivered heat				
	Non-condensing boiler	Condensing boiler	Non-condensing furnace	Condensing furnace	Air-source absorption heat pump
CO2 from atmosphere in feedstock	-157,047	-148,951	-163,073	-150,817	-103,202
CO2 from atmosphere in input chemicals -corn ethanol	-26,392	-25,032	-27,405	-25,345	-17,343
Feedstock production/collection and transport	3,754	3,561	3,899	3,606	2,467
Gross Conversion - excl biogenic	21,634	20,519	22,464	20,776	14,217
Conversion - biogenic -CHP combustion, ethanol production	114,845	108,925	119,252	110,289	75,469
Coproduct Credits -avoided product	-30,002	-28,455	-31,153	-28,812	-19,715

Electricity Credit -avoided product	-2,087	-1,980	-2,167	-2,004	-1,372
Distribution	22	21	23	22	15
Use -Combustion at burner tip - Fossil	0	0	0	0	0
Use -Combustion at burner tip - Biogenic	92,844	88,058	96,406	89,161	61,011
Total including biogenic	*17,572*	*16,666*	*18,246*	*16,875*	*11,547*
Total without biogenic	*-6,678*	*-6,333*	*-6,934*	*-6,413*	*-4,388*
Net Conversion - excl biogenic	**-10,455**	**-9,916**	**-10,856**	**-10,040**	**-6,870**

Uptake of CO2 from atmosphere ultimately stored in non-combusted co-products	-39,553	-37,514	-41,070	-37,984	-25,992
CO2 stored in non-combusted co-products	39,553	37,514	41,070	37,984	25,992
Total including biogenic	-21,981	-20,848	-22,824	-21,109	-14,445
Total without biogenic	-6,678	-6,333	-6,934	-6,413	-4,388

Table 8-3: GWP 100y (IPCC2013) results for EL produced from post consumer waste paper at a 1,000 tpd plant

1,000 tpd Forest Residue	g CO2e / MMBTU delivered heat				
	Non-condensing boiler	Condensing boiler	Non-condensing furnace	Condensing furnace	Air-source absorption heat pump
CO2 from atmosphere in feedstock	-109,842	-104,180	-114,057	-105,485	-72,182
CO2 from atmosphere in input chemicals -corn ethanol	-39,705	-37,659	-41,229	-38,130	-26,092
Feedstock production/collection and transport	86	82	90	83	57
Gross Conversion - excl biogenic	40,951	38,840	42,522	39,327	26,911
Conversion - biogenic -CHP combustion, ethanol production	56,704	53,781	58,880	54,455	37,263
Coproduct Credits -avoided product	-35,933	-34,080	-37,311	-34,507	-23,613
Electricity Credit -avoided product	0	0	0	0	0
Distribution	22	21	23	22	15
Use -Combustion at burner tip - Fossil	0	0	0	0	0
Use -Combustion at burner tip - Biogenic	92,844	88,058	96,406	89,161	61,011
Total including biogenic	*5,127*	*4,863*	*5,324*	*4,924*	*3,369*
Total without biogenic	*5,127*	*4,863*	*5,324*	*4,924*	*3,369*
Net Conversion - excl biogenic	5,018	4,760	5,211	4,819	3,298

Uptake of CO2 from atmosphere ultimately stored in non-combusted co-products	-11,858	-11,247	-12,313	-11,388	-7,793
CO2 stored in non-combusted co-products	11,858	11,247	12,313	11,388	7,793
Total including biogenic	-6,731	-6,384	-6,990	-6,464	-4,423
Total without biogenic	5,127	4,863	5,324	4,924	3,369

Table 8-4: GWP 100y (IPCC2013) results for EL produced from post consumer waste paper at a 100 tpd plant

