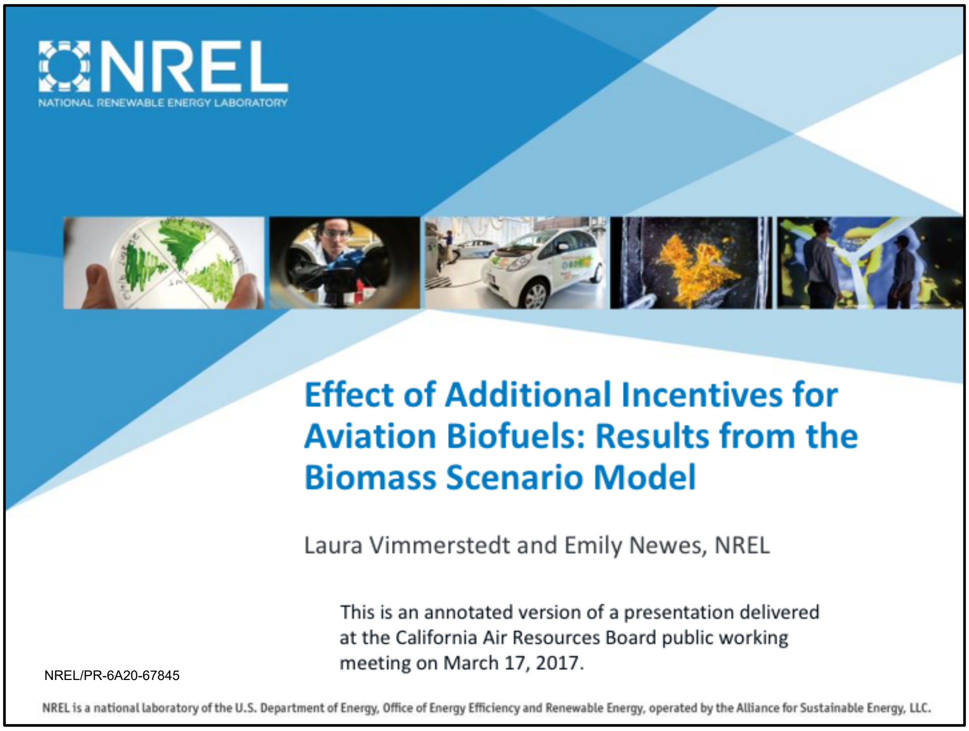


NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Effect of Additional Incentives for Aviation Biofuels: Results from the Biomass Scenario Model

