Required Document No.2 – Pathway Life Cycle Analysis Report

Life Cycle GHG Emissions

For Fulcrum Sierra BioFuels, LLC's

MSW-to-Fischer Tropsch Fuel Production Process

LCA.6060.120.2015
December 2015

Prepared by:
Stefan Unnasch

DISCLAIMER

This report was prepared by Life Cycle Associates, LLC for Fulcrum Sierra BioFuels, LLC ("Sierra BioFuels"). Life Cycle Associates, LLC is not liable to any third parties who might make use of this work. No warranty or representation, express or implied, is made with respect to the accuracy, completeness, and/or usefulness of information contained in this report. Finally, no liability is assumed with respect to the use of, or for damages resulting from the use of, any information, method or process disclosed in this report. In accepting this report, the reader agrees to these terms.

This report contains confidential information and may not be distributed except as required by law.

ACKNOWLEDGEMENT

Life Cycle Associates, LLC performed this study with funding from Sierra BioFuels. Sierra BioFuels' Project Manager was Jeanne Benedetti. The study's authors are indicated in the citation below.

Contact Information:

Stefan Unnasch
Life Cycle Associates, LLC
(650) 461-9048
unnasch@LifeCycleAssociates.com
www.LifeCycleAssociates.com

Recommended Citation: Unnasch. S. (2015) Avoided Life Cycle GHG Emissions from MSW Disposal, Life Cycle Associates, Report No. LCA6060.120.2015, Prepared for Fulcrum BioEnergy, Inc.

Contents

Tables

Figures

Summary

Fulcrum BioEnergy, Inc. ("Fulcrum"), is the parent company of Fulcrum Sierra BioFuels, LLC ("Sierra BioFuels" or the "Applicant"), that has prepared a Method 2B Application for the establishment of a new fuel pathway under the California Low Carbon Fuel Standard ("LCFS") for its process of converting municipal solid waste ("MSW") into low-carbon, Fischer-Tropsch ("FT") diesel fuel.

Sierra BioFuels is constructing and will own and operate a commercial scale MSW-to-FT diesel fuel facility comprised of a Feedstock Processing Facility and a Biorefinery (together the "Sierra BioFuels Plant"). The Feedstock Processing Facility is located near the Lockwood Regional Landfill in Storey County, Nevada. The Biorefinery is located approximately 20 miles east of Reno in the Tahoe-Reno Industrial Center.

The Feedstock Processing Facility will receive MSW that would otherwise be landfilled. A sophisticated feedstock processing system shreds, screens, and sorts the MSW producing a MSW-derived feedstock meeting the feedstock specification required for conversion into renewable fuel at the Biorefinery and recovers materials that can be recycled (e.g. ferrous and nonferrous metals and high value plastics) for sale.

The Biorefinery will convert the MSW Feedstock into fuel by using a three-step process comprised of steam reforming gasification, FT liquids synthesis and hydroprocessing upgrading technologies to produce FT diesel. Additional natural gas is used in this process.

The objective of this study is to determine the life cycle greenhouse gas ("GHG") emissions from Sierra BioFuels' MSW-to-FT fuel production process using parameters based on Fulcrum's process design for the Sierra BioFuels Plant.

Converting MSW into biofuels or landfilling the material both result in GHG emissions. The landfilling of biomass results in emissions when the biogenic material decomposes into landfill gas ("LFG"). The LFG is either captured and flared, seeps from the landfill, or is oxidized through biological activity as the gas migrates through the cover soil and is converted to carbon monoxide ("CO_2").

The total GHG emissions are equal to those associated with the FT fuel production process minus the avoided emissions from landfilling the MSW. The recovery of recyclable material also results in lower GHG emissions by displacing the production of new metals and plastics as well as producing ash which can be put to a beneficial use (e.g. cement production).

Life Cycle Associates calculated the life cycle GHG emissions using the biomass to FT fuel approach in California modified Greenhouse gases, Regulated Emissions, and Energy use in Transportation model, version 1.8b, released December 2009 ("CA-GREET"). Upstream fuel cycle emissions are from CA-GREET and avoided emissions from landfilling are based on the California Air Resources Board's ("CARB") analysis of landfill materials for fuel pathways.

The GHG emissions are reported with a functional unit of grams carbon dioxide equivalent (“CO_{2e}”) per mega joule (“MJ”) of FT diesel product and then compared with petroleum-based fuels on a per MJ basis.

Producing FT diesel in Sierra BioFuels’ MSW-to-FT fuel production process results in more than 60% reduction in GHG emissions.

The carbon intensity (CI) under the LCFS for Sierra BioFuels’ FT diesel is 37.47g CO2e/MJ. **Figure 1** shows the CI resulting from the production of FT diesel as compared to baseline petroleum. The negative emissions from the feedstock correspond to avoided landfill emissions that would occur if the feedstock were not converted to biofuel as well as a credit for recovering additional materials for recycling.

