Biofuel Supply Module

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Introduction

The Biofuel Supply Module (BFSM) is an excel-based model that has been designed to integrate with the PATHWAYS model developed by E3 for the 2030 Scoping Plan process.[1] BFSM is a bottom-up modeling approach that builds on engineering process estimates and parameters alongside economic principles to assess biofuel supply under a variety of policy conditions.

The BFSM can be used to estimate the biofuel supply that may be available for use in California's vehicles. This includes gaseous transportation fuels derived from biomass, such as biomethane. Transportation sector energy demand in California is supplied from the PATHWAYS model.

Model Motivation

BFSM is motivated by the need to better understand the potential biofuel supply available to California. The availability of biofuel informs the 2030 Scoping Plan process. Additionally, the BFSM can be used to better understand how prices and policies impact long-run Low Carbon Fuel Standard (LCFS) targets, and may also be used to identify focus areas for additional policy support. The BFSM standardizes a format for many engineering assumptions, offering a tool for regulatory analysis that may be used to systematically assess how biofuel may help achieve California's greenhouse gas (GHG) emission reduction goals.

The BFSM provides a transparent and systematically consistent approach for projecting transportation fuel supply in the State of California. Similar to prior analysis at the ARB [2] regarding biofuel supply, the BFSM considers a variety of biofuel policies, including the Federal Renewable Fuel Standard (RFS), the LCFS, and other direct policies. Fundamental to BFSM is the assumption that price incentives motivate the necessary commitment of capital to encourage low carbon fuel production.

Development of BFSM is a work in progress. The current public version may be used to further the discussions on how biofuels can and should contribute to California's greenhouse gas reduction targets for 2030. ARB staff have made a reasonable effort to populate the model with feedstock availability data, carbon intensity values, production and transport costs, near-term production estimates, and estimated rates for capacity expansion of innovative, low-carbon fuels. Stakeholder feedback on the methodology, assumptions, and data inputs is highly encouraged and will be used to improve future iterations of the model.

Model Structure and Worksheet Descriptions

The model is divided into a set of excel worksheets that carryout intermediate calculations. These calculations are used to assess biofuel supply that is accessible to California. Throughout the model, user-defined values may be input into any of the light-blue boxes. Greyed-out boxes and boxes with a red-hash background are values that should not be altered, or represent functionality that has not yet been fully implemented in the model.

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[1] https://www.arb.ca.gov/cc/scopingplan/meetings/1142016/e3pathways.pdf
[2] https://www.arb.ca.gov/regact/2015/lcfs2015/lcfs15isor.pdf

The model operates with the assumption that cost competition between fuel choices ultimately drives fuel supply decisions. As such, this model takes a bottom-up approach, working to estimate the finished cost of fuels produced through various feedstock-to-fuel pathways with transport to California. Figure A shows a visual schematic of the model process.

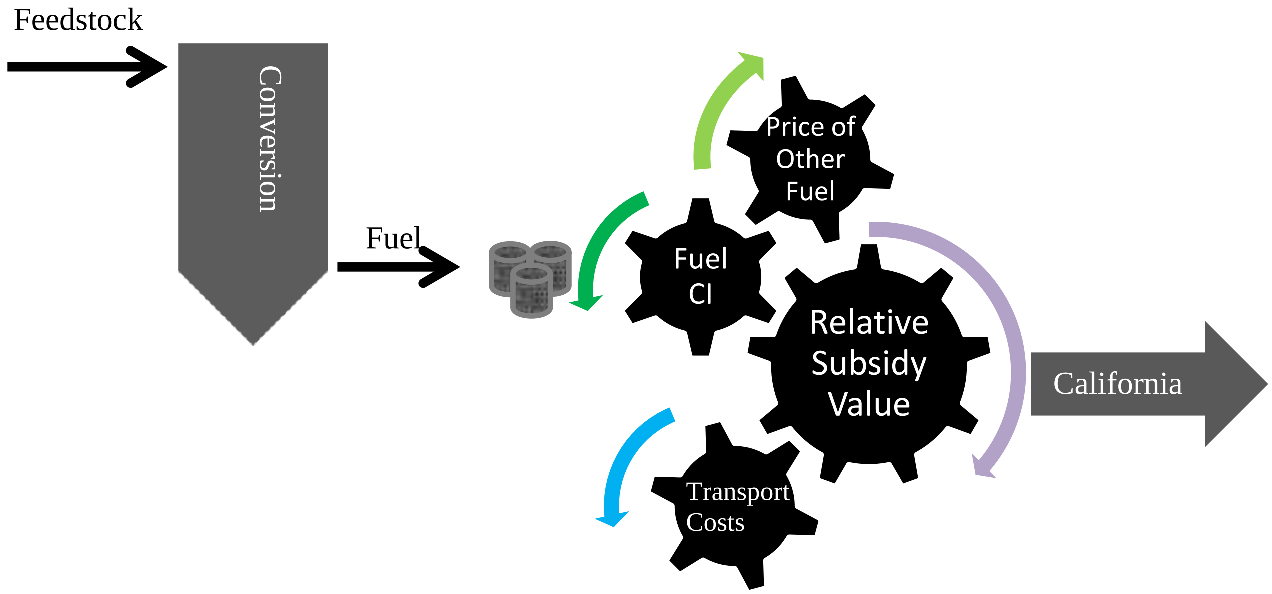

Figure A. Schematic of the BFSM structure

As portrayed in Figure A, the model converts feedstock to fuel, applies a variety of cost parameters, and then assesses whether or not the fuel out-competes other fuel supply that would otherwise enter the California market.