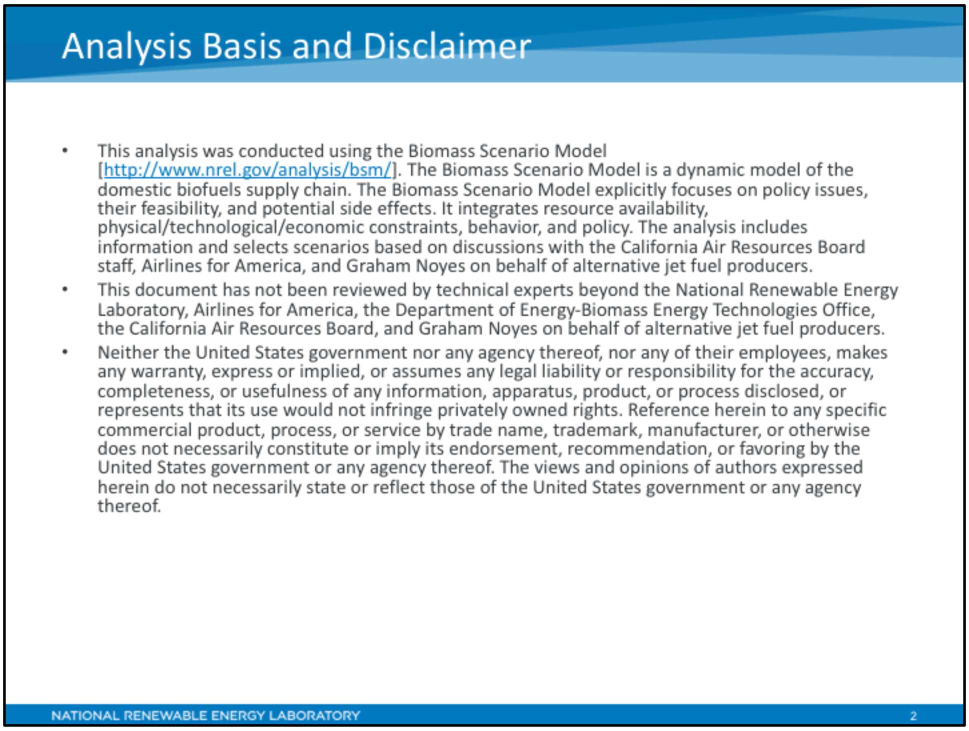
Laura Vimmerstedt and Emily Newes, NREL

This is an annotated version of a presentation delivered at the California Air Resources Board public working meeting on March 17, 2017.

NREL/PR-6A20-67845

The California Air Resources Board is considering extending the Low Carbon Fuel Standard (LCFS) to include alternative jet fuel.

The Biomass Scenario Model (BSM) is able to develop scenarios of future biofuels industry development with and without this policy change.

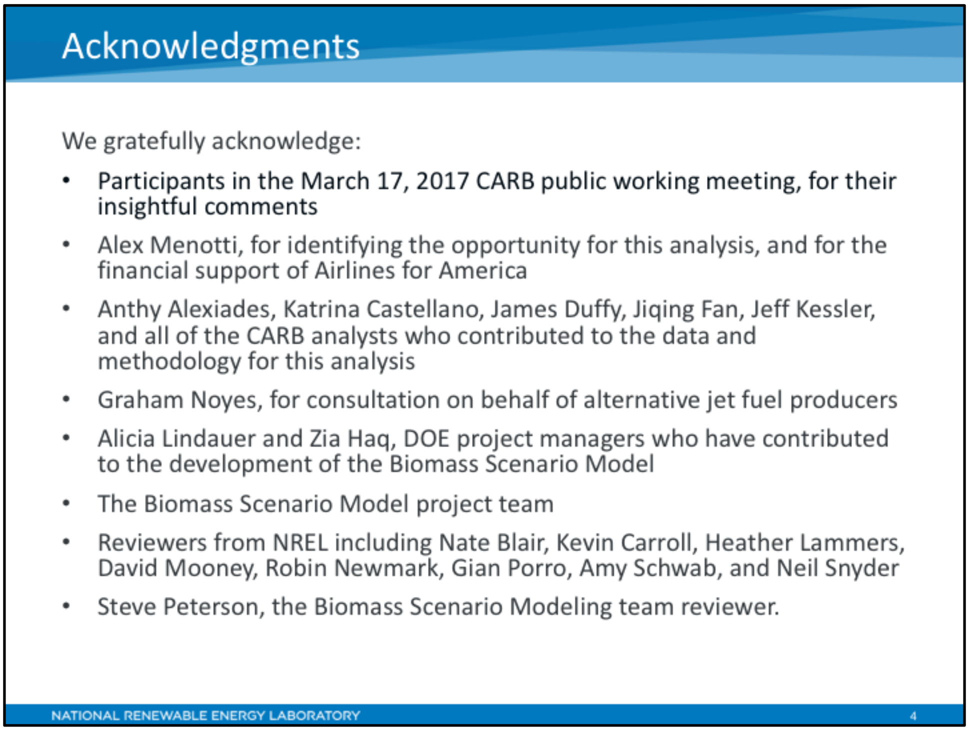


Analysis Basis and Disclaimer

- This analysis was conducted using the Biomass Scenario Model [http://www.nrel.gov/analysis/bsm/]. The Biomass Scenario Model is a dynamic model of the domestic biofuels supply chain. The Biomass Scenario Model explicitly focuses on policy issues, their feasibility, and potential side effects. It integrates resource availability, physical/technological/economic constraints, behavior, and policy. The analysis includes information and selects scenarios based on discussions with the California Air Resources Board staff, Airlines for America, and Graham Noyes on behalf of alternative jet fuel producers.
- This document has not been reviewed by technical experts beyond the National Renewable Energy Laboratory, Airlines for America, the Department of Energy-Biomass Energy Technologies Office, the California Air Resources Board, and Graham Noyes on behalf of alternative jet fuel producers.
- Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Introduction