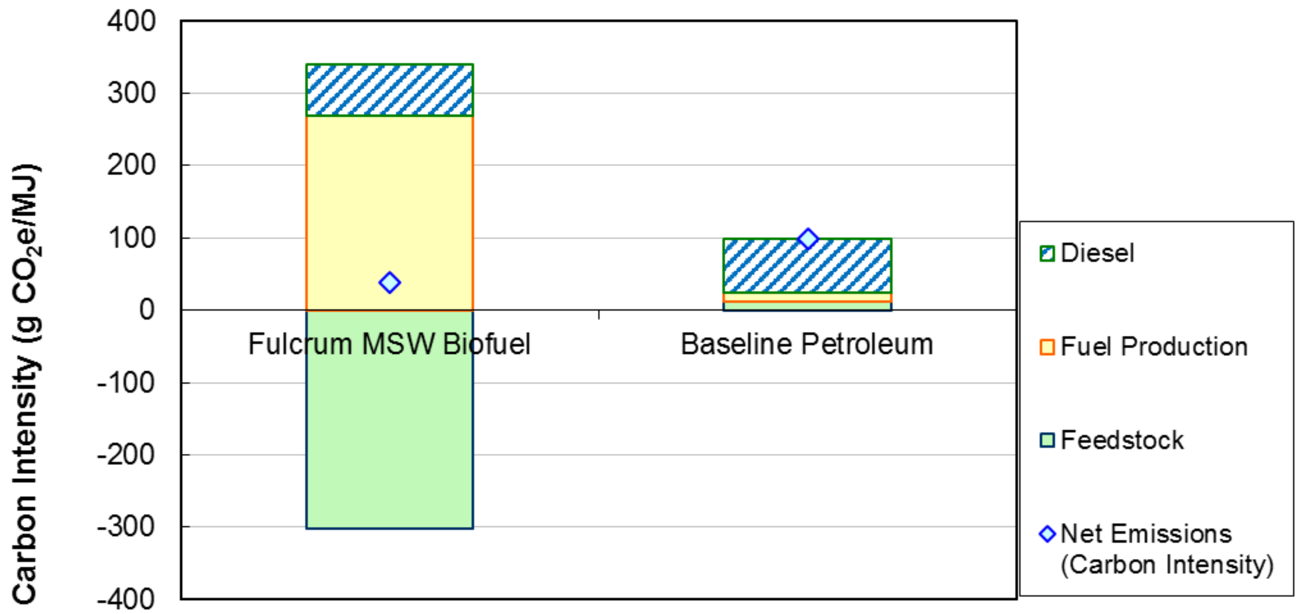

Figure 1. Carbon Intensity for Production of FT Diesel Compared to Petroleum

1. Introduction

1.1 Background

MSW provides a potential feedstock for a variety of biofuel production technologies. These include digestion of the wet organic fraction of MSW (e.g. food and yard waste) and gasification of the dry organic fraction of MSW (e.g. cardboard, textiles, wood, etc.) to produce synthesis gas for further conversion to fuels. The U.S. Environmental Protection Agency ("EPA") has determined that the biogenic fraction of MSW-derived fuels qualifies as a cellulosic biofuel, assuming a 60% reduction in GHG emissions (EPA 2014a). The CARB developed a fuel pathway based on the use of food waste and green waste as a feedstock for anaerobic digestion (CARB 2012). A study from the International Council on Clean Transportation ("ICCT") also examines GHG emissions from MSW to fuels (Baral 2014). These studies and others show the GHG reduction potential of diverting biogenic material from landfilling to fuel production.

The Fulcrum FT fuel production process is unique because it uses a biogenic material as a feedstock, recovers materials for recycling, and produces a renewable fuel product. The life cycle GHG emissions from the Sierra BioFuels Plant are examined here based on the specific feedstock composition, process configuration, and quantity of recycled materials recovered.

1.2 Objective and Scope

The objective of this analysis is to calculate the life cycle GHG emissions from Sierra BioFuels' MSW-to-FT fuel process. The analysis is being performed to support a Method 2B Application for the establishment of a new pathway under the LCFS using the CA-GREET model. The analysis is consistent with EPA's use of the GREET model under the 2007 Energy Independence Act expansion of the Renewable Fuels Standard ("RFS2") (EPA 2010a), EPA's Waste Reduction Model ("WaRM") (EPA 2010b), and CARB's analysis of landfilled material under the LCFS (ARB 2012). The analysis is follows the framework for biomass to FT diesel in a modified CA-GREET. The calculation of avoided landfill emissions follows the CARB's approach used for waste material pathways.

The emissions are reported with a functional unit of g CO_{2e} per MJ of FT diesel and then compared with petroleum-based fuels on a per MJ basis. CA-GREET provide the basis for the life cycle GHG analysis and comparison with petroleum fuels. The impacts from the recyclable materials (e.g. ferrous and nonferrous metals and high value plastics) separated from the MSW, the ash produced in the gasification process and avoided landfill emissions are distributed between the FT diesel and recycled material.

2. Life Cycle Associates' Approach

2.1 Scope of Well to Wheels Calculation

The life cycle components include the sum of the process inputs from the Sierra BioFuels Plant, including the processing and transportation of feedstock, recovery of recyclable materials, natural gas usage at the Biorefinery, FT diesel delivery to California and vehicle operation. These steps encompass the well-to-tank ("WTT") and tank-to-wheel ("TTW") scope that are calculated in the CA-GREET model. The WTT phase includes the upstream or fuel cycle emissions. The TTW phase includes the emissions from the vehicle including fuel carbon converted to CO_2 as well as oxides of nitrogen ("NO_x") and methane ("CH_4") emissions generated by combustion equipment.

2.1.1 System Boundary

The typical fate of MSW disposed of in a landfill is depicted in **Figure 2** as the MSW Disposal Reference System. The avoided landfill emissions are consistent with the total emissions approach used by CARB for the high solids anaerobic digester pathway from food waste and green waste to CNG (ARB 2012). This method accounts for all of the carbon in the feedstock, which absent biofuel production, would be converted to CO2, CH4, or remain in the landfill.