1,000 tpd Forest Residue	g CO2e / MMBTU delivered heat				
	Non-condensing boiler	Condensing boiler	Non-condensing furnace	Condensing furnace	Air-source absorption heat pump
CO2 from atmosphere in feedstock	-108,902	-103,288	-113,081	-104,582	-71,564
CO2 from atmosphere in input chemicals -corn ethanol	-34,944	-33,143	-36,285	-33,558	-22,963
Feedstock production/collection and transport	90	86	94	87	59
Gross Conversion - excl biogenic	45,805	43,444	47,563	43,988	30,100
Conversion - biogenic -CHP combustion, ethanol production	57,500	54,536	59,707	55,219	37,786
Coproduct Credits -avoided product	-37,685	-35,742	-39,131	-36,190	-24,764
Electricity Credit -avoided product	0	0	0	0	0
Distribution	22	21	23	22	15
Use -Combustion at burner tip - Fossil	0	0	0	0	0
Use -Combustion at burner tip - Biogenic	92,844	88,058	96,406	89,161	61,011
Total including biogenic	*14,731*	*13,972*	*15,297*	*14,147*	*9,681*
Total without biogenic	*8,233*	*7,809*	*8,549*	*7,907*	*5,410*
Net Conversion - excl biogenic	**8,120**	**7,702**	**8,432**	**7,798**	**5,336**

Uptake of CO2 from atmosphere ultimately stored in non-combusted co-products	-20,382	-19,332	-21,164	-19,574	-13,394
CO2 stored in non-combusted co-products	20,382	19,332	21,164	19,574	13,394
Total including biogenic	-5,651	-5,360	-5,868	-5,427	-3,713
Total without biogenic	8,233	7,809	8,549	7,907	5,410

8.2 Impact assessment results using GWP 20y (AR5)

Below are the results of the impact assessment for production of ethyl levulinate for the 20y global warming potential. All use the ISO New England electrical grid and use system expansion to accommodate the formic acid and excess electricity generated during conversion of biomass in the EL. Environmental burdens for furfural have been accounted for using energy allocation after the formic acid and electricity have been accounted for.

Table 8-5: GWP 20y (IPCC2013) results for EL produced from forest residues at a 1,000 tpd plant

1,000 tpd Forest Residue	g CO2e / MMBTU delivered heat				
	Non-condensing boiler	Condensing boiler	Non-condensing furnace	Condensing furnace	Air-source absorption heat pump
CO2 from atmosphere in feedstock	-155,527.21	-147,510.34	-161,495.52	-149,358.07	-102,203.59
CO2 from atmosphere in input chemicals -corn ethanol	-41,883.69	-39,724.74	-43,490.96	-40,222.33	-27,523.57
Feedstock production/collection and transport	3,189	3,025	3,311	3,062	2,096
Gross Conversion - excl biogenic	33,440.60	31,716.86	34,723.88	32,114.15	21,975.25
Conversion - biogenic -CHP combustion, ethanol production	104,567.38	99,177.31	108,580.13	100,419.62	68,715.71
Coproduct Credits -avoided product	-29,311.93	-27,801.01	-30,436.77	-28,149.25	-19,262.13
Electricity Credit -avoided product	-11,818.98	-11,209.75	-12,272.53	-11,350.16	-7,766.76
Distribution	22.49	21.33	23.36	21.60	14.78
Use -Combustion at burner tip - Fossil	-	-	-	-	-
Use -Combustion at burner tip - Biogenic	92,843.51	88,057.76	96,406.35	89,160.78	61,011.45
Total including biogenic	*-4,478.88*	*-4,248.01*	*-4,650.75*	*-4,301.22*	*-2,943.26*
Total without biogenic	*-4,478.88*	*-4,248.01*	*-4,650.75*	*-4,301.22*	*-2,943.26*
Net Conversion - excl biogenic	**-7,690.31**	**-7,293.90**	**-7,985.42**	**-7,385.26**	**-5,053.63**

Uptake of CO2 from atmosphere ultimately stored in non-combusted co-products	-8,409.68	-7,976.19	-8,732.40	-8,076.10	-5,526.36
CO2 stored in non-combusted co-products	8,409.68	7,976.19	8,732.40	8,076.10	5,526.36
Total including biogenic	-12,889	-12,224	-13,383	-12,377	-8,470
Total without biogenic	-4,479	-4,248	-4,651	-4,301	-2,943

Table 8-6: GWP 20y (IPCC2013) results for EL produced from forest residues at a 100 tpd plant