What follows is a brief breakdown and discussion of the worksheets contained within the model.

About

This worksheet provides information about the model, including the release version, a summary of the model intent, and contact information if there are questions about the model.

Run Model

This worksheet includes major inputs and the primary user-decision variables. This worksheet also acts as the dashboard to provide aggregate outputs from the model. Additional fuel subsidies (or taxes) can be specified in this worksheet, as well as other built-in policy levers. The user-defined LCFS credit price is specified in this worksheet, which may be used to better assess and determine possible compliance scenarios.

Feedstock CI Values

This worksheet allows the user to define CI values associated with various feedstock considered in the model. These values are provided in a gCO_2e/ton of feedstock basis. Intermediate calculations are also carried out on this worksheet that convert the gCO_2e/ton emission factor into emission factors for various technological processes. These results are combined with the calculations from the carbon intensity on the *Technology CI* worksheet to generate the overall fuel CI for a production pathway. These values are reported as gCO_2e/MJ of fuel on this worksheet.

Fuel Prices

This worksheet contains a set of user-defined fuel prices. The default price is the wholesale price for gasoline, diesel, and natural gas in real dollars under the 2015 Annual Energy Outlook base case scenario for the Pacific Region[3]. These fuel prices are also used to estimate cellulosic RIN waiver prices under the RFS.

The Fuel Prices worksheet also creates intermediate calculations for fuel costs that include carbon pricing and taxes on a gallon of gasoline equivalent basis. Aggregate results from the model run for fuel energy given in exajoule (EJ) of fuel is shown. This value is converted to fuel volume on a gasoline equivalent basis in the “Run Model” worksheet.

Technology CI

This worksheet allows the user to input the carbon intensity value for different processes that convert feedstock to fuel. Each feedstock is classified as belonging to one of 6 different feedstock categories: Cellulosic, Wood, Manure, Landfill Gas, Lipids, or Sugars. Each fuel is then assigned a carbon intensity rating of gCO_2e/ton of feedstock converted for a given feedstock type. This is an intermediate calculation, that covers emissions solely from the fuel production process.

Technology Cost

This worksheet allows the user to input the cost required to convert one ton of feedstock to fuel. Feedstock is classified into one of 6 different categories (see above). Additionally, this worksheet assigns given fuel technologies to different fuel pools (gasoline, diesel or natural gas), and also assigns RIN-types to each fuel end-product. D4 and D5 RINs are assumed to be at cost parity in the model.

Fuel Demand Input

This worksheet contains the user-defined fuel energy demand input for which supply is generated in the model. Additional demand scenarios can be implemented in this worksheet, which can be selected in the “Run Model” worksheet in cell B4. The default fuel demand scenarios have been provided by E3.

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[3] https://www.eia.gov/forecasts/aeo/

Electricity CI

This worksheet calculates the aggregate energy economy ratio for electricity and hydrogen. This ratio changes over time as the mix of electric drive-train vehicles displacing diesel and gasoline changes overtime. The default electric vehicle share in each fuel pool is taken from PATHWAYS fuel demand.

Supply Restrictions

This worksheet contains a set of fuel supply restriction assumptions and calculations put in place on fuel supply. These restrictions include fuel blend wall constraints ("Run Model" worksheet input) and capacity expansion limitations which are discussed later.

US Biomass Supply

This worksheet contains the biomass feedstock supply curves. These data were derived in part from the Billion Ton Study (BTS)[4]. Conventional crop data were derived from the historic utilization rates for crop material used to produce biofuels consumed in the United States. The BTS supply curve costs were adjusted to account for the transportation and logistics costs associated with bringing produced fuel to California.

Tech Supply Curves

This worksheet contains the intermediate calculations necessary to create fuel technology supply curves. Each feedstock is converted to fuel for each available technology conversion pathway. Conversion costs, subsidies, and taxes are applied, and the associated feedstock usable at a given price point compared to conventional fuel is aggregated and shown in columns AE to FX. Additional calculations are done to assess the lower heating value and average fuel carbon intensity for fuel produced at each price point.

Fuel Selection

This worksheet holds the fuel selection algorithm. This algorithm was implemented to allow the model to choose the lowest-cost fuel production pathway. The algorithm also avoids double counting for feedstock that could otherwise be simultaneously used for multiple fuel pathways. The algorithm looks to see if there are any fuel production restrictions in place (capacity constraint), selects feedstock for fuel that is the lowest-cost pathway, and then utilizes all available feedstock at a given price point until feedstock availability or fuel volume constraints are met.

H2 Refinery Credits

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[4] http://energy.gov/eere/bioenergy/downloads/us-billion-ton-update-biomass-supply-bioenergy-and-bioproducts-industry

This worksheet is used to estimate the economics for hydrogen production from biomethane. Refinery credits are generated when the cost of substituting renewable hydrogen produced from biomethane for conventional process hydrogen is motivated by LCFS credit prices.

EJ Fuel

This worksheet takes the feedstock quantities calculated for each fuel group in the "Fuel Selection" worksheet and calculates the fuel volume produced in exajoules.

California Biomass Allocation

This worksheet allows the user to define a start year and an end year for California to reduce its biomass feedstock availability to a "fair-share" allocation. This is used to ramp down available feedstock supply to California in future years, when other state and national policies outside of California may come into effect, diminishing available feedstock supply.