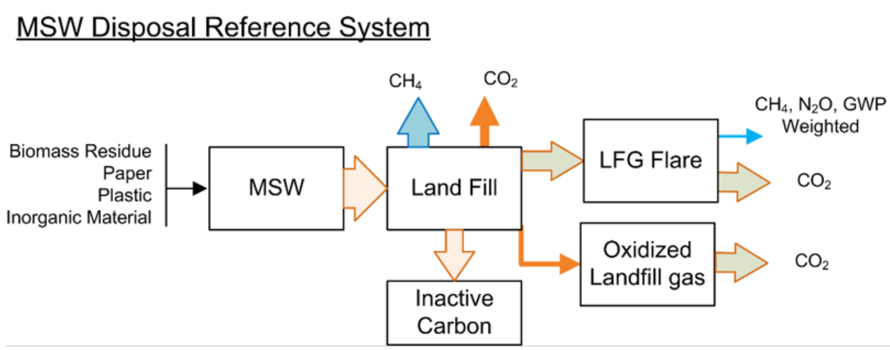

Figure 2. Typical Fate of MSW disposed of in a Landfill

Figure 3 shows the inputs and emission sources for the Fulcrum FT fuel production process for the conversion of MSW feedstock into FT diesel.

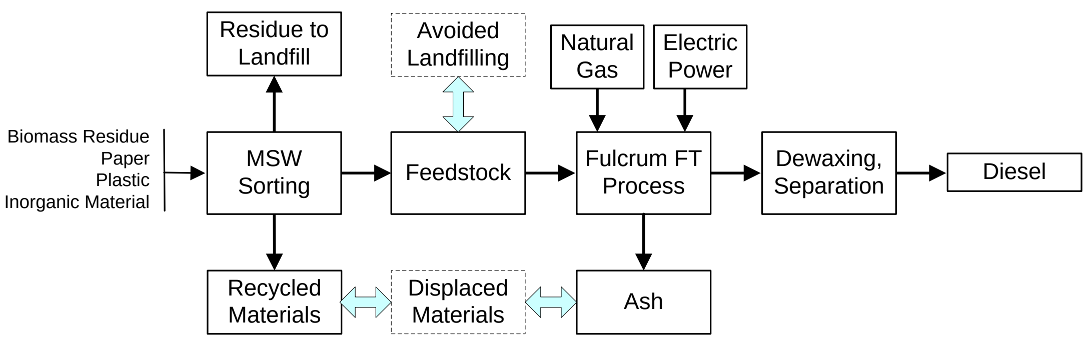

Figure 3. Fulcrum's FT Fuel Production Process

The Feedstock Processing Facility will receive MSW that would otherwise be landfilled. A sophisticated feedstock processing system shreds, screens, and sorts the MSW producing a MSW-derived feedstock meeting the feedstock specification required for conversion into renewable fuel at the Biorefinery. Recyclable materials (e.g. ferrous and nonferrous metals and high value plastics) are recovered and sold to the commodity market. Residual materials (e.g. inerts, high moisture content waste) are sent to the landfill. The MSW feedstock is transported to the Biorefinery where it is converted to FT diesel using a three-step process comprised of steam reforming gasification, FT liquids synthesis and hydroprocessing upgrading technologies. Natural gas is also burned for process energy and additional power is imported from the grid.

The production of FT diesel in the Fulcrum FT fuel production process results in several carbon streams, including process emissions, traces of carbon in the form of char or ash, and synthesis gas that is converted to fuel product. In the case of Sierra BioFuels Plant, the majority of the carbon in the feedstock is either converted to fuel or CO_2.

Thus, determining the life cycle GHG impacts of the MSW-to-FT diesel process requires comparing the emissions from MSW-to-FT fuel production with those from landfilling MSW[1]. The life cycle GHG emissions from the production of FT diesel from MSW based on the Sierra BioFuels Plant design are compared against the emissions associated with the alternative fate of hauling and landfilling MSW and the production and combustion of the petroleum-derived diesel which is displaced by the FT diesel.

GHG emission sources from the Sierra BioFuels Plant include the fuel production process, transport, and vehicle end use. The process also produces recyclable materials that would otherwise be disposed of in the landfill. These materials are instead recycled. Landfill impacts including transport are allocated to FT diesel and recycled material based on mass.

2.2 Life Cycle of MSW to Landfill and Biofuel Production

The alternative fate of the MSW is disposal in a landfill, which is still the most common procedure for waste disposal. Landfill operations include distributing the MSW into a so-called working face, followed by crushing of the material. MSW is deposited into an open area of the landfill called a cell. Once the cell is filled, it will be covered with soil or other alternative daily cover ("ADC") materials. During the life time of the landfill cell, biogenic material decomposes to form LFG. The fraction of the material that is converted to LFG depends on the type of materials in the buried MSW as well as the landfill conditions and gas recovery system.

Landfill material undergoes many processes over time. A portion of carbon remains in the landfill and a portion undergoes anaerobic decomposition, which converts the material into CH_4 and CO_2.

[1] This concept seems self evident. However, many efforts to examine MSW processing only take into account the CH_4 emissions from landfills and not the total emissions.

Several mechanisms represent the fate of carbonaceous materials in landfills. The carbon can remain in the landfill in long-term carbon storage or biologically degrade to form CH_4 and CO_2. Today, many landfill sites have landfill gas collection systems which collect a majority of the LFG produced by decomposition of the MSW. The LFG is actively collected in a series of pipes then either burned in a flare or combusted in a waste-to-energy system such as an internal combustion engine to produce electricity, both of which result in the production of CH_4 and NO_x. emissions[2]. In some landfills, LFG is flared because LFG-fired engines cannot meet applicable NOx emission standards. The LFG can also escapes from the landfill before being captured by a collection system or undergo aerobic decomposition where the CH_4 is converted to CO_2.

