Supporting documentation for the life cycle assessment of bio-jet fuel production from poplar biomass via bioconversion at a biorefinery

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This study has been conducted according to requirements of the International Standards Organization (ISO) document 14040/14044 (ISO 2006a, 20006b).

Introduction (Goal of the Study)

A partial Life Cycle Assessment (LCA) is conducted to investigate the life cycle impacts of a biorefinery designed to convert poplar tree chips into jet fuel via fermentation and subsequent hydrogenation. The goal of producing jet fuel from *Populus* (poplar) trees (bio-jet) is to create an alternative to petroleum based jet fuel (petro-jet). Currently no jet fuel producing biorefineries are in commercial operation and the results of this LCA will be used to assess a potential environmental impact that could result from scaling up the proposed system. Work is part of the Advanced Hardwood Biofuels Northwest project. The LCA does not include any proprietary information and is suitable for release to the public domain. Life cycle inventory assessment and conclusion are not included in this document. The work in this partial LCA is to be uploaded to the USDA LCA Commons, which will provide open access to all the Life Cycle Inventory (LCI) data included below.

Description of product

The biorefinery in this LCA is assumed be located somewhere in the continental U.S and will produce jet fuel similar to Jet-A fuel with a high heating value (HHV) of 45.5 mega joule (MJ) / kilogram (kg) and a density of 0.820 kg/ liters (L). The biorefinery is designed to operate using 3200 bonne dry tonnes (BDt) of poplar chips per day (1.1 million BDt/yr). It is predicted to produce 300 L/ BDt (380 million L per year) of bio-jet fuel per year. The biorefinery is simulated in ASPEN-Plus v.2004.1chemical engineering software (Aspen Technology Inc., 2005). The LCA work is performed using SimaPro v.8.0 LCA software (Pre Consultants, 2012). The report does not include comparative assertions.

Functional unit

The functional unit used is 1 MJ of bio-jet fuel at the biorefinery gate.

System boundaries

The system boundaries begin with the delivery of poplar chips to the biorefinery gate (Figure 1). Growth and harvesting of poplar chips is not included within the system boundaries. All biorefinery operations are included and stated in detail below (Figure 1 – Biorefinery Operations). All manufacturing, use, and disposal (where applicable) of chemicals necessary to operate the biorefinery are included in the system boundaries (Figure 1 – Ancillary Chemicals). Table 1 lists all chemicals required for biorefinery operations. Descriptions of each chemical are included below in the LCI unit processes section. The transportation of all materials to, and wastes from the biorefinery are included and discussed in detail in the data collection section. Neither delivery nor use of the bio-jet fuel produced at the biorefinery is included. Production and maintenance of infrastructure is outside the system boundaries.