Carbon Prices

This worksheet contains the user-defined price increase in gasoline, diesel, and natural gas fuels due to a carbon pricing policy such as Cap and Trade.

Yields

A number of worksheets containing intermediate calculations were hidden to improve legibility and user experience when working with the model. "yields" is a hidden worksheet that contains the maximum theoretical yields that are used for converting feedstock into fuel. These values originate from the E3 PATHWAYS model.

Credit Calculations

This is a hidden worksheet that carries out intermediate calculations to determine the number of credits that would be generated given a defined LCFS standard up to 10%. The values calculated here are used to determine a theoretically achievable carbon intensity standard on the Run Model worksheet.

Feedstock Conversion Efficiency

This is a hidden worksheet that makes use of conversion efficiencies and the values found in the yields worksheet to create an array of associated conversion efficiency for different feedstock-technology pairs. The units are given in gge/ton.

CA Biomass Supply

This is a hidden worksheet that offers the opportunity to scale the US Biomass Supply curves to further restrict national supply accessible to California. The default value is set such that the CA Biomass Supply is identical to the supply curve in the "US Biomass Supply" worksheet.

Conversion Cost Array

This is a hidden worksheet that takes conversion costs from the “Technology Costs” worksheet and creates an array containing values for each feedstock-technology pair.

Electricity

This is a hidden worksheet used to determine conversion efficiencies for biomass to electricity applications. Electricity considerations are not presently incorporated into the model.

Transport Demand

This is a hidden worksheet that is used to take the selected demand scenario and input it into the model. The “Fuel Demand Input” worksheet and Cell B4 in the “Run Model” worksheet determine what is ultimately used in the model for transport demand.

Yields Matrix

This is a hidden worksheet that takes the feedstock conversion efficiencies and applies these efficiencies to each feedstock-technology pair for each feedstock supply cost point. This creates an array of values that are incorporated in the feedstock calculations on other worksheets.

AFCI Matrix

This is a hidden worksheet that transforms the carbon intensity values calculated in the “Feedstock CI Values” worksheet into an array of values for feedstock-technology pairs at various price points. This creates an array of values that are incorporated in the feedstock calculations on other worksheets.

Feedstock Ramp Rate

This is a hidden worksheet that can be used to restrict the rate at which feedstock becomes available overtime. The default case is that all feedstock is immediately available for use, with the exception of manure for anaerobic digestion, which scales up overtime, as it is substantially limited by the number of anaerobic digesters currently operating. This ramp rate was determined through assessment of the EIA dairy digester database[5].

RampRateMatrix

This is a hidden worksheet that takes the ramp rates from the “Feedstock Ramp Rate” worksheet and applies the ramp rates across each feedstock for all price points over time.

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[5] https://www.epa.gov/agstar/livestock-anaerobic-digester-database