3. Fulcrum Process Data

Sierra BioFuels developed a process simulation model for the Fulcrum FT fuel production process, using the design basis for the Sierra BioFuels Plant. The Fulcrum FT fuel production process includes the gasification of MSW to a synthesis gas ("syngas"), further processing the syngas into a FT fuel product, and removal of CO_2 among the many processing steps.

Sierra BioFuels' process simulation model takes into account:

- Composition of Feedstock
- Feedstock to Fuel Yield
- Conversion of Feedstock into Synthesis Gas and CO_2 Separation
- Combustion of Natural Gas and Tail Gas
- Mix of Additional Recyclable Materials

The simulation model estimates the material balance for reactants from feedstock to FT reactor feed, heat loads and process fuel requirements, compression and other utility requirements. The FT diesel produced at the Biorefinery is shipped to a terminal in California for blending and/or sale to the market.

The primary inputs provided to Life Cycle Associates included purged CO_2, power consumption, natural gas consumption, and feedstock to fuel yield. **Table 1** below, displays the inputs and yields for the Fulcrum FT fuel production process. This yields a total daily production of REDACTED gallons and REDACTED GJ of fuel. The avoided landfill emissions and co-product credit for recovered recyclable materials is based on the feedstock composition and discussed in Section 4, below.

[2] LFG can be used for electric power production or in other energy recovery applications

Table 1. Inputs and Yields for FT Production Configurations

REDACTED

Figure 4 shows the sources of GHG emissions from the production of FT diesel using the Fulcrum FT fuel production process. Except for the CO_2 vent, all of the other sources correspond to natural gas combustion.

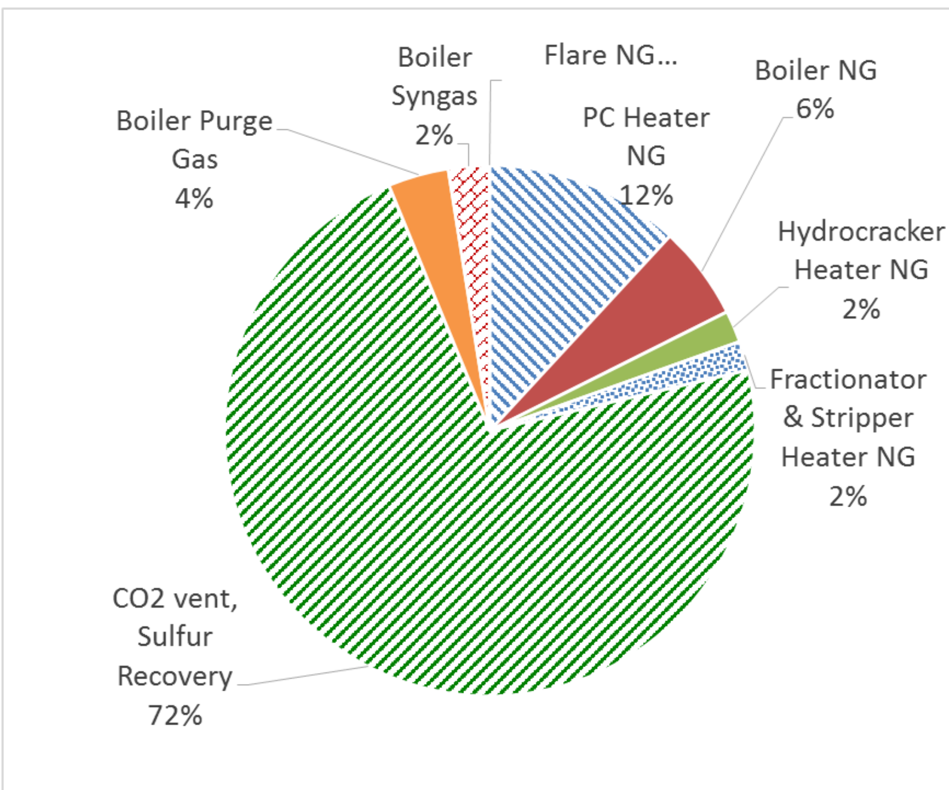

Figure 4. CO_2 Emission Sources from the Production of FT Diesel

The carbon balance for the Fulcrum FT fuel production process was verified to assure closure such that the input carbon equals the output carbon. Input carbon includes MSW and natural gas. Output carbon includes FT diesel product, the emissions sources from the Biorefinery, and small amounts in the gasifier ash.

4. LCA Model

An Excel™ spreadsheet model calculates the life cycle GHG emissions from the Fulcrum FT fuel production process. The spreadsheet model provides the following functions:

- Calculation of feedstock, recycled material mass, carbon content, and inactive carbon
- Calculation of avoided landfill emissions
- Calculation of emissions for the Sierra BioFuels Plant
- Calculation of transportation related emissions
- Aggregation of annual data into g CO_{2e} per MJ values
- Calculation of life cycle GHG emissions
- GHG emission results

The key modeling steps are described below.

4.1 GHG Emissions from Landfills

The avoided emissions from landfilling MSW are estimated from landfill parameters, the composition of MSW, and landfill emission control parameters. These emissions are estimated with a carbon balance model using data that are derived from literature as well as EPA and ARB landfill models.

LCA Associates estimated the landfill emissions over the lifetime of the landfill based on parameters used in the landfill industry to characterize LFG production, capture efficiencies, and emission control. The methodology for determining the emissions from avoiding landfilling of MSW is provided in **Appendix A**. A carbon balance model was used to determine the total landfill emissions and the basis for the emission estimates is consistent with the methodology used by CARB in assessing the diversion of biomass feedstock for biofuel production (ARB 2012). The carbon balance model constrains the feedstock to the possible fates in the landfill. Flared LFG is primarily combusted to form CO_2 and leaked gas is a mixture of CO_2 and CH_4.