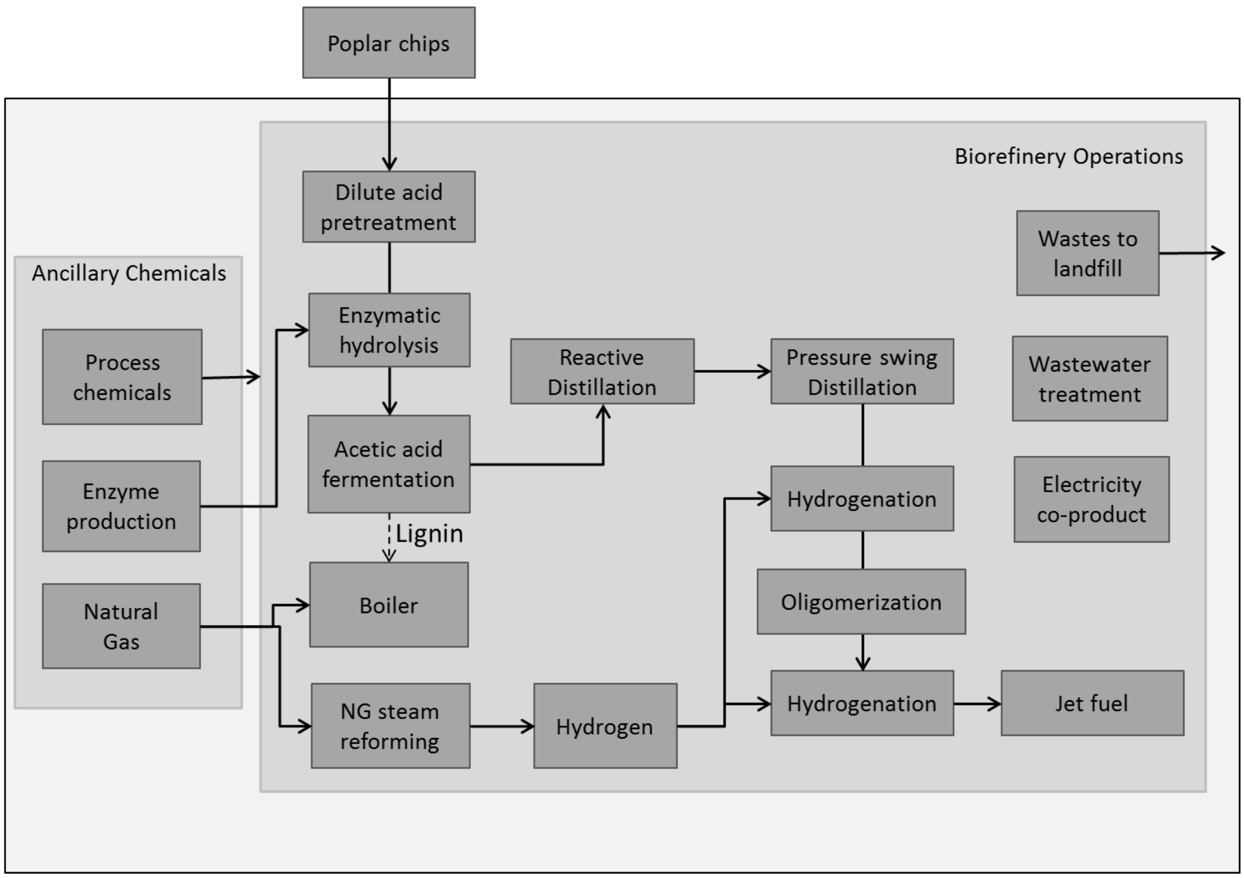

Figure 1: Biorefinery LCA system boundaries

Table 1: Biorefinery inputs and outputs per mega joule of jet fuel. Carbon dioxide emissions from the biorefinery are identified by source.

Input	**Amount**	**Unit**
Poplar (bone dry)	0.0814	kg
Enzymes	0.000683	kg
Sulfuric acid	0.00146	kg
Lime	0.00151	kg
Carbon dioxide (CO_2)	0.000185	kg
Calcium carbonate	0.000211	kg
Ammonia	0.00103	kg
Nickel based catalyst	0.00000174	kg
Alumina based catalyst	0.00000102	kg
Clarifier polymer	0.000047	kg
Corn steep liquor	0.00218	kg
Sodium hydroxide	0.00194	kg
Natural gas - to burner	0.00172	kg
Natural gas - SMR	0.00966	kg
Output		
Jet fuel	1	MJ
Electricity	0.00254	kwh
CO_2 - burner (biogenic source)	0.0761	kg
CO_2 – SMR (non-biogenic source)	0.0307	kg
CO_2 – WWT (bio genic source)	.0114	kg
CO_2 - Fugitive loss	0.000206	kg
CO	0.00000726	kg
NOx	0.00000726	kg
SO_2	0.0000565	kg
Gypsum	0.000397	kg
Ash	0.00155	kg

Description of data/ process

The biorefinery design has been developed and simulated using ASPEN-Plus v.2004.1 chemical engineering software. The ASPEN simulation is based on a combination of a National Renewable Energy Laboratory (NREL) bioethanol production facility (Humbird et al. 2011), ZeaChem's proposed fermentation process (Verser and Eggeman, 2011), and laboratory work at the Biofuels and Bioproducts Laboratory at the University of Washington. All inputs and outputs from the biorefinery are assessed relative to amount needed to produce 1 MJ of jet fuel (Table 1). The chemical and elemental chemical composition of the poplar biomass entering the biorefinery simulation is listed in Tables 2a &

2b. There is no data missing from the biorefinery operations. Detailed process parameters are listed in Crawford (2013).