Figure B shows a visual abstraction of the primary worksheets used in the model

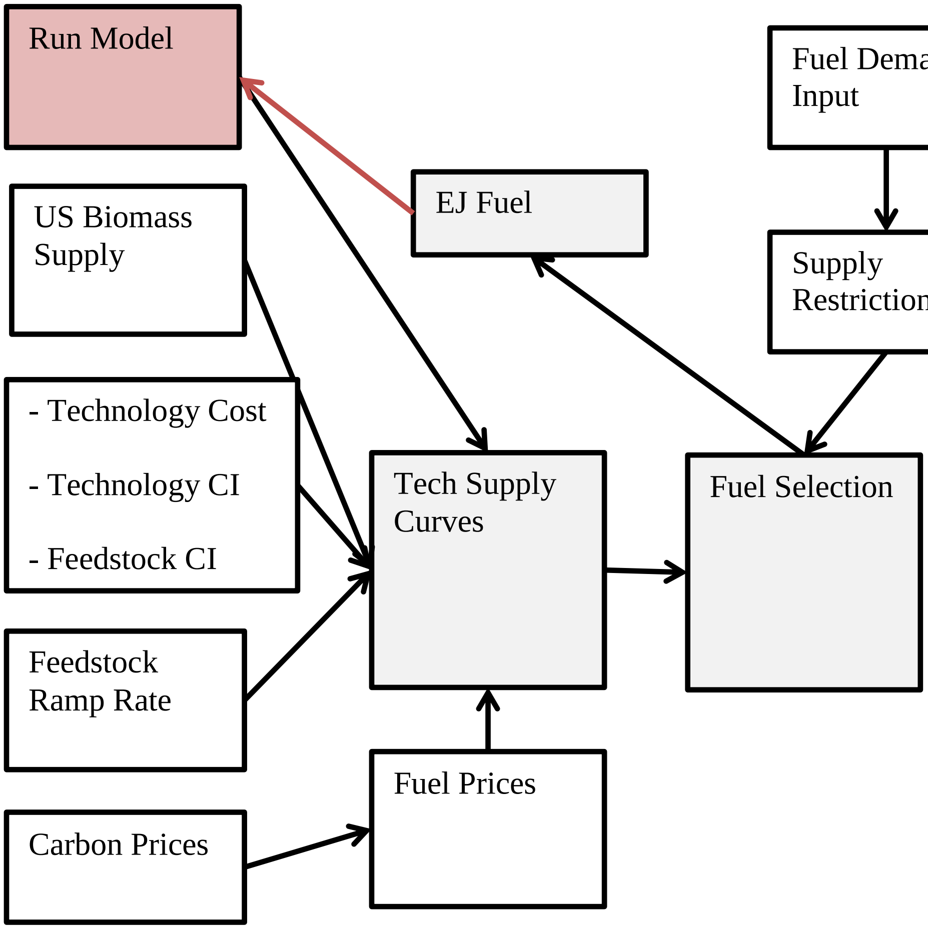

Figure B. Flowchart abstraction for worksheet links in BFSM

Model Limitations and Potential Future Work

The BFSM is suitable primarily for assessing potential biofuel supply available to enter California in the case where California's policies draw a large share of the global supply of the cleanest fuels. The model in its current stage does not explicitly model the demand for fuels from other regions with similarly aggressive policies. However, BFSM incorporates the option to scale biomass supply availability for California in each year, which can act as a rough approximation for demand that may exist from other regions.. Also absent is the effect that global demand might have in incenting investment certainty for low-carbon fuel producers. Moreover, the model only provides outcomes associated with point estimates for fuel production costs, which may not fully capture uncertainties associated with market outcomes and technology immaturity or learning overtime. ARB is looking into addressing these limitations in future model iterations.

Modeling Methods and Assumptions

Policy Implementation
The main policies that impact biofuel supply are: the LCFS, the Renewable Fuel Standard, and the Biomass-based Diesel Blenders' Credit.

Because the Blenders' Credit must be renewed through legislative action, the default assumption is that this credit will expire at the end of 2016. The user may define the year at which this fuel subsidy is no longer valid.

The RFS directly affects fuel costs due to RIN pricing. Fuel subsidies due to RIN pricing have been incorporated into the model, and default RIN prices through 2050 are set at current RIN prices. These values may be adjusted by the user. Cellulosic RIN values were calculated as a function of D5 RIN prices and the specific cellulosic credit waiver calculation.[6]

The LCFS is modeled as a fuel subsidy, which impacts fuels differently due to their carbon intensity score.

The LCFS credit price is a user-selected value for each year. When LCFS credit prices are chosen, the available fuel supply for that year shifts based on the calculated fuel subsidy. The cost for each biofuel is compared to the cost of the conventional fuel being displaced, and the fuels that have the lowest relative costs (often due to lower carbon intensities and production costs) are selected.

Other policies may be added to the model in the form of specific technology subsidies in the "Run Model" worksheet.

Feedstock Costs and Supply
Feedstock supply curves were taken from the Department of Energy's Billion Ton Update (2011).[7] These supply curves were aggregated by state, and the cost of providing feedstock to the fuel production facility was adjusted to account for transportation costs and feedstock logistics.

The DOE has done recent modeling to better understand the cost and logistics associated with collecting feedstock and bringing that feedstock to the production facility.[8] Feedstock logistics and transport add considerable cost to the overall fuel supply curve. Although the DOE has not released their complete dataset, feedstock logistics and transport costs have been estimated for all feedstock used in the model through a regression analysis. The additional transport and logistics cost was allowed to vary as a function of feedstock price from data presented in the 2016 Billion Ton Study.[9]

Fuel transport costs were considered for transporting fuel to California. Rather than calculating new supply curves for each region that fuel may be produced in, this process is simplified. For fuel transport costs the model assumes that, on average, feedstock yields liquid fuel volumes of 60 gallons of gasoline

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[6] https://www.epa.gov/renewable-fuel-standard-program/notice-cellulosic-waiver-credit-price-calculation-2016
[7] https://bioenergykdf.net/content/billiontonupdate
[8] http://energy.gov/eere/bioenergy/2016-billion-ton-report
[9] https://bioenergykdf.net/billionton2016/6/2/tableau

equivalent per ton of feedstock. This simplifying assumption, however, is not applied when calculating conversion costs or fuel carbon intensities.

Centroid-distances from each state to California were used to attribute fuel transport costs to the feedstock under consideration. Using this method, the feedstock supply curve intrinsically reflects the value of transporting finished product to California. We utilize the modal breakdown and costs for ethanol fuel transport as a proxy for finished fuel transport costs. [10,11]

From the above data, BFSM assumes that ethanol is transported at a weighted cost of $0.139 dollars per gallon per 1000-miles. Converting back to feedstock (60 gallons per ton), this gave a transport cost, δ, of $0.0083 per ton-mile.

The centroid distance from each state to California was determined using the Google maps API to give a distance approximation, D, for fuel transport.

Using the calculated values for transport costs and logistics (σ), a new supply curve was established for all feedstock considered. Fuel transport distances were multiplied by the transport cost factor and added to the transport and logistics costs, alongside the original feedstock cost from the Billion Ton Study (P_{BTS}) to find the new feedstock cost, $P_{F\text{-}adj}$.

$$P_{F-adj} = \sigma + P_{BTS,r} + \delta D_r \qquad \text{(eq. 2)}$$

The original feedstock supply was then binned by the adjusted price and incorporated into the model.