Table 2 shows the parameters used to estimate the fate of carbon in MSW in landfills and the related GHG emissions. Emissions are estimated over the life of the material rather than on a time-dependent basis[3]. The GHG emissions are determined by accounting for

[3] An alternative approach would be to estimate emissions through the application of a first-order decay model for LFG generation using the annual mass of organic waste diverted for the life of the project and the appropriate “k” (decay rate) and methane generation potential for the specific organic waste being diverted. This can be modeled on an annual average or total lifetime basis for the length of the project. Ultimately a

all of the carbon by first subtracting the inactive carbon, then flare emissions, and then finally distributing leaked LFG between the leaks and the fraction that is aerobically converted to CO_2.

Table 2. Landfill Carbon Balance Parameters

Parameter	Variable	Value	Range/Source
Collection Efficiency	LFη	75%	65% to 85%/ARB 2012
Inactive Carbon	INC	24%	EPA's WaRM
CH_4/CO_2 mol fraction	X CH4	50:50	45% to 54%
Oxidized Fraction	OX	10%	10% to 30%/ARB 2012
Flare Efficiency	FLη	99%	98% to 99.77%
Flare N_2O/CO_2	X N_2O	1.6×10^{-4}	GREET

LFG collection efficiency depends on landfill operations, moisture conditions, and other parameters. The inputs used by LCA Associates is consistent with the inputs and values by CARB for avoided landfill emissions for biofuel production (ARB 2012).

Not all of the carbon in MSW is converted to LFG during the biological conversion processes in the landfill. EPA also estimates the fraction of stored carbon from different materials (EPA 2010c). In general plastics do not decompose in landfills and biogenic materials decompose at a rate dependent upon their composition. **Table 3** provides the inactive carbon content for various types of landfilled material. Carbon from inorganic materials like plastic tends to remain in the landfill while food waste degrades almost completely.

collection efficiency must be applied to the generation estimates to account for the amount of LFG that escapes from the landfill so the approach presented here is no less uncertain.

Table 3. Inactive Carbon Storage Factors for Landfilled Materials

Material	Carbon Storage Factor
Biomass Materials [a]	
Paper, Mixed	0.24
OCC (cardboard)	0.26
Wood Waste	0.38
Textiles, Fabric	0.01
Food Waste	0.08
Green Waste	0.355
Fines	0.22
Inorganic Materials	
Plastic	100%
Glass	100%
Foam	100%
Metal	100%

[a] EPA 2010c, Exhibit 5

The fraction of carbon in the feedstock produced by the Sierra BioFuels Plant that remains in the landfill is calculated from the EPA's carbon storage factors shown in **Table 3**, above. The total and stored carbon for the Sierra BioFuels Plant's projected feedstock composition is shown in **Figure 5**.

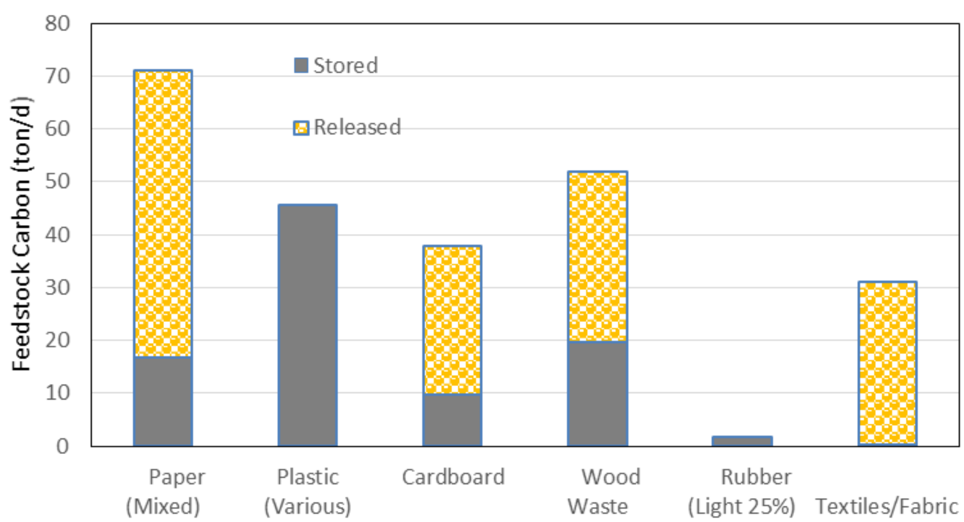

Figure 5. Fate of carbon in Fulcrum's Feedstock

The emission factor for flare emissions in the CA-GREET model corresponds to 99.77% conversion of CH_4[4]. CARB's flare emission factor for inventory purposes is 99%. This factor is also used for estimating emissions from avoided MSW landfilling.

Degradable material in MSW decomposes in the presence of bacteria. Over time the fate of the carbon in the material can be:

- LFG that is captured;
- LFG that escapes from the landfill;
- LFG that is oxidized as it passes through the soil cap and escapes as CO_2; or
- Stored carbon that remains in the MSW or dissolves in leachate and is distributed back to the landfill.

Table 4 shows the carbon balance for the material that is diverted from the landfill. The fate of the carbon in the feedstock is either stored carbon (STC), flared gas (FL), seeped LFG (LFS), or oxidized seeped LFG (LFOX). The corresponding GHG emissions include CO_2, CH_4, and N_2O from the flare. The details of the calculations are provided in **Appendix A**.