- NREL is a national lab supporting the U.S. Department of Energy, Biomass Energy Technologies Office (BETO).
- BETO engagement on aviation biofuels led to analysis for U.S. Department of Transportation, Federal Aviation Administration (FAA).
- Airlines for America (A4A) requested additional exploratory scenarios within the FAA analytic framework.
- A4A requested additional scenarios in support of California Air Resources Board (CARB) rulemaking through a technical services agreement with NREL.
- NREL does not advocate for or against the policies analyzed in this study.



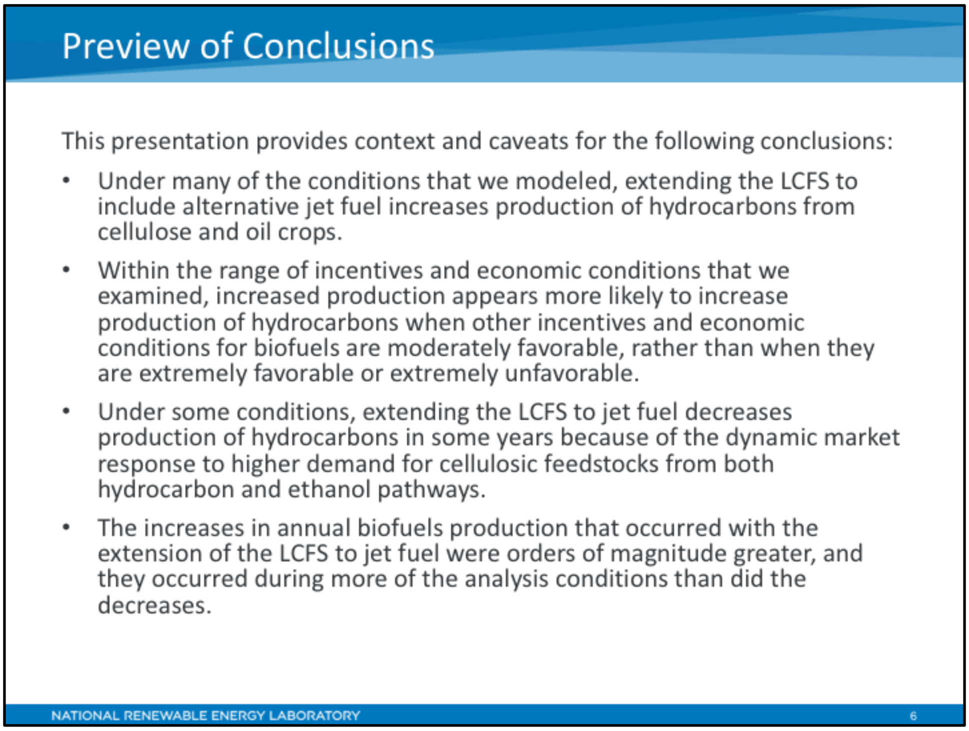
Acknowledgments

We gratefully acknowledge:

- Participants in the March 17, 2017 CARB public working meeting, for their insightful comments
- Alex Menotti, for identifying the opportunity for this analysis, and for the financial support of Airlines for America
- Anthy Alexiades, Katrina Castellano, James Duffy, Jiqing Fan, Jeff Kessler, and all of the CARB analysts who contributed to the data and methodology for this analysis
- Graham Noyes, for consultation on behalf of alternative jet fuel producers
- Alicia Lindauer and Zia Haq, DOE project managers who have contributed to the development of the Biomass Scenario Model
- The Biomass Scenario Model project team
- Reviewers from NREL including Nate Blair, Kevin Carroll, Heather Lammers, David Mooney, Robin Newmark, Gian Porro, Amy Schwab, and Neil Snyder
- Steve Peterson, the Biomass Scenario Modeling team reviewer.

Analysis Scope Selected in Consultation with CARB, A4A, and Representative of Alternative Jet Fuel Producers

- What would be the impact of extending to aviation biofuels a Low Carbon Fuel Standard (LCFS) credit worth $90/metric ton, starting in 2019?
- Impacts of interest include:
    - Biofuels production by conversion pathway
    - Biofuels production by product type
    - Feedstock use.
- How would these impacts change under different scenarios for
    - Oil price?
    - Renewable Identification Number (RIN) credit value?
    - Offtake agreements?