For feedstock not covered in the billion ton study (Corn, Sugar, Lipids, etc.), the feedstock cost was based on approximate market prices for trading that commodity on the Chicago Mercantile Exchange in 2016. [12]

Table A. Transport Distances for Fuel

Origin	Distance (miles)
Alaska	3,179
Arizona	737
California	1
Colorado	1,119
Connecticut	2,993
Delaware	2,848
Florida	2,706
Georgia	2,454
Idaho	908
Illinois	2,085
Indiana	2,231
Iowa	1,848

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[10] http://www.nap.edu/read/12620/chapter/8#231

[11] https://www.ams.usda.gov/sites/default/files/media/Ethanol%20Transportation%20Backgrounder.pdf

[12] http://www.cmegroup.com/trading/products/

Kansas	1,539
Kentucky	2,311
Louisiana	1,906
Maine	3,243
Maryland	2,782
Massachusetts	3,097
Michigan	2,406
Minnesota	1,993
Mississippi	2,010
Missouri	1,845
Montana	1,258
Nebraska	1,459
Nevada	543
New Hampshire	3,083
New Jersey	2,888
New Mexico	992
New York	2,915
North Carolina	2,650
North Dakota	1,717
Ohio	2,390
Oklahoma	1,504
Oregon	667
Pennsylvania	2,735
Rhode Island	3,080
South Carolina	2,503
South Dakota	1,643
Tennessee	2,161
Texas	1,408
Utah	794
Vermont	3,082
Virginia	2,648
Washington	2,794
West Virginia	2,548
Wisconsin	2,178
Wyoming	1,156
Alabama	2,166
Arkansas	1,805

Feedstock Conversion

Each feedstock represented in the model was grouped into 1 of 6 different feedstock categories: cellulosic, wood, manure, landfill gas (LFG), lipids, and sugars. These classifications are used for selecting conversion costs and yields. The grouping for each feedstock is shown below.

Table B. Feedstock classifications

Feedstock	Classification
Cotton residue	Cellulosic
Manure	Manure
Mill residue, unused secondary	Wood
Mill residue, unused primary (State)	Wood
Orchard and vineyard prunings	Wood
Rice straw	Cellulosic
Sugarcane trash	Cellulosic
Urban wood waste, construction and demolition (State)	Wood
Urban wood waste, municipal solid waste (State)	Wood
Integrated composite operations	Wood
Other removal residue	Wood
Treatment thinnings, other forest lands	Wood
Barley straw	Cellulosic
Corn stover	Cellulosic
Oat straw	Cellulosic
Sorghum stubble	Cellulosic
Wheat straw	Cellulosic
Perennial grasses	Cellulosic
Coppice and non-coppice woody crops	Cellulosic
Landfill Gas	LFG
Lipids (crop based)	Lipids
Lipids (waste based)	Lipids
Municipal Solid Waste	Cellulosic
Corn (Ethanol)	Sugars
Sugarcane (Ethanol)	Sugars

Feedstock conversion parameters came primarily from approved LCFS pathways, engineering pathway assessments, and peer reviewed literature. Table C shows the provided range for fuel yields depending on the feedstock used.

Table C. Summary of conversion yields

Feedstock	Conversion Pathway	Conversion (gge/dry ton-feedstock)	Basis	Source
Cellulose and Wood	Thermal Gasification - Biomethane	75 - 101	Tons of whole biomass, tons of wood	PATHWAYS v2.3[13]
Municipal Solid Waste	Anaerobic Digestion – Biomethane	26	Tons of waste	Pathway for the Production of Biomethane from High Solids Anaerobic

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[13] https://www.ethree.com/documents/California_PATHWAYS_Technical_Appendix_20150720.pdf

				Digestion (HSAD) of Organic (Food and Green) Wastes. Version 2.0. Pathway CNG005
Cellulose and Wood	Hydrolysis – Ethanol	34 - 53	Tons of whole biomass, tons of wood	70% feedstock conversion efficiency calibrated to Dilute Acid Basecase from NREL/TP-6A2-46588[14]
Cellulose and Wood	Thermochemical – Gasoline	35 - 47	Tons of whole biomass, tons of wood	Conversion efficiency calibrated to JEDI Fast Pyrolysis Model[15] yields
Cellulose and Wood	Thermochemical – Diesel	35 - 47	Tons of whole biomass, tons of wood	Conversion efficiency calibrated to JEDI Fast Pyrolysis Model yields
Manure	Anaerobic Digestion - Biomethane	54	Tons of manure	Black and Veatch[16]
Lipids	Hydrotreatment – Diesel	285	Tons of rendered oil	Average reported conversion yield for approved LCFS pathways
Landfill Gas	Landfill Gas - Biomethane	323	Tons of methane	Staff calculation using CA-GREET2.0 model default assumptions
Lipids	FAME – Biodiesel	283	Tons of rendered oil	Average reported conversion yield for approved LCFS pathways
Starch	Fermentation - Ethanol	69	Tons of grain	Average reported conversion yield for approved LCFS pathways
Sugars	Fermentation – Ethanol	12	Tons of whole biomass	CA-GREET2.0 Model

Conversion costs are similarly applied to the fuel pathway on a $/ton of converted feedstock.

Table D. Feedstock conversion cost estimates

Feedstock	Conversion Pathway	Conversion ($/ton-feedstock converted)	Source
Cellulose and Wood	Thermal Gasification - Biomethane	$70-143	Commissioned report[17]
Cellulose and Wood	Hydrolysis – Ethanol	$128	Average cost for

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[14] http://www.nrel.gov/docs/fy10osti/46588.pdf

[15] http://www.nrel.gov/analysis/jedi/download.html

[16] Recent detailed design modeling by B&V. Inputs adjusted to align with other pathways' techno-economic references.