100 tpd Forest Residue	g CO2e / MMBTU delivered heat				
	Non-condensing boiler	Condensing boiler	Non-condensing furnace	Condensing furnace	Air-source absorption heat pump
CO2 from atmosphere in feedstock	-157,046.64	-148,951.45	-163,073.26	-150,817.23	-103,202.08
CO2 from atmosphere in input chemicals -corn ethanol	-26,392.18	-25,031.76	-27,404.97	-25,345.31	-17,343.43
Feedstock production/collection and transport	3,754	3,561	3,899	3,606	2,467
Gross Conversion - excl biogenic	23,088.40	21,898.28	23,974.41	22,172.58	15,172.38
Conversion - biogenic -CHP combustion, ethanol production	114,844.55	108,924.73	119,251.68	110,289.13	75,469.28
Coproduct Credits -avoided product	-34,510.08	-32,731.21	-35,834.40	-33,141.21	-22,678.06

Electricity Credit -avoided product	-2,087.24	-1,979.65	-2,167.34	-2,004.45	-1,371.62
Distribution	22.49	21.33	23.36	21.60	14.78
Use -Combustion at burner tip - Fossil	-	-	-	-	-
Use -Combustion at burner tip - Biogenic	92,843.51	88,057.76	96,406.35	89,160.78	61,011.45
Total including biogenic	*14,517.27*	*13,768.96*	*15,074.37*	*13,941.43*	*9,539.92*
Total without biogenic	*-9,731.97*	*-9,230.32*	*-10,105.43*	*-9,345.94*	*-6,395.29*
Net Conversion - excl biogenic	**-13,508.92**	**-12,812.59**	**-14,027.32**	**-12,973.08**	**-8,877.29**

Uptake of CO2 from atmosphere ultimately stored in non-combusted co-products	-39,552.61	-37,513.82	-41,070.43	-37,983.72	-25,991.71
CO2 stored in non-combusted co-products	39,552.61	37,513.82	41,070.43	37,983.72	25,991.71
Total including biogenic	-25,035	-23,745	-25,996	-24,042	-16,452
Total without biogenic	-9,732	-9,230	-10,105	-9,346	-6,395

Table 8-7: GWP 20y (IPCC2013) results for EL produced from post consumer waste paper at a 1,000 tpd plant.

100 tpd Forest Residue	g CO2e / MMBTU delivered heat				
	Non-condensing boiler	Condensing boiler	Non-condensing furnace	Condensing furnace	Air-source absorption heat pump
CO2 from atmosphere in feedstock	-109,842.13	-104,180.17	-114,057.29	-105,485.14	-72,181.97
CO2 from atmosphere in input chemicals -corn ethanol	-39,705.34	-37,658.67	-41,229.02	-38,130.39	-26,092.08
Feedstock production/collection and transport	86	82	90	83	57
Gross Conversion - excl biogenic	43,017.92	40,800.50	44,668.72	41,311.57	28,268.92
Conversion - biogenic -CHP combustion, ethanol production	56,703.96	53,781.07	58,879.96	54,454.74	37,262.60
Coproduct Credits -avoided product	-41,332.34	-39,201.81	-42,918.45	-39,692.85	-27,161.25
Electricity Credit -avoided product	-	-	-	-	-
Distribution	22.49	21.33	23.36	21.60	14.78
Use -Combustion at burner tip - Fossil	-	-	-	-	-
Use -Combustion at burner tip - Biogenic	92,843.51	88,057.76	96,406.35	89,160.78	61,011.45
Total including biogenic	*1,794.27*	*1,701.78*	*1,863.12*	*1,723.10*	*1,179.09*
Total without biogenic	*1,794.27*	*1,701.78*	*1,863.12*	*1,723.10*	*1,179.09*
Net Conversion - excl biogenic	**1,685.58**	**1,598.69**	**1,750.26**	**1,618.72**	**1,107.66**

Uptake of CO2 from atmosphere ultimately stored in non-combusted co-products	-11,858.37	-11,247.11	-12,313.43	-11,388.00	-7,792.64
CO2 stored in non-combusted co-products	11,858.37	11,247.11	12,313.43	11,388.00	7,792.64
Total including biogenic	-10,064	-9,545	-10,450	-9,665	-6,614
Total without biogenic	1,794	1,702	1,863	1,723	1,179

Table 8-8: GWP 20y (IPCC2013) results for EL produced from post consumer waste paper at a 100 tpd plant.