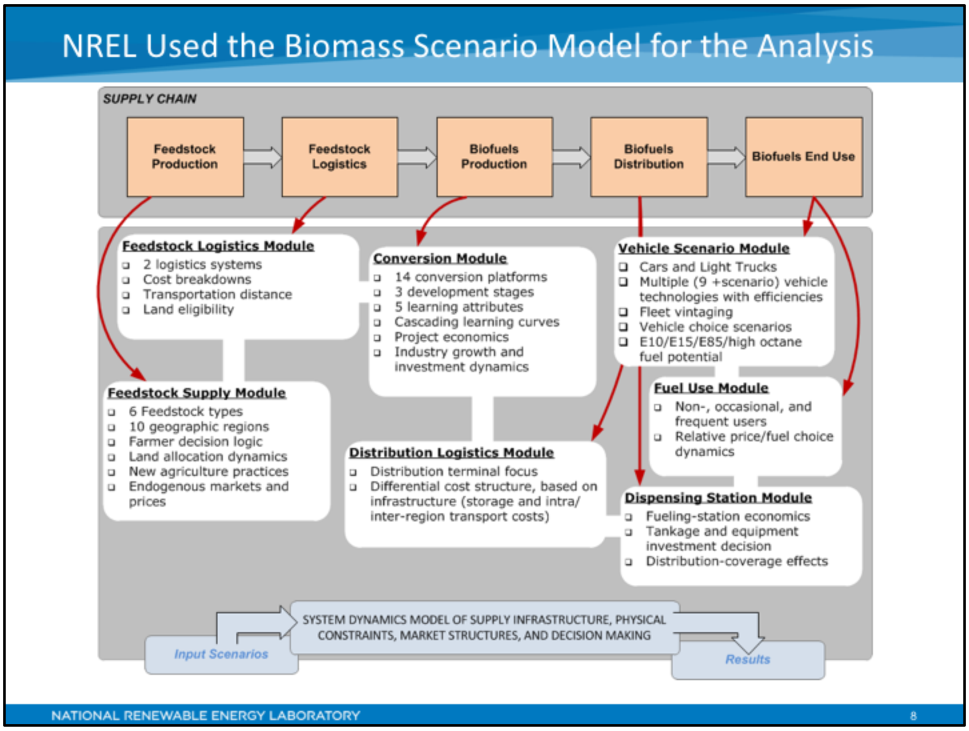
Preview of Conclusions

This presentation provides context and caveats for the following conclusions:

- Under many of the conditions that we modeled, extending the LCFS to include alternative jet fuel increases production of hydrocarbons from cellulose and oil crops.
- Within the range of incentives and economic conditions that we examined, increased production appears more likely to increase production of hydrocarbons when other incentives and economic conditions for biofuels are moderately favorable, rather than when they are extremely favorable or extremely unfavorable.
- Under some conditions, extending the LCFS to jet fuel decreases production of hydrocarbons in some years because of the dynamic market response to higher demand for cellulosic feedstocks from both hydrocarbon and ethanol pathways.
- The increases in annual biofuels production that occurred with the extension of the LCFS to jet fuel were orders of magnitude greater, and they occurred during more of the analysis conditions than did the decreases.

The BSM is best used to explore many scenarios and to support analysis that describes the different system behaviors that occur in those scenarios. Interpreting model results to infer predictions about future real-world events is always uncertain. This slide summarizes results of many BSM simulations.