[17] Jaffe, AM et al. The Potential to Build Current Natural Gas Infrastructure to Accommodate the Future Conversion to Near-Zero Transportation Technology Contract No. 14-317

			processes from NREL/TP-6A2-46588 (2010), NREL/TP-5100-47764 (2011)[18]
Cellulose and Wood	Thermochemical – Gasoline	\$145 - \$162	JEDI Fast Pyrolysis Model
Cellulose and Wood	Thermochemical – Diesel	\$145 - \$162	JEDI Fast Pyrolysis Model
Manure	Digester - Biomethane	\$168	Commissioned report[19]
Lipids	Hydrotreatment – Diesel	\$314	PATHWAYS v2.3[20]
Landfill Gas	Landfill Gas - Biomethane	\$266	Commissioned report
Lipids	FAME – Biodiesel	\$220	From conversation with industry
Sugars/Starch	Fermentation - Ethanol	\$22	Kwiatkowski et al. (2006)

Fuel Supply Restrictions

Although feedstock availability is a primary consideration for the viability of biofuel production, plant capacity must also be considered. Due to the long lag times required to secure financing, permit, and build biofuel production facilities, instantaneous production of biofuel is unlikely even if there is economic motivation to produce that fuel. Staff has tried to capture some of this lag-effect in BFSM.

For early-term projections of biofuel plant capacity, the Bloomberg New Energy Finance (BNEF) Renewable Energy Project database was used. This is a listing of renewable energy projects--including biofuel production facilities-- that is updated and maintained by Bloomberg. Bloomberg indicates the status of a facility from “announced” to “commissioned” to provide some overview of market developments in the near and medium-term.

Biofuel projects that have already been commissioned in the United States were taken as the starting point for available fuel supply in 2016. For thermochemical pathways, capacity was limited to already-built facilities in the U.S. in 2017.

The default growth rate for biofuel projects after 2018 is 31%. This default is the average growth rate for the historic production growth rate of biodiesel and ethanol.[21] The average annual growth rate for biodiesel production from 2001 through 2015 was 60%, and the average annual growth rate for conventional ethanol from 1981 through 2015 was 19%. We selected the average annual growth rates for both fuel types as the default for the expected annual expansion in production capabilities for nascent biofuel production past 2018.

Carbon Intensity Values

Carbon intensity values for each feedstock-to-fuel pathway were calculated using values from CA-GREET. Feedstock carbon intensity values were assigned to each feedstock. Similarly, fuel processing and end-use values were added to the technology pathway. This allows the model to create a set of fuel carbon intensities for various feedstock-technology pairs. Blank feedstock values are those for which carbon intensity values have not yet been calculated and are excluded from model choice.

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[18] http://www.nrel.gov/docs/fy11osti/47764.pdf

[19] Jaffe, AM. et al. The Feasibility of Renewable Natural Gas as a Large-Scale, Low Carbon Substitute Contract No. 13-307

[20] https://www.ethree.com/documents/California_PATHWAYS_Technical_Appendix_20150720.pdf

[21] http://www.eia.gov/totalenergy/data/annual/index.cfm

Table E. Feedstock carbon intensity values (gCO_2e/ton)

Feedstock	Carbon Intensity Values
Cotton residue	73,003
Manure	-3,007,645
Mill residue, unused secondary	44,769
Mill residue, unused primary (State)	44,769
Orchard and vineyard prunings	55,038
Rice straw	73,003
Sugarcane trash	46,418
Urban wood waste, construction and demolition (State)	55,038
Urban wood waste, municipal solid waste (State)	55,038
Integrated composite operations	59,935
Other removal residue	59,935
Treatment thinnings, other forest lands	59,935
Barley straw	73,003
Corn stover	93,076
Oat straw	73,003
Sorghum stubble	73,003
Wheat straw	77,019
Perennial grasses	146,061
Coppice and non-coppice woody crops	82,123
Landfill Gas	527,698
Lipids (crop based)	1,223,673
Lipids (waste based)	550,617
Municiple Solid Waste	-472,559
Corn (Ethanol)	448,747
Sugarcane (Ethanol)	42,756

Similar to conversion costs, the carbon intensity associated with given technology processing was broken down into the 6 possible feedstock types, for each of the 9 different technologies. The table below shows carbon intensity ranges for each technology for processing different feedstock. These ranges reflect different feedstock-technology pairs:

Table F. Carbon intensity values associated with feedstock conversion

Feedstock	Conversion Pathway	Conversion-attributed Carbon Intensity (gCO_2e/MJ)
Wood	Thermal Gasification - Biomethane	20
Cellulose and Wood	Hydrolysis – Ethanol	-11.46 – 5.15
Cellulose and Wood	Thermochemical – Gasoline	8.11 – 24.66
Cellulose and Wood	Thermochemical – Diesel	8.07 – 24.82
Manure	Digester - Biomethane	208
Lipids	Hydrotreatment – Diesel	12.95
Landfill Gas	Landfill Gas - Biomethane	17
Lipids	FAME - Biodiesel	13.11
Sugars/Starch	Fermentation - Ethanol	14