The biorefinery process begins with a dilute acid pretreatment step that breaks down the poplar chips into three major components: cellulose, hemicellulose, and lignin. During the pretreatment the hemicellulose is hydrolyzed into its constituent monomer sugars. Enzymatic hydrolysis is required to convert cellulose to glucose. These monomer sugars, consisting predominantly of glucose and xylose are fermented to acetic acid using *Moorella thermoacetica*. Acetic acid undergoes two distillation steps, hydrogenation, oligomerization, and hydrogenation to become jet fuel. A key feature of the biorefinery is the hydrogenation steps, which are vital to producing the jet fuel hydrocarbon. Hydrogen necessary for these steps is modeled to be produced from a Steam Methane Reforming (SMR) plant integrated into the biorefinery. The integrated SMR system is based on the work at the Idaho National Laboratory (Gandrik et al 2010). Natural gas is used as the methane source.

The lignin, separated out after sugars are converted to acetic acid (Figure 1), is recovered and sent to an onsite burner/boiler, where it is combusted to produce heat, steam, and electricity to operate the biorefinery. The combustion of lignin will not produce all the heat and steam necessary to operate the biorefinery. Natural gas is combusted to make up the rest of the plants demand for process steam and heat. Due to the nature of electricity production within the biorefinery a small amount of excess electricity is generated as a by-product.

Waste water is treated onsite in a Waste Water Treatment (WWT) plant. The WWT design is based on Humbird et al. (2011). Gypsum is produced from the burner exhaust gas during the removal of sulfur containing gases. Gypsum is also produced in a pre-hydrolysis acid neutralization step. The gypsum and ash from the burner are collected and sent to a landfill for disposal.

Table 2a: Poplar chemical composition per mega joule of jet fuel. This table is representative of how the poplar composition is entered in the ASPEN biorefinery model. Xylan, five carbon polysaccharides (C5SOLD) (other than xylan), and six carbon polysaccharides (C6SOLD) combined represent the hemicellulose content.

Chemical	% dry weight	kg/MJ jetfuel
Cellulose	42	0.0372
Xylan	15.3	0.0135
Lignin	25.8	0.0228
C5SOLD	1.91	0.00169
C6SOLD	5.73	0.00507
Acetate	2.86	0.00253
Extractives	4.5	0.00398
Ash	1.91	0.0169
Total	100	0.0884

Table 2b: Poplar elemental composition per mega joule of jet fuel. . Xylan, five carbon polysaccharides (C5SOLD) (other than xylan), and six carbon polysaccharides (C6SOLD) combined represent the hemicellulose content.

Chemical	**Carbon**	**Hydrogen**	**Oxygen**	**Nitrogen**	**Sulfur**
Cellulose	0.0165	0.00231	0.0183	0	0
Xylan	0.00615	0.000827	0.00655	0	0
Lignin	0.0177	0.00207	0.00306	0	0
C5SOLD	0.000767	0.000103	0.000818	0	0
C6SOLD	0.00225	0.000316	0.0020	0	0
Acetate	0.00101	0.00017	0.00135	0	0
Extractives	0.000486	4.48E-06	0.00328	0.000208	3.61E-06
Ash	NA	NA	NA	NA	NA
Total	0.0448	0.0058	0.0359	0.000208	3.61E-06
%	51.7	6.69	41.4	0.239	0.00417

Data quality requirements

To ensure the greatest amount of honesty about accuracy and transparency the following data quality requirements are outlined as per Cooper and Kahn (2012). This data quality approach will allow for data to be scored as an A if it meets the below requirements, or a B if it does not. The data quality is stated for each unit process below.