[4] The flare efficiency factor is used for flared natural gas as well as LFG in the LFG-to-LNG pathway for the LCFS. Some test data show efficiencies over 99.9% of the CH_4 (SWICS 2009)

Table 4. Carbon Balance for Landfill Emissions

Material	Variable Name	Carbon Balance	Carbon (ton/d)	GHG Emissions (g CO_2e/ton) [d]
Feedstock	LFT	From waste profile	241	2,350,082
Stored Carbon	STC	INC × STC	121	0
Flared LFG	FL	from FLη [a]	137	858,879
Fugitive Aerobic LFG	LFOX	from OX [b]	4.6	27,368
Fugitive Anaerobic LFG	LFS	by difference [c]	41.1	1,245,733

[a] FL = FLη × (LFT - STC)

[b] LFOX + LFS = LFT - STC - FL

[c] LFS = (1-OX) × (LFT - STC - FL)

[d] Avoided landfill emissions = 1,874,328 g CO_2e/ton, 56.4 gal/ton, and 126.4 MJ/gal for FT diesel.

4.2 Recycling

The Fulcrum FT fuel production process recovers 92.4 tons per day of recyclable materials out of approximately 1,101gross tons per day of MSW as part of the separation process that is required to reduce the inert content of the feedstock. These materials would otherwise enter the landfill and they are only recovered after shredding, sorting, magnetic separation, and other processes that would normally not be applied to landfilled MSW. Avoided landfill emissions and MSW movement are allocated to the FT diesel product and recycled material based on mass.

Figure 6 shows the recovered recyclable materials, which are about half metals and one fourth ash which has a beneficial use in the cement manufacturing industry.

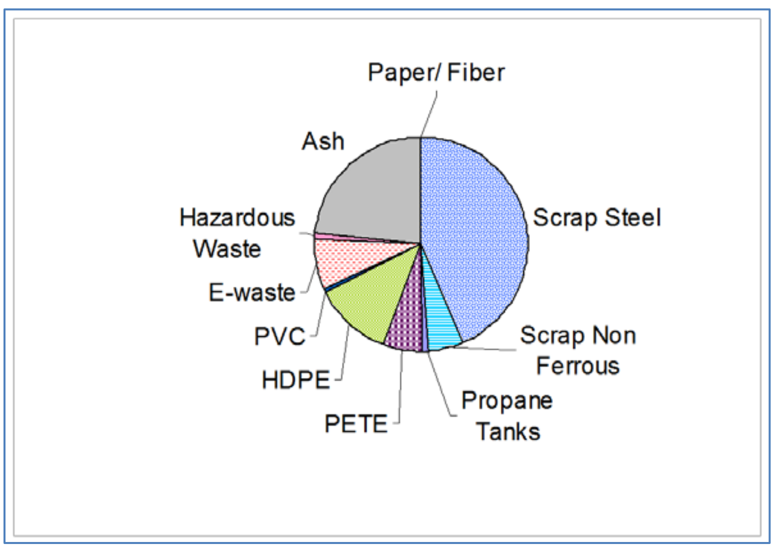

Figure 6. Mix of Recycled Materials Recovered by the Sierra BioFuels Plant.

The quantity of recycle material is shown in **Table 5**. Fulcrum performed waste characterization studies combined with process simulation model to determine the flow of MSW through the separation process to determine the composition of recyclable materials recovered from the MSW.

Table 5. Sierra BioFuels Recycled Material

REDACTED

4.3 Transportation

Transportation impacts associated with the Fulcrum FT fuel production process include differences in the transportation logistics of MSW and the transport of fuel to markets. Diversion of MSW to the Feedstock Processing Facility results in 0.5 miles of reduced transport. Feedstock is then transported 15 miles to the Biorefinery and the residual material is hauled to the landfill. Recycled material is assumed to be hauled 137 miles, which is consistent with the movement of other recycled materials in Nevada. The FT diesel is hauled 215 miles to blending terminals in California.

5. GHG Emission Results

Life cycle GHG emissions results are shown in **Table 6**, below. These reflect the impacts of the avoided landfilling of MSW, various transportation segments, credit for recycled material, emissions associated with the Sierra BioFuels Plant, and fuel combustion.

Table 6. Life Cycle GHG Results

Source	**Fulcrum MSW Biofuel**
Avoided Direct Emissions	-303.8
Recycled Paper/Fiber	0.0
Recycled Metal	
Recycled Plastic	
Recycle e-waste	
Recycled Ash	
MSW Hauling - Material Transport	0.9
Diesel Yard Equipment	0.8
Natural Gas Upstream Fuel Cycle	6.19
Process Emissions, Vents	198.2
Imported Power	62.7
Truck Delivery	1.44
Fuel Station	0.04
FT Diesel	71.0
Total	37.5
WTT GHG Emissions	**-33.5**
Feedstock	-302.9
Recycling	0.0
Fuel Production	269.4
TTW GHG Emissions	
Diesel	70.97
Net Emissions (Carbon Intensity)	**37.47**
Petroleum Baseline	98.8
Reduction	62.1%

GHG emissions are more than 60% below a petroleum baseline. The most significant emissions correspond to the avoided landfilling of MSW, which are roughly equal to the process emissions plus fuel production.

6. GHG Policy Rating Implications

The FT diesel produced by the Sierra BioFuels Plant result in significant GHG reductions compared to petroleum derived diesel. These GHG reductions provide the potential to capture incentives under biofuel policies including the RFS2, various state low carbon fuel standards, including California's LCFS, and the European Union's (EU) Renewable

Energy Directive. Key considerations under each of these programs is summarized below.

6.1 RFS2

The EPA has designated the biogenic fraction of MSW as a cellulosic biofuel (EPA 2014a). About 80% of the feedstock used in the Fulcrum FT fuel production process is biogenic derived feedstock. The determination of the actual biogenic content would likely need to be determined with the use of radiocarbon dating. Sierra BioFuels could potentially sell all of the fuel as advanced biofuel with a 50% GHG reduction threshold. However, EPA has not made a determination about this approach and it would require further analysis by EPA. EPA uses a baseline petroleum diesel emissions that represent the agency's estimate of emissions in the year 2005 as required under the RFS2 regulations.