Fuel Selection Algorithm

Fuel costs (C) associated with low-carbon fuel production for each feedstock (f) and conversion technology (t) pair are calculated based on the cost of feedstock, the feedstock conversion cost to produce fuel, and any subsidies or taxes that apply to that fuel and fuel pathway. This is best represented by the following equation:

$$C_{f,t} = \frac{P_{f-adj}+X_{f,t}}{\gamma_{f,t}} + S_{LCFS,f,t} + S_{Other,t} \text{ (eq. 3)}$$

$$f \in (Billion\ Ton\ Study\ Feedstock,\ Lipid\ Supply,\ Sugarcane,\ Corn)$$

$$\text{t} \in \begin{pmatrix} RD-pyro,\ RD-HT,\ Biodiesel,\ RG-Pyro, \\ Ethanol-Fermentation, \\ Ethanol-EH,\ Biomethane-LFG,\ Biomethane-DD \end{pmatrix}$$

Where $\gamma_{f,t}$ is the fuel yield (gge/ton), S is the relevant fuel subsidies for the LCFS or other policies, $X_{f,t}$ is the conversion cost, and P_{f-adj} is the feedstock price

Conventional fuels follow a similar cost adjustment:

$$C_l = P_l + S_{LCFS,l} + S_{CAT,l} + S_{Other,l} \qquad \text{(eq. 4)}$$

$$l \in (Gasoline,\ Diesel,\ Natural\ Gas)$$

Where P_l is the wholesale fuel price in the pacific region from the EIA annual energy outlook (2015), and $S_{CAT,l}$ is the effective fee levied on conventional fuels due to cap and trade.

Ultimately, LCFS credits pay a big role in driving model outputs and the supply that comes into California. The effective fuel subsidy due to LCFS policy is calculated as:

$$S_{LCFS,f,t} = (CI_{f,t} - CI_{std})E_D \times \frac{P_{LCFS}}{10^6} \qquad \text{(eq. 5)}$$

Where $CI_{f,t}$ is the fuel carbon intensity associated with a given feedstock (f) technology (t) pair, CI_{std} is the carbon intensity standard for a given year, E_D is the amount of energy displaced by that fuel (the model uses a gallon of gasoline as the basis), and P_{LCFS} is the LCFS credit price, a user-defined value.

The competitive fuel price (the difference between equation 3 and equation 4) is used to assess which fuel comes into California first. However, there are a number of constraints that prevent fuel selection from occurring even if the fuel, after subsidies, is economical.

The fuel is constrained by the available feedstock supply, the capacity schedule for that fuel production (which is a function of time), and the demand requirement for a given fuel pool.

When taken together, this selection algorithm is incorporated in the “Tech Supply Curves” and “Fuel Selection” worksheet of BFSM. The “Tech Supply Curves” worksheet carries out the initial calculations to determine if a given pathway is economically favored, and shows the quantity of feedstock that could be allocated to that fuel pathway in isolation. “Fuel Selection” incorporates the output from the “Tech Supply Curve” worksheet to rank-order the technology pathway used, and to remove that allocated feedstock from feedstock that would otherwise be available for use to other fuel pathways.

Refinery Credits from use of Renewable Hydrogen

The model calculates the quantity of refinery credits that may be used for compliance with the LCFS due to the use of renewable hydrogen substitution in refinery processes. These credits are limited to 10% of deficits generated.[22] These credits are assumed to come from landfill-derived biomethane that is converted to hydrogen and used onsite at the refinery. A conservative carbon intensity value of 65 gCO_2e/MJ is used for calculating the subsidy for these credits.

The cost of utilizing renewable hydrogen compared to conventional hydrogen is calculated. For years in which refinery credits are economically viable, three constraints are considered: (1) the 10% credit ceiling, (2) the hydrogen utilization to produce gasoline and diesel, and (3) the resource limit on the amount of landfill gas used to create hydrogen.

Feedstock-specific Carbon Intensity Modeling Assumptions

This section describes how carbon intensity (CI) values were assigned for each pathway. CI ranges for the feedstock production phase, and separately, conversion (fuel production) phase were chosen to reflect parameters available from existing certified pathways and CA-GREET2.0 default parameters. The two discrete subtotals for each phase are linked by a conversion efficiency factor representing the fuel yield for each process technology. No attempt has been made to forecast pathway CI values to reflect the lower-CI electric grid which should result from increased renewable resources in the electricity generation mix, or to predict future production innovations, though such improvements are expected.

The hydrolysis pathways for woody and cellulosic biomass assume that surplus steam or electricity is co-produced from lignin residue. Conversion efficiencies for thermochemical pathways are wide-ranging and uncertain.

Landfill gas

The CI of landfill gas (LFG) used as a feedstock for renewable CNG or LNG production includes the energy-related emissions for gas extraction, gas processing using 13% of LFG as process fuel, and the net credit for avoided flaring. The conversion efficiency reflects use of LFG for process energy at the gas processing facility and is given in per ton of biomethane.

The fuel production phase includes transport to the refueling station, storage, compression and refueling. A transmission distance of 2000 miles was chosen representing the weighted average distance current sources of biomethane travel to California through the interstate natural gas transmission pipeline. CA-GREET default parameters are applied to determine emissions from the dispensing station.

Municipal Solid Waste

The CI of Municipal Solid Waste (MSW) reflects the avoided methane emissions resulting from diversion of organics from landfilling. The CI is based on the High Solids Anaerobic Digestion (HSAD) Lookup Table pathway[23] . When MSW is directed to a thermochemical or biochemical conversion process, fuel yields may be lower than other feedstocks and additional feedstock processing may be necessary. There is a high degree of uncertainty associated with the CI applied to any fuel volumes originating from this novel pathway.