Category Requirements for a data quality score of A

1. Reliability and reproducibility

The flow data were based on measurements using a specified and standardized measurement method OR The flow data were estimated using methods and data described in specified archival or other consistently publically available sources.

2. Flow data completeness

The flow data were collected over at least 3 years for agricultural (crop, livestock,forest, range) processes or other processes in which the data point varies for uncontrolled annual conditions (e.g., weather) AND The flow data balance the mass and energy in and out of the unit process.

3. Temporal coverage

The flow data represent operations that occurred between the unit process start and end dates without forecasting.

4. Geographical coverage

The flow data represent operations that occurred within the location of the unit process, including non-agricultural process data that have been adapted to reflect logistics and market shares for the unit process location.

5.Technological coverage

The flow data represent the process(es) and/or material(s) specified without surrogacy or aggregation with other technologies.

6. Uncertainty

The flow data either include estimates of the first quartile, mean, median, and third quartile values OR data or probability distribution from which these values can be estimated.

7. Precision

The relative standard error of the flow data is less than or equal to 25% OR The interquartile range divided by the median is less than or equal to 50% OR For a triangular distribution, the minimum flow data value is 75% and maximum flow data value is "125% of the most likely value OR For a uniform distribution, the minimum flow data value is 75% and maximum flow data value is "125% of the average of the minimum and maximum values.

Life Cycle Inventory

Data collection

Simapro is used to access unit processes in the United States Life Cycle Inventory (USLCI) (NREL, 2011) and Ecoinvent (Swiss Centre for Life Cycle Inventories, 2009) databases. Many of the unit processes used are modified to use electricity from the 2012 U.S. national grid (see discussion below). This was done so that European process in Ecoinvent would be more representative of production in the U.S. Descriptions of which unit processes have been modified are included in the LCI unit processes section below.

Electricity

All unit processes within the system boundaries are set for production in the U.S. To simulate this, all electricity used in each unit process was set to come from the 2012 U.S. national electrical grid. In Simapro a unit process was created that reflects this electrical grid makeup (Table 3). Descriptions of each type of electricity and their respective data sources are listed in the LCI unit processes section below. For “green” sources of electricity (hydroelectric, wind, wood, geothermal and solar) it is assumed that they would not produce emissions so the use of a dummy flow is acceptable. The ‘other’ type of electricity listed in Table 3 is not included as this is made up of various minor fossil fuel electrical production processes and does not have a significant contribution to the LCA work.

Table 3: 2012 U.S. National Electrical Grid Makeup (EIA.gov)

Type	%
Coal	37.4
Natural gas	30.4
Nuclear	19.0
Hydroelectric	6.7
Wind	4.43
Waste biomass	0.963
Wood biomass	0.688
Petroleum (modeled as residual fuel oil)	0.565
Geothermal	0.563
Solar	0.0642
Other	0.584

Transportation

The poplar chips are assumed to be transported a distance of 100 km to the refinery via a chip van. This is the maximum economic transport distance (Wiloso et al. 2012). The chip van is modeled to return empty back to the poplar tree farm.

Enzymes are assumed to be transported from the Novozymes manufacturing plant in Franklinton, NC. A shipping distance of 4300 kilometers is used. This distance would allow for transportation to a biorefinery anywhere in the lower 48 states (Table 4).