6.2 LCFS

The analysis presented in this study could serve as a template for the certification of fuels under California's LCFS and the low carbon fuel standards of other states. The CA-GREET model is a different version than that used by EPA but the steps in the analysis should result in similar carbon intensity ("CI") values. The treatment of the avoided landfilling of MSW follows the approach used by CARB for diverting food waste and green waste from landfills (ARB 2012). ARB has performed further evaluations of the CI of crude oil and the California crude oil. The CI of diesel fuel is 99 g CO_2/MJ compared with the RFS2 baseline of 91 g CO_2e/MJ.

6.3 Other Initiatives

The FT diesel produced by the Sierra BioFuels Plant could also be sold into markets in the EU and Canada, which also have GHG incentive programs. The details of these programs will vary. One of the proposed measures under the Renewable Energy Directive is a further incentive for biofuels produced from wastes, residues and (ligno) cellulose material. The European Commission proposes to count these biofuels two or four times towards national biofuel mandates.

The Fulcrum FT fuel production process could also help achieve compliance with Canadian GHG reductions programs, including a LCFS in British Columbia. Oregon and Washington are also in the process of implementing or considering clean fuel standards similar in structure to California's LCFS program.

7. References

ARB (2012) Proposed Low Carbon Fuel Standard (LCFS). Pathway for the Production of Biomethane from High Solids Anaerobic Digestion (HSAD) of Organic (Food and Green) Wastes. Version 1.0 California Air Resources Board, Stationary Source Divistion.

Baral, A. and C. Malins (2014) Potential of Biofuels Derived from Residues and Wastes in the European Context. International Council on Clean Transportation (ICCT).

Barlaz (2008) WARM Model Update, Prepared for EPA, ICF International, http://epa.gov/climatechange/wycd/waste/downloads/Barlaz_Update_Memo_4_21_08.pdf

Barlaz (2009) Controls of Landfill Gas Collection Efficiency: Instantaneous and Lifetime Performance. J. Air & Waste Management Assoc. Vol. 59: 1399-1404.

EPA (2010a) EPA Finalizes Regulations for the National Renewable Fuel Standard Program for 2010 and Beyond. EPA-420-F-10-007, February 2010. http://www.epa.gov/otaq/renewablefuels/420f10007.pdf.

EPA (2010b) Landfill Carbon Storage in WARM October 27, 2010.

EPA (2010c) Waste Reduction Model, Landfills. http://epa.gov/climatechange/wycd/waste/downloads/composting-chapter10-28-10.pdf

EPA (2014a) Regulation of Fuels and Fuel Additives: RFS Pathways II, and Technical Amendments to the RFS Standards and E15 Misfueling Mitigation Requirements; Final Rule. Federal Register Volume 79, No. 138.

EPA (2014b) WARM version 13 documentation, Recycling. http://www.epa.gov/epawaste/conserve/tools/warm/pdfs/Recycling.pdf

Forman, G. S., V. B. Divita, J. Han, H. Cai, A. Elgowainy, and M. Wang. (2014) U.S. refinery efficiency: impacts analysis and implications for fuel carbon policy implementation. Environ Sci Technol. 2014 Jul 1;48(13):7625-33. doi: 10.1021/es501035a.

Stratton, R. W., H. M. Wong, and J. I. Hileman, (2010) Life Cycle Greenhouse Gas Emissions from Alternative Jet Fuels, Partnership for AiR Transportation Noise and Emissions Reduction, Project 28 Report, Version 1.1.

Appendix A - Emissions from the Avoided Landfilling of MSW

The net contribution of MSW to the life cycle GHG emissions is reflected by the difference between the biofuel production emissions and the avoided landfill emissions. The difference in emissions is indicated as the MSW factor in **Table A-1**, below. For the MSW composition shown here the conversion to fuel results in a GHG reduction of 1,874,328 g CO_2e per ton of MSW. These emissions correspond to about -216 g CO_2e/MJ of FT diesel.

The fate of the total landfill ("LFT") carbon from MSW is either stored carbon (STC), flared gas (FL), seeped LFG (LFS), or oxidized seeped LFG (LFOX). The inputs in the CA-GREET represent a closed carbon balance accounting for all of the carbon in the feedstock. The carbon balance is accomplished through the following relationships:

Total carbon mass is conserved such that:

$$LFT = LFOX + LFS + FL + STC \quad (1)$$

Inactive carbon in landfill is based on the inactive carbon fraction

$$STC = LFT \times INC \quad (2)$$

Where the inactive carbon fraction, INC, is estimated for the type of MSW being modeled.

The balance of the organic material is either captured and flared or seeps from the landfill. The amount of LFG that is captured is reflected by the LFG flare efficiency, $FL\eta$, where,

$$FL\eta = FL/(LFT - STC) \quad (3)$$

The gas composition generated in the landfill gas (LFG) is assumed to be the same for the captured gas (FL) as well as the gas that escapes from the landfill.