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[22] LCFS Regulation section 95485(d). Available at: http://www.arb.ca.gov/regact/2015/lcfs2015/lcfsfinalregorder.pdf

[23] LCFS Regulation Section 95488 Table 6.

Dairy Manure

The CI is based on a single LCFS-certified pathway reflecting capture of methane generated from anaerobic lagoon treatment of dairy waste. The feedstock CI includes a credit for avoided venting of methane as determined by the Cap and Trade Offset Livestock Protocol. These assumptions and inputs are not representative of all manure resources available but the resource availability used in the model is constrained by the values for manure in the 2011 Billion Ton Update.

Woody Biomass Removal Residue

This category includes biomass from categorized in the Billion Ton Update, which includes: Integrated composite operations, Treatment thinnings, other forest lands removals, and Other removal residue. A single feedstock CI was determined for these materials based on CA-GREET default values for Forest Residue; the system boundary includes only production impacts, assuming that the collection and transport of the feedstock is attributed to other (non-fuel) management activities. This category of feedstock may be anaerobically digested to produce biomethane, hydrolyzed to produce ethanol, or pyrolyzed for drop-in renewable gasoline or diesel.

Urban Wood Waste and Orchard/Vineyard Prunings

The feedstock system boundary includes only 200 miles of transport, representing the assumption that these materials would be produced and collected regardless of demand for their use or end fate.

Coppice and non-coppice woody crops

CA-GREET2.0 default values for Poplar (non-coppice) and Willow (coppice) are used to represent this purpose-grown short-rotation source of woody biomass. The system boundary includes cultivation, harvest, and transport to a biorefinery. No LCFS-certified pathway exists using farmed trees, and an indirect land use change value has not been determined for these crops.

Perennial Grasses

CA-GREET2.0 default values for Switchgrass were used to determine the feedstock CI for perennial grasses. System boundary includes cultivation, harvest, collection and transport. No LCFS pathway has been certified using switchgrass, and an indirect land use change value has not been determined for these crops.

Corn Stover

The CI of corn stover is based on four pathways from certified LCFS pathways and CA-GREET default values. The system boundary of corn stover includes impacts from harvest, collection, transport, and application of make-up nutrients to account for the loss of nitrogen, phosphorus and potassium associated with removal. Impacts from cultivation are entirely attributed to the primary agricultural product (corn grain). An indirect land use change value has not been determined for corn stover.

Wheat Straw

The feedstock CI is based on a single LCFS-certified pathway for wheat straw. The system boundary includes the harvest, collection, transport and make-up nutrients.

Sugarcane trash

The feedstock CI is based on a single LCFS-certified pathway for sugarcane straw. Like stover, the system boundary includes the harvest, collection, transport and make-up nutrient application.

Other Agricultural Residues

A CI value was estimated for general agricultural residues and is applied to rice straw, cotton residue, barley straw, oat straw, and sorghum stubble. The CI value is an average of impacts from three agricultural residue feedstocks with LCFS-certified pathway CI values: sugarcane trash, wheat straw, and corn stover. Actual impacts are highly dependent on the composition of the specific feedstock and removal rate. An indirect land use change value has not been determined for these crop residues.

Lipids (from crops)

The CI value for crop-based oil feedstocks is an average of the CA-GREET2.0 default values for soy and canola farming, indirect land use change, oil extraction, and feedstock transport (both whole seed or bean and extracted oil). Soy oil default parameters include a yield of 0.2 lb oil per lb soybean and mass-based allocation of emissions from farming and extraction to co-produced soy meal.

Biodiesel production (fatty acid methyl esterification, or FAME process) is based on an average of five pathways. The fuel phase includes the conversion process, fuel transport, non-CO_2 tailpipe emissions, and uses energy-based allocation to account for co-produced glycerin. Renewable diesel (hydrotreating process) is based on an average of five pathways. The fuel phase includes the conversion process, fuel transport, and non-CO_2 tailpipe emissions.

Lipids (from waste resources)

The CI value for waste-based oil feedstocks is an average of 8 certified pathways and three CA-GREET default-based pathways for used cooking oil, tallow and other animal-based oils, corn oil (extracted from distiller grain and solubles, a co-product of ethanol production). The feedstock phase includes oil rendering and any filtration or other purification, and rendered oil transport.

Biodiesel production (fatty acid methyl esterification, or FAME process) is based on an average of five pathways. The fuel phase includes the conversion process, fuel transport, non-CO_2 tailpipe emissions, and uses energy-based allocation to account for co-produced glycerin. Renewable diesel (hydrotreating process) is based on an average of five pathways. The fuel phase includes the conversion process, fuel transport, and non-CO_2 tailpipe emissions.

Starch and Sugar Crops [to Conventional Ethanol]

The CI value for corn is the average of 22 certified pathways. CA-GREET2.0 default values for farming, corn transport, and indirect land use change are used to determine the feedstock phase CI. The fuel phase includes enzyme, yeast and chemical inputs to fermentation, energy use in fermentation and distillation, fuel transport, the addition of denaturant, and a credit for co-product DGS determined by system expansion (displacement method).

The CI value of sugarcane is the average of 16 certified pathways. CA-GREET2.0 default values for farming, cane transport, and indirect land use change are used to determine the feedstock phase CI; mechanized harvest was assumed (no burning). . The fuel phase includes enzyme, yeast and chemical inputs to fermentation, energy use in fermentation and distillation, fuel transport, the addition of denaturant, and a credit for surplus electricity from bagasse combustion determined by system expansion (displacement method).