100 tpd Forest Residue	g CO2e / MMBTU delivered heat				
	Non-condensing boiler	Condensing boiler	Non-condensing furnace	Condensing furnace	Air-source absorption heat pump
CO2 from atmosphere in feedstock	-108,901.66	-103,288.17	-113,080.73	-104,581.97	-71,563.95
CO2 from atmosphere in input chemicals -corn ethanol	-34,944.00	-33,142.76	-36,284.96	-33,557.91	-22,963.20
Feedstock production/collection and transport	90	86	94	87	59
Gross Conversion - excl biogenic	47,634.28	45,178.91	49,462.23	45,744.82	31,302.53
Conversion - biogenic -CHP combustion, ethanol production	57,500.09	54,536.17	59,706.64	55,219.30	37,785.78
Coproduct Credits -avoided product	-43,347.62	-41,113.21	-45,011.07	-41,628.19	-28,485.58
Electricity Credit -avoided product	-	-	-	-	-
Distribution	22.49	21.33	23.36	21.60	14.78
Use -Combustion at burner tip - Fossil	-	-	-	-	-
Use -Combustion at burner tip - Biogenic	92,843.51	88,057.76	96,406.35	89,160.78	61,011.45
Total including biogenic	*10,897.50*	*10,335.78*	*11,315.69*	*10,465.24*	*7,161.22*
Total without biogenic	*4,399.56*	*4,172.77*	*4,568.39*	*4,225.04*	*2,891.14*
Net Conversion - excl biogenic	**4,286.66**	**4,065.70**	**4,451.16**	**4,116.63**	**2,816.95**

Uptake of CO2 from atmosphere ultimately stored in non-combusted co-products	-20,382.14	-19,331.51	-21,164.30	-19,573.66	-13,393.98
CO2 stored in non-combusted co-products	20,382.14	19,331.51	21,164.30	19,573.66	13,393.98
Total including biogenic	-9,485	-8,996	-9,849	-9,108	-6,233
Total without biogenic	4,400	4,173	4,568	4,225	2,891

8.3 Critical review reports

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Critical Review Statement

Date: July 21, 2022

LCA Commissioned by: National Oilheat Research Alliance (NORA) and Biofine Developments Northeast Inc.

LCA Conducted by: Caroline Taylor, PhD and Lise Laurin, CEO
EarthShift Global
33 Mill Pond Road
Kittery, ME 03904

Report Title: Greenhouse Gas Analysis of Biomass-based Ethyl Levulinate for Residential Heating

Panel Review Conducted by: Terrie K. Boguski, Harmony Environmental, LLC

ISO Referenced Standards: ISO 14040:2006; ISO 14044:2006+Amd1:2017+Amd2:2020; ISO 14067:2018; ISO/TS 14071:2014

Critical Review Process, Scope and Conclusion

In accordance with the international standard, ISO 14044:2006, a Critical Review was conducted of the life cycle assessment (LCA) report, *Greenhouse Gas Analysis of Biomass-based Ethyl Levulinate for Residential Heating*. This life cycle Greenhouse gas (GHG) assessment focuses on the average well-to-heat (in this case, at the residential burner tip) emissions associated with the production and use of Biofine's ethyl levulinate (EL) fuel for heat in the northeastern US, specifically Maine and surrounding states. The critical review was an end-of-report review, and the reviewer received the entire draft report. Review was based on the stipulations in ISO 14044+Amd1:2017, which requires product carbon footprint reports to follow the stipulations in ISO 14067. The review followed guidance in ISO 14071:2014.

The reviewer received the draft report on March 22, 2022 and provided initial comments to EarthShift Global on April 8, 2022. Two additional rounds of review and comments were provided. The review was conducted by exchanging comments and responses via email. Comments were recorded in an Excel spreadsheet in tabular format based on Annex A of ISO/TS 14071:2014. All significant comments regarding conformity to ISO 14044 were addressed, and all open issues resolved to the extent possible, with one notable exception. The report uses GWP values without carbon feedbacks, whereas ISO 14067 requires GWP, including carbon feedbacks. The report authors provided a reasonable explanation for this deviation: The fuel oil/oil heat industry uses GREET values, GREET does not use climate carbon feedback contributions at this time.