The 2007 commodity flow survey (CFS) (U.S. Department of Transportation (DOT), 2010) is used to calculate transportation distances of materials to the biorefinery when the suppliers location is undetermined (sulfuric acid, lime, etc.). The CFS is also used to calculate the transportation distance of wastes from the biorefinery to a landfill. Unit processes that use the CFS for transportation are identified in the LCI unit process descriptions. To determine transportation distances materials/wastes are assigned to a corresponding two-digit commodity listed in the CFS. For each two digit commodity the average weighted distances for three single modes of transportation (truck, rail, water) are calculated by multiplying the average miles per transportation method by their relative percent of usage (based on total tonnage) (Table 7 in US DOT, 2010). Average weighted distances are presented in Table 4. The average shared weighted kilometers are used to determine the tonnes*kilometer for transportation of each material/waste.

Table 4: Distances used for materials and wastes transported to and from the biorefinery.

	Type of transportation (km)			
Commodity	**Truck**	**Rail**	**Water**	**Data source**
Poplar chips	100	0	0	Wiloso et al. 2012
Enzymes	4300	0	0	Google maps
Chemical products and preparations (SCTG* 23)	438	73	0	Commodity flow survey (US DOT, 2010)
Other agricultural products (SCTG* 03)	242	122	150	Commodity flow survey (US DOT, 2010)
Waste and scrap (SCTG* 41)	164	60	23	Commodity flow survey (US DOT, 2010)

*Standard Classification of Transported Goods

LCI Unit Processes

Poplar chips – All activities associated with poplar chip production except delivery to the biorefinery gate from a tree farm are outside of the system boundaries. The chemical and elemental composition of the poplar chips used in the ASPEN model are listed in Table 2a&b. (Table 4). The chip van is modeled using USLCI unit process: *Transport, combination truck, diesel powered/*US. The chips are simulated to be transported 100km to the biorefinery (Table 4). Data quality (A,B,B,B,A,B,B)

Truck transportation - Unit process data come from the USLCI. Unit process name: *Transport, combination truck, average fuel mix/US*. Used for transportation calculations. Data quality (A,B,B,B,A,B,B)

Rail transportation - Unit process data come from the USLCI. Unit process base name: *Transport, train, diesel powered/US.* Used for transportation calculations. Data quality (A,B,B,B,A,B,B)

Water transportation - Unit process data come from the USLCI. Used for transportation calculations. Unit process name: *Transport, ocean freighter, average fuel mix/US*. Data quality (A,B,B,B,A,B,B)

Coal electricity – Unit process data come from the USLCI. Unit process name: *Electricity, bituminous coal, at power plant/US*. Used in the 2012 U.S. electrical grid unit process. Data quality (A,B,B,B,A,B,B)

Natural gas electricity – Unit process data come from the USLCI. Unit process name: *Electricity, natural gas, at power plant/US*. Used in the 2012 U.S. electrical grid unit process. Data quality (A,B,B,B,A,B,B)

Nuclear electricity – Unit process data come from the USLCI. Unit process name: *Electricity, nuclear, at power plant/US*. Used in the 2012 U.S. electrical grid unit process. Data quality (A,B,B,B,A,B,B)

Hydroelectricity – USLCI Dummy flow. Unit process name: *Dummy_Electricity, hydropower, at power plant, unspecified/US*. It is assumed that electricity produced from hydropower (renewable energy source) would not produce emissions so the use of a dummy flow is acceptable. Used in the 2012 U.S. electrical grid unit process. Data Quality(B,B,B,B,B,B,B)

Wind electricity – USLCI Dummy flow. Unit process name: *Dummy_Electricity, at wind power plant, unspecified/US*. It is assumed that electricity produced from wind power would not produce emissions (renewable energy source) so the use of a dummy flow is acceptable. Used in the 2012 U.S. electrical grid unit process. Data Quality(B,B,B,B,B,B,B)

Waste biomass electricity – Unit process data come from EcoInvent 2.0. Unit process name: *Electrcity from waste, at municipal waste incineration plant/CH with US electricity U*. Dummy flow in EcoInvent. Used in the 2012 U.S. electrical grid unit process. Data Quality(B,B,B,B,B,B,B)

Wood biomass electricity – Unit process data come from USLCI. Unit process name: *Eletricity, biomass, at power plant/US*. Used in the 2012 U.S. electrical grid unit process. Data Quality (B,B,B,B,B,B,B)