Methods



NREL Used the Biomass Scenario Model for the Analysis

SUPPLY CHAIN

Feedstock Production → Feedstock Logistics → Biofuels Production → Biofuels Distribution → Biofuels End Use

Feedstock Logistics Module
- 2 logistics systems
- Cost breakdowns
- Transportation distance
- Land eligibility

Conversion Module
- 14 conversion platforms
- 3 development stages
- 5 learning attributes
- Cascading learning curves
- Project economics
- Industry growth and investment dynamics

Vehicle Scenario Module
- Cars and Light Trucks
- Multiple (9 +scenario) vehicle technologies with efficiencies
- Fleet vintaging
- Vehicle choice scenarios
- E10/E15/E85/high octane fuel potential

Feedstock Supply Module
- 6 Feedstock types
- 10 geographic regions
- Farmer decision logic
- Land allocation dynamics
- New agriculture practices
- Endogenous markets and prices

Fuel Use Module
- Non-, occasional, and frequent users
- Relative price/fuel choice dynamics

Distribution Logistics Module
- Distribution terminal focus
- Differential cost structure, based on infrastructure (storage and intra/inter-region transport costs)

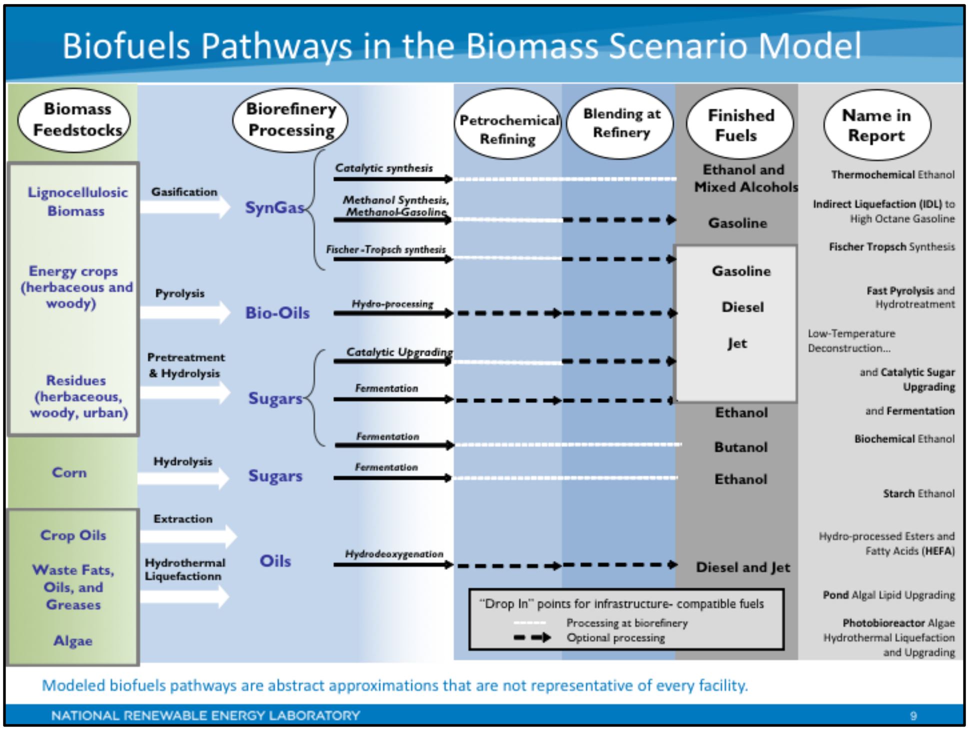
Dispensing Station Module
- Fueling-station economics
- Tankage and equipment investment decision
- Distribution-coverage effects

Input Scenarios → SYSTEM DYNAMICS MODEL OF SUPPLY INFRASTRUCTURE, PHYSICAL CONSTRAINTS, MARKET STRUCTURES, AND DECISION MAKING → *Results*

NATIONAL RENEWABLE ENERGY LABORATORY 8

The BSM is a carefully validated state-of-the-art, dynamic model of the U.S. biofuels supply chain. It focuses on policy alternatives and potential effects, integrating resource availability, constraints (physical, technological, and economic), and behavior. The model simulates the system dynamics of interactions across the supply chain. The BSM tracks biofuels production given technology improvement and the response of investors in the context of land availability, the competing oil market, consumer demand for biofuels, and government policies over time. It emphasizes the behavior and decision-making of various agents across the supply chain, from feedstock producers to fuel users.

The BSM is used to develop insights into biofuels industry growth and market penetration, particularly with respect to effects of policies and incentives for each supply-chain element (volumetric, capital, and operating subsidies; carbon caps/taxes; R&D investment; loan guarantees; and tax credits). It is suitable for coupling to vehicle-choice, agriculture, oil-industry, and general economic models.