The reviewer finds that all required stipulations in ISO 14044:2006 6.3 were met in the revisions to the report (final version dated July 20, 2022). In particular,

- The methods used to carry out the LCA are consistent with this International Standard,
- The methods used to carry out the LCA are scientifically and technically valid,
- The data used are appropriate and reasonable in relation to the goal of the study,
- The interpretations reflect the limitations identified and the goal of the study, and
- The study report is transparent and consistent.

The reviewer did not have access to LCA calculations, underlying data or models. Therefore, the review is primarily limited to the summary data and model results included in the report. Completing the critical review does not mean that the reviewer endorses the results of the LCA study, nor does it mean that she endorses any of the assessed products.

ISO 14044:2006 requires that this critical review statement, as well as the reviewer's comments and any responses to recommendations made by the reviewer be included in the final LCA report.

Submitted by

Terrie K Boguski

Terrie Boguski

LCA Report	**Greenhouse Gas Analysis of Biomass-based Ethyl Levulinate for Residential Heating**
LCA Commisioner	**National Oilheat Research Alliance (NORA) and Biofine Developments Northeast Inc.**
LCA Practitioner	**EarthShift Global**
Reviewers	**Terrie Boguski, Harmony Environmental**
Date	**July 21, 2022**

14044 Section	**Requirements**	**Conforms (Y=yes; N=No; na=not applicable**	**page (par./ fig./table)**	**Reviewer Initials**	**Reviewer Comments**	**Practitioner Response**	**Reviewer Final Comments**
Reporting							
5.1.1	Are the results and conclusions of the LCA completely and accurately reported without bias to the intended audience?	Y					
5.1.1	Are the results, data, methods, assumptions, and limitations transparent and presented in sufficient details to allow the reader to comprehend the complexities and trade-offs inherent to LCA?	Y					
5.1.1	Does the report allow the results and interpretation to be used in a manner consistent with the goals of the study?	Y					
5.2	LCA commissioner, LCA practitioner (internal or external)?	Y	title page				
5.2	Date of report?	Y	title page				
5.2	Statement that the study has been conducted according to the requirements of ISO 14040 and 14044?	Y	title page				
5.2	Reasons for carrying out the study?	Y	Section 2.1				
5.2	Intended applications?	Y	Section 2.1				
5.2	Target audiences?	Y	Section 2.1				
5.2	Statement whether the study intends to support comparative assertions intended to be disclosed to the public?	Y	Section 1				
5.2	Definition of the function?	Y	Section 2.2				
5.2	Statement of product performance characteristics?	Y	Section 2.3.1				
5.2	Any omission of additional functions in comparisons?	na			No omissions identified.		
5.2	Definition of the functional unit?	Y	Section 2.2				
5.2	Consistency with goal and scope?	Y	Section 2.2				
5.2	Results of performance measurement?	na					
5.2	Definition of the system boundary?	Y	Section 2.3				

5.2	Are omissions of any life cycle stages, processes or data needs explained?	Y	Section 2.4		It is unclear whether there are any known omissions. Clarify in the report.	The transportation of post-consumer waste paper to the recycling center is omitted from this study and is considered as a municipal service. A zero-burden approach is applied beginning from the collection at recycling center). The use phase of the heat delivery is also excluded from the study as it is beyond the scope of the study and depends on consumer behaviour. The supporting infrastructure like buildings and the capital equipment were also excluded.	Closed
5.2	Quantification of energy and material inputs and outputs?	Y	Section 3.1				
5.2	Assumptions about electricity production?	Y	Sections 2.6.1 and 3.3				
5.2	Description of cut-off criteria and assumptions; effect on results; inclusion of mass, energy and environmental criteria?	Y	Section 2.5		It is unclear whether any known flows are excluded or cut off. Also, I do not understand the significance of this statement: "Cut-off criteria were not applied to the GREET processes used in this study." Clarify in the report.	The ommitted flows have been added (line 25).	Closed
5.2	Data collection procedures?	Y	Section 3.2				
5.2	Qualitative and quantitative description of unit processes?	Y	Section 3.2				
5.2	Sources of published literature?	Y	Section 7				
5.2	LCI calculation procedures?	Y	Section 3.2				
5.2	Data quality analysis to validate data?	Y	Section 3.2				
5.2	Is treatment of any missing data explained?	Y	Section 2.4		It is not clear whether there is known missing data. Clarify in the report.	Missing data on the transportation of wastepaper to recycling centre and the use of heat delivery to residents has been added in the report.	Closed
5.2	Is there sensitivity analyses to refine the system boundaries?	Y	Section 5.3.1				
5.2	Documentation and justification of allocation procedures?	Y	Section 2.6				
5.2	Uniform application of allocation procedures?	Y	Section 2.6				
5.2	Are LCIA procedures, calculations and results of the study explained?	Y	Section 5				
5.2	Are limitations of the LCIA results relative to the defined goal and scope of the LCA explained?	Y	Section 5.4		See Annex A of ISO 14067 for carbon footprint limitations that should be mentioned. Annex A is normative, thus required.	Annex B (normative) Limitations of the carbon footprint of a product have been included in the report.	Closed