Petroleum electricity - Unit process data come from the USLCI. Unit process name: *Electricity, residual fuel oil, at power plant/US*. Used in the 2012 U.S. electrical grid unit process. Data quality (A,B,B,B,A,B,B)

Geothermal electricity – USLCI Dummy flow. Unit process name: *Dummy_Electricity, geothermal, unspecified/US*. It is assumed that electricity produced from geothermal power would not produce emissions (renewable energy source) so the use of a dummy flow is acceptable. Used in the 2012 U.S. electrical grid unit process. Data Quality(B,B,B,B,B,B,B)

Solar electricity – USLCI Dummy flow. Unit process name: *Dummy_Electricity, solar, unspecified, at power plant/US*. It is assumed that electricity produced from solar power would not produce emissions (renewable energy source) so the use of a dummy flow is acceptable. Used in the 2012 U.S. electrical grid unit process. Data Quality(B,B,B,B,B,B,B)

2012 U.S. electrical grid - Unit process created to simulate the 2012 U.S. national electrical grid. Makeup of grid is listed in Table 3. Data Quality (B,B,B,B,B,B,B)

Biorefinery design - The biorefinery design was developed and simulated using ASPEN-Plus v.2004.1 chemical engineering software. The ASPEN simulation is based on a combination of a National Renewable Energy Laboratory (NREL) bioethanol production facility (Humbird et al. 2011), ZeaChem's proposed fermentation process (Verser and Eggeman, 2011), and laboratory work at the Biofuels and Bioproducts Laboratory at the University of Washington. All inputs and outputs from the biorefinery are assessed relative to amount needed to produce 1 MJ of jet fuel (Table 1). Data quality (A,B,B,B,A,B,B)

Sulphuric acid – Unit process data modified from the EcoInvent 2.0 dataset. Unit process base name: *Sulphuric acid, liquid, at plant/RER, U*. Electricity used in the production of sulphuric acid is set to the 2012 U.S. National Grid (Table 3). Transportation of sulphuric acid from the manufacturing plant to the biorefinery is based on the average transportation distance of "chemical products and preparations" reported in the 2007 commodity flow survey (US DOT, 2010) (Table 4). Data quality (A,B,B,B,A,B,B)

Lime – Unit process data modified from the EcoInvent 2.0 dataset. Unit process base name: *Lime, hydrated, packed, at plant/CH U*. Electricity used in the production of lime is set to the 2012 U.S. National Grid (Table 3). Transportation of lime from the manufacturing plant to the biorefinery is based on the average transportation distance of "chemical products and preparations" reported in the 2007 commodity flow survey (US DOT, 2010) (Table 4). Data quality (A,B,B,B,A,B,B)

Calcium carbonate – Unit process data modified from the EcoInvent 2.0 dataset. Unit process base name: *Limestone, milled, packed, at plant/CH U*. Electricity used in the production of limestone is set to the 2012 U.S. National Grid (Table 3). Transportation of limestone from the manufacturing plant to the biorefinery is based on the average transportation distance of "chemical products and preparations" reported in the 2007 commodity flow survey (US DOT, 2010) (Table 4). Data quality (A,B,B,B,A,B,B)

Ammonia – Unit process data modified from the EcoInvent 2.0 dataset. Unit process base name: *Ammonia, steam reforming, liquid, at plant/RER with US electricity U*. Electricity used in the production of ammonia is set to the 2012 U.S. National Grid (Table 3). Transportation of ammonia from the manufacturing plant to the biorefinery is based on the average transportation distance of "chemical products and preparations" reported in the 2007 commodity flow survey (US DOT, 2010) (Table 4). Data quality (A,B,B,B,A,B,B)