The composition of the LFG is approximately an equimolar mixture of CH_4 and CO_2. The fraction of degradable carbon that becomes methane is defined as:

$$LF_{CH4}/(LFG_C) = X\ CH_4 \text{ on a molar basis} \quad (4)$$

CH_4 emissions from the flare are determined by the flare efficiency,

$$FL\eta = 1 - FL_{CH4} \text{ emissions}/(X\ CH_4 \times FL_{Carbon}) \text{ on a molar basis} \quad (5)$$

N_2O emissions are proportional to combusted fuel such that

$$FL_{N2O} = FL_{CO2} \times X_{N2O} \quad (6)$$

These relationships account for the stored carbon and the emissions associated with flaring LFG. The balance of the carbon is emitted through seepage from the landfill via the carbon balance in equation 1. These losses are estimated to be a direct emission of LFG and LFG that is oxidized when it is in contact with oxygen in the soil. These aerobic losses (LFOX) are calculated from the aerobic fraction of LFG. The fraction OX reflects the portion of LFG that is oxidized as it traverses the landfill cap (i.e., as it escapes). The calculation of AC is based on the calculation of LF_L such that

$$LFL = LFOX + LFS = LFT - STC - FL \quad (7)$$
$$OX = LFOX/LFL \quad (8)$$

The carbon in LFL is first calculated from equation 1. Then the CH_4 fraction is determined via equation 4. The portion of CH_4 that is aerobically converted to CO_2 is:

$$LFOX = OX \times LFL, \text{ applied to moles of } CH_4 \quad (4)$$

Thus all of the carbon in the MSW is accounted for and distributed among the different emission streams. **Table A-1** shows the distribution of carbon and GHG emissions from MSW. The variables identified above are shown at the bottom of the table.

Table A-1. Landfill Emissions and Biofuel Processing Emissions for Mixed MSW.

REDACTED

Table A-2 shows the fate of the carbon from 1 ton of MSW when it is converted to fuel. The breakdown of the fate of the carbon is shown in **Figure A-1**.

Biofuel Scenario			
Vehicle Fuel	**Process Emission**	**Stored C**	**Biofuel Sum**
			0
			0
496,928	1,088,395		1,585,323
496,928	1,088,395	0	1,585,323
135,651	297,108	907	433,666
V	PL	STCB	BFT

Table A-2. Carbon Balance for Landfill Material

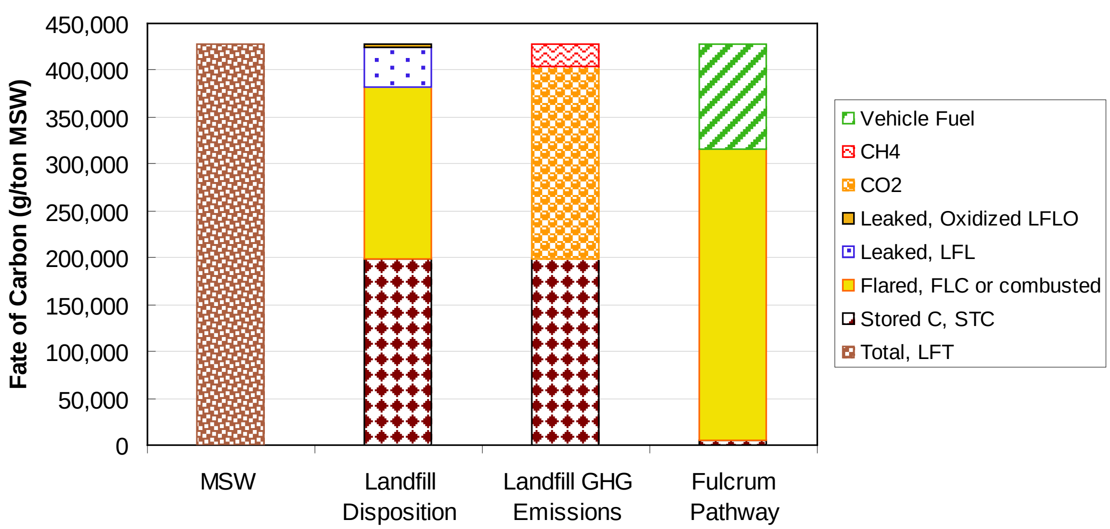

Figure A-1. Fate of Carbon for FT Fuel Production.

The disposition of material in landfills is not measured or typically modeled in terms of the fate of the carbon shown in **Figure A-1** above. Instead, the capture efficiencies are observed at different stages of the landfill process. Landfill gas collection efficiency, LFGη represents the fraction of all gas that is generated. Flare efficiency FLη is based on the gas sent to the flare, and oxidized LFG, OX, is based on the fraction of gas that is not captured.

The third column in **Figure A-1** shows the disposition of the MSW in terms of its landfill GHG emissions. Carbon is converted to CO_2, CH_4 and other traces of hydrocarbons, or it remains in the landfill. The stored carbon has no GHG impact other than avoiding the production of gaseous emissions.

The fate of the MSW material in the Fulcrum FT fuels production process is shown in the fourth column in **Figure A-1**. Essentially all of the free carbon in the feedstock is converted to either fuel or synthesis gas which, when combusted, is converted to CO_2.

The flare efficiency reflects the conversion of CH_4 to CO_2 and other combustion products such as formaldehyde and CO. Typically a combustion efficiency refers to the conversion of fuel to CO_2 such that the efficiency COMBη is

COMBη = (carbon as CO_2) / (total carbon in fuel)

Unburned fuel primarily forms CH_4 and CO. When using flare efficiency data, the distinction between combustion efficiency and methane destruction efficiency should be borne in mind since a combustion efficiency term reflects the incomplete combustion to both CH_4 and CO.

The model predicts 51,147 g CH_4/ton, 1,066,434 g CO_2/ton with a global warming potential weighted GHG of 2,350,082 g CO_2e/ton.

Emissions from landfilling MSW range from 10,000 to over 60,000 g CH_4/ton of MSW (EPA 2006). This parameter is an input to the model such that the land fill capture efficiency corresponds to the target value (for example 80% LFG capture efficiency corresponds to 20,000 g CH_4/ton of MSW).