5.2	Is the relationship of LCIA results to the defined goal and scope explained, see 4.2?	Y	Section 2.1				
5.2	Is the relationship of the LCIA results to the LCI results explained, see 4.4?	Y (Except used GWPs without feedbacks)	Section 2.7		When I look at Chapter 8 of AR5, I see methane GWP factor of 28, without carbon feedback. Table 2 indicated the methan GWP factor used is 30. Is this an error? Also, Annex C of ISO 14044 (Amendment 1, 2017) requires ISO 14067 to be followed for carbon footprints. ISO 14067 requires the most recent IPCC GWFs, including carbon feedbacks. In AR5, these are 1, 34 and 298 for CO2, CH4 and N2O, respectively. However, AR6 is the most recent IPCC report. Follow ISO 14067 carbon footprint requirements. Update GWP factors to the most recent IPCC report and include carbon feedbacks.	According to the AR5 synthsis report (pg 87) The following emission metric values are stated : 1 CO2; 28 CH4 and 265 NO2. This has been corrected in 2.7. ISO 14067 allows for use of the prior values for the GWP with justification. The AR5 values without climate-carbon feedbacks as included in GREET are currently the expectation for the US oil heat industry, and while AR6 has been relesed, it is not yet available in GREET (the most widely used tool) and we anticipate its addition in the next release (Oct 2022). Thus, to remain consistent with the industry expectation, this analysis has used the base AR5 GWP values.	Closed
5.2	Are impact categories and category indicators explained, including a rationale for their selection and a reference to their source?	Y			See comment above.		
5.2	Are there descriptions of or reference to all characterization models, characterization factors and methods used, including all assumptions and limitations?	Y	Section 2.7		See comment above.		
5.2	Are there Descriptions of or reference to all value-choices used, a justification for their use and their influence on the results, conclusions and recommendations?	Y					
5.2	Is there a statement that the LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks?	Y			Statement is missing. Add statement.	Statement has been added on 5.6 under study limitations.	Closed
5.2	Are any new impact categories, category indicators or characterization models used for the LCIA defined and justified?	na					
5.2	Is any grouping of the impact categories explained and justified?	na					

5.2	Are any further procedures that transform the indicator results, such as weighting, justified?	na					
5.2	Is there an analysis of the indicator results (sensitivity and uncertainty analysis or the use of environmental data, including any implication for the results)?	Y	Section 2.5		Section 2.5 indicates a sensitivity analysis based on 1% of environmental relevance criterion, but I do not see this sensitivity analysis in the report.	Sensitivity analysis results have been included and are addressed in the text. Ultimately,only the variation in catchment radius (collection area) for the feedstocks and whether treating forest residues as coproducts changed the results related to this threshold. As mentioned in the text when addressing the results, the transport distances are based on available local data and varying them, even by large amounts (e.g., from 5mi to 200mi for PCW), had had negligible effect on the study results. The more impactful factors assessed via sensitivity analysis -- the carbon intensity of avoided products - are described in detail, indicating their impact on the study results.	Closed
5.2	Are data and indicator results reached prior to any normalization, grouping or weighting made available?	Y	Section 5				
5.2	Are assumptions and limitations associated with the interpretation of results, both methodology and data related Data quality analysis reported?	Y	Sections 3.2 and 5.4		A data quality assessment is missing from the Interpretation.	The data are from the project study based on primary data provided BIOFINE. Due to the limitations of the CFP study a sensitivity analysis was peformed to test the validity on some assumptions made (addressed in the text).	Closed
5.2	Is there full transparency in terms of value-choices, rationales and expert judgments?	Y					
ADDITIONAL COMMENTS		**Conforms (Y=yes; N=No; na=not applicable**	**page (par./ fig./table)**	**Reviewer Initials**	**Reviewer Comments**	**Practitioner Response**	**Reviewer Final Comments**
	"The default system boundaries for production of forest residue provided in GREET were used for this study. " It is unclear what the default system boundaries are.		Section 3.2.2		Add some details to the report.	The system boundary for the forest residue process begins from collection of the residue (forest residue as waste of logging), in keeping with the default treatment of forest residue pathways in GREET.	Closed