Carbon dioxide – Unit process data modified from the EcoInvent 2.0 dataset. Unit process base name: *Carbon dioxide liquid, at plant/RER with US electricity U*. Electricity used in the production of carbon dioxide is set to the 2012 U.S. National Grid (Table 3). Transportation of carbon dioxide from the manufacturing plant to the biorefinery is based on the average transportation distance of "chemical products and preparations" reported in the 2007 commodity flow survey (US DOT, 2010) (Table 4). Data quality (A,B,B,B,A,B,B)

Enzymes –The enzyme data included in this LCA comes from Novozymes, a predominant manufacturer of enzymes. The data is based on their Cellic Ctec 3 enzyme system. The environmental flows that result from all inputs of heat, electricity, waste management and 96% of ingredients for enzyme production were provided by Novozymes and uploaded to SimaPro (personal communication, 2012). The electricity source used is unknown, but the enzyme data is based on production in the U.S. in 2012. A shipping distance of 4300 kilometers is used (Table 4). Data quality (A,B,B,B,A,B,B)

Clarifier polymer – Assumed to be polypropylene, a common clarifier polymer. Unit process data modified from the EcoInvent 2.0 dataset. Unit process base name: *Polypropylene, granulate, at plant/RER with US electricity U*. Electricity used in the production of polypropylene is set to the 2012 U.S. National Grid (Table 3). Transportation of polypropylene from the manufacturing plant to the biorefinery is based on the average transportation distance of "chemical products and preparations" reported in the 2007 commodity flow survey (US DOT, 2010) (Table 4). Data quality (A,B,B,B,B,B,B)

Corn steep liquor – Unit process data modified from the USLCI dataset. Unit process base name: *Corn steep liquor*. Transportation of corn steep liquor from the manufacturing plant to the biorefinery is based on the average transportation distance of "other agricultural products" reported in the 2007 commodity flow survey (US DOT, 2010) (Table 4). Data quality (A,B,B,B,A,B,B)

Sodium hydroxide – Unit process data modified from the EcoInvent 2.0 dataset. Unit process base name: *Sodium hydroxide, 50% in H_2O, production mix, at plant/RER U*. Electricity used in the production of sodium hydroxide is set to the 2012 U.S. National Grid (Table 3). Transportation of sodium hydroxide from the manufacturing plant to the biorefinery is based on the average transportation distance of "chemical products and preparations" reported in the 2007 commodity flow survey (US DOT, 2010) (Table 4). Data quality (A,B,B,B,A,B,B)

Nickel catalyst – Data that only includes the production of nickel is used. The type of nickel catalyst used and how it is produced is proprietary information. However, the amount of catalyst used is very small and converting the nickel to a catalytic form would likely not affect the LCA. Unit process data modified from the EcoInvent 2.0 dataset. Unit process base name: *Nickel, 99.5%, at plant/GLO with US electricity U*. Electricity used in the production of nickel is set to the 2012 U.S. National Grid (Table 3). Transportation of nickel from the manufacturing plant to the biorefinery is based on the average transportation distance of "chemical products and preparations" reported in the 2007 commodity flow survey (US DOT, 2010) (Table 4). Data quality (A,B,B,B,B,B,B)

Alumina catalyst – Data that only includes the production of alumina is used. The type of alumina catalyst used and how it is produced is proprietary information. However, amount of catalyst used is very small and converting the alumina to a catalytic form would likely not affect the LCA. Unit process data come from the USLCI dataset. Unit process base name: *Alumina at plant/US*. Transportation of alumina from the manufacturing plant to the biorefinery is based on the average transportation distance of "chemical products and preparations" reported in the 2007 commodity flow survey (US DOT, 2010) (Table 4). Data quality (A,B,B,B,B,B,B)

Natural gas – Unit process data modified from the EcoInvent 2.0 dataset. Unit process base name: *Natural gas, at consumer/RNA with US electricity U*. Electricity used in the production of natural gas is set to the 2012 U.S. National Grid (Table 3). A HHV of 54.4 MJ/kg is used to convert natural gas mass to energy. Data quality (A,B,B,B,A,B,B)