	I do not understand how the miles per gallon delivered is calculated using the numbers in Table 4.		Section 3.2.5		Provide an example calculation.	Table 4 and its caption have been revised.	Closed
	Most people are not familiar with electricity grid acronyms or areas		Section 3.3		Consider providing a map of the electricity grids, or more description of the areas included.	We have added the map and defined the acronyms	Closed
	The text indicates 5 grids, but 6 are listed in Table 5		Section 3.3		Clarify, as needed.	5 grids with one being a projected future grid. Changes have been added	Closed
	In Table 6, some of the numbers seem to have decimal points in the wrong place.		Section 3.4		Revise, as needed.	Revised	Closed
	In Table 8, the presentation of results is confusing. It is not clear if the biomass carbon credit is for the carbon in EL feedstock, in char or in both. It is not clear how the conversion stage credits relate to the total net GWP.		Section 5.1		Consider using ISO 14067 terminology in presenting CO2 removals from the atmosphere and showing these as related to the feedstock. Clarify how conversion stage credits contribute to the total GWP results.	Thank you for this guidance. Terminology and data have been added which reflect ISO 14067. In addition, terminology has been updated to the latest GREET terminology for audiences familiar with GREET, specifically the heating oil community.	Closed
	Figure 4 is difficult to understand.		Section 5.1		It may help to also provide these results in tabular format.	Figure 4 has been converted into a chart with a table for more clarity.	Closed
	The discussion of results in the 3 paragraphs under Figure 4 is difficult to understand.		Section 5.1		See questions in the report. Clarify, as needed.	The paragraph has been paraphased as requested.	Closed
	"We also allocated the impacts entirely by mass and energy as a check; those results are not shown here as the ISO guidance is to avoid allocation where possible by using system expansion." This is confusing. Why discuss if no further information about the check is presented?		Section 5.3.1		Provide details and results of the allocation check.	The results comparing allocation and system expansion have been added in Figure 13. The quoted allocation statement has also been revised.	Closed
	Figure 12. Are the bar labels correct? I expected the sensitivity results to bound the baseline results.		Section 5.3.1		Revise or explain, as needed.	The bars are correct. Figure caption has been revised to more clearly describe the intent of the importance of avoided product selection/assumptions to the primary product impacts.	Closed
	Here and througout the report, I find the terminology of "credit for the biomass-based Carbon released in the use phase" and "credit for biomass-based Carbon released during cogeneration" to be confusing and not always reflected clearly in the results tables and figures.		Section 6		Following ISO 14067, removals of carbon dioxide from air during plant growth should be associated with the feedstocks as negative values. No credits needed. Revise report, as needed.	Replaced credit with carbon emissions reduction due to the negative values as a result of the carbon credits. Further clarification is explain in Figure 4 results.	Closed

	Last sentence: Consequently, the pilot scale emissions are lower than the commercial scale.		Section 6		If the pilot scale emissions are lower due to the commercial scale converting furfural, would you recommend that the company consider not converting the furfural at commercial scale?	The by-product furfural will be re-used back into the system. It is also possible to supply the by product to other industries or companies that require it as a raw material. This options has the potential to create synergies among industries that operate within the same area. All byproduct re-use options are somehow determined by financial viability.	Closed
	Typos, format, editorial comments		throughout		These are noted in a copy of the draft report for your consideration.	Revised as necessary.	Closed