Gypsum waste – Unit process data modified from the EcoInvent 2.0 dataset. Unit process base name: *Disposal, gypsum, 19.4% water, to inert material landfill/CH U*. Electricity used in the production of gypsum is set to the 2012 U.S. National Grid (Table 3) Transportation of gypsum from the biorefinery to the landfill is based on the average transportation distance of “waste and scrap” reported in the 2007 commodity flow survey (US DOT, 2010) (Table 4). Data quality (A,B,B,B,A,B,B)

Ash waste – Unit process data modified from the EcoInvent 2.0 dataset. Unit process base name: *Disposal, wood ash mixture, pure, 0% water, to sanitary landfill/CH with US electricity U*. Electricity used in the production of wood ash is set to the 2012 U.S. National Grid (Table 3). Transportation of ash from the biorefinery to the landfill is based on the average transportation distance of “waste and scrap” reported in the 2007 commodity flow survey (US DOT, 2010) (Table 4). Data quality (A,B,B,B,A,B,B)

Critical reviews

The external review process is intended to ensure consistency between the completed LCA and the principals and requirements of the International Standards on LCA (ISO 2006). Documents were submitted to WoodLife Environmental Consultants for independent external review. The independent external review performed by WoodLife Environmental Consultants was conducted by:

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References

Aspen Technology Inc. (ATI). 2005. Aspen Plus, version 2004.1. ATI, Cambridge, Massachusetts.

Crawford, J. 2013. Techno-economic analysis of hydrocarbon biofuels from poplar biomass (Masters thesis). University of Washington, Seattle, WA. Retrieved from https://digital.lib.washington.edu/researchworks/bitstream/handle/1773/25142/Crawford_washington_0250O_12629.pdf?sequence=1.

Gandrik A.M., Wood R.A., Patterson M.W., and P.M. Mills. 2010 HTGR-Integrated Hydrogen Production via Steam Methane Reforming Process Analysis. Idaho Falls (ID): Idaho National Laboratory; Technical Evaluation Study TEV-954 Project No. 23843

Humbird, D., Davis, R., Tao, L., Kinchin, C., Hsu, D., Aden, A., Schoen, P., Lukas, J., Olthof, B., Worley, M., Sexton, D., and D. Dudgeon. 2011. Process Design and Economics for Biochemical Conversion of

Lignocellulosic Biomass to Ethanol; Dilute-acid Pretreatment and Enzymatic Hydroylsis of Corn Stover. National Renewable Energy Laboratory, Golden, Colorado.

International Organization for Standardization (ISO). 2006a. Environmental management. Life cycle assessment. Principles and framework. ISO 14040:2006. ISO, Geneva.

International Organization for Standardization (ISO). 2006b. Environmental management. Life cycle assessment. Requirements and guidelines. ISO 14044:2006. ISO, Geneva.

National Renewable Energy Laboratory (NREL). 2011. US life cycle inventory database. http://www.nrel.gov/lci/. Accessed September 5, 2012.

Pre Consultants. 2012. Simapro 8 Life-Cycle Assessment Software package. Version 8.0. Plotter 12, 3821 BB Amersfoort, The Netherlands. Http://www.pre.nl/.

Swiss Centre for Life Cycle Inventories (SCLCI). 2009. EcoInvent database 2.1. SCLCI, Duebendorf, Switzerland.

U.S. Department of Transportation (US DOT) and U.S. Department of Commerce (US DOC). 2010. 2007 Commodity Flow Survey. http://www.census.gov/prod/2010pubs/ec07tcf-us.pdf accessed on July 11, 2013.

Verser, D., and T.J. Eggeman. 2011. United States Patent No. 7,964,379 B2.

Wiloso, E.I., Heijungs, R., and G. R. de Snoo. 2012. LCA of second generation bioethanol: A review and some issues to be resolved for good LCA practice. Renewable and Sustainable Energy Reviews. 16, 5295-5308.