Biofuels Pathways in the Biomass Scenario Model

Biomass Feedstocks

Lignocellulosic Biomass

Energy crops (herbaceous and woody)

Residues (herbaceous, woody, urban)

Corn

Crop Oils

Waste Fats, Oils, and Greases

Algae

Gasification

Pyrolysis

Pretreatment & Hydrolysis

Hydrolysis

Extraction

Hydrothermal Liquefactionn

Biorefinery Processing

SynGas

Bio-Oils

Sugars

Sugars

Oils

Catalytic synthesis

Methanol Synthesis, Methanol-Gasoline

Fischer -Tropsch synthesis

Hydro-processing

Catalytic Upgrading

Fermentation

Fermentation

Fermentation

Hydrodeoxygenation

Petrochemical Refining

Blending at Refinery

Finished Fuels

Ethanol and Mixed Alcohols

Gasoline

Gasoline

Diesel

Jet

Ethanol

Butanol

Ethanol

Diesel and Jet

"Drop In" points for infrastructure- compatible fuels

Processing at biorefinery

Optional processing

Name in Report

Thermochemical Ethanol

Indirect Liquefaction (IDL) to High Octane Gasoline

Fischer Tropsch Synthesis

Fast Pyrolysis and Hydrotreatment

Low-Temperature Deconstruction…

and **Catalytic Sugar Upgrading**

and **Fermentation**

Biochemical Ethanol

Starch Ethanol

Hydro-processed Esters and Fatty Acids (**HEFA**)

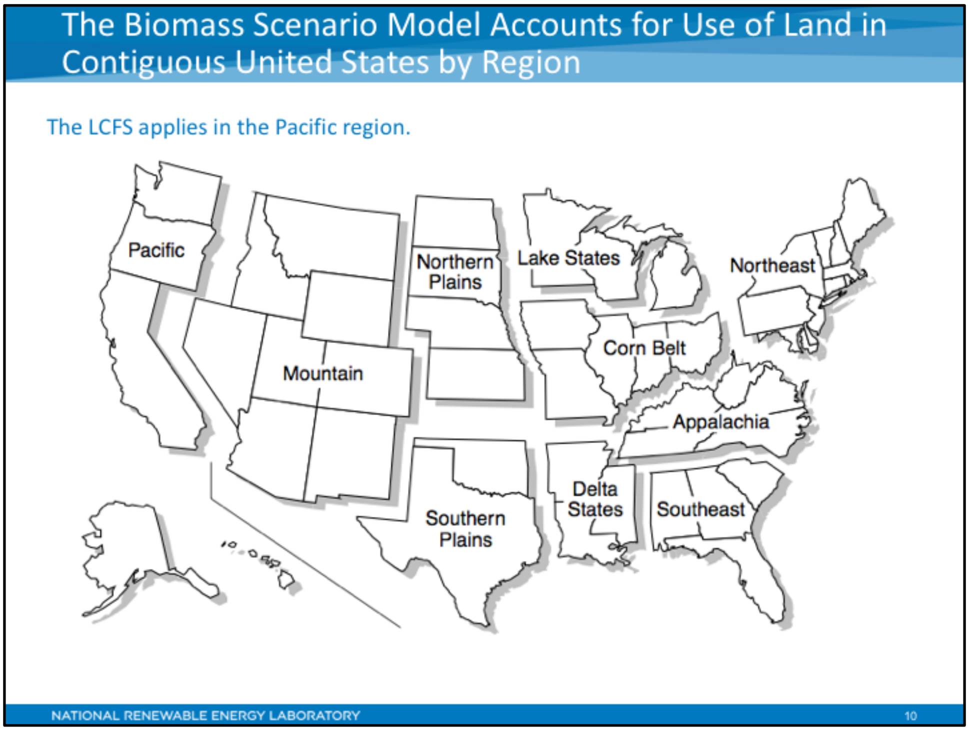
Pond Algal Lipid Upgrading

Photobioreactor Algae

Hydrothermal Liquefaction and Upgrading

Modeled biofuels pathways are abstract approximations that are not representative of every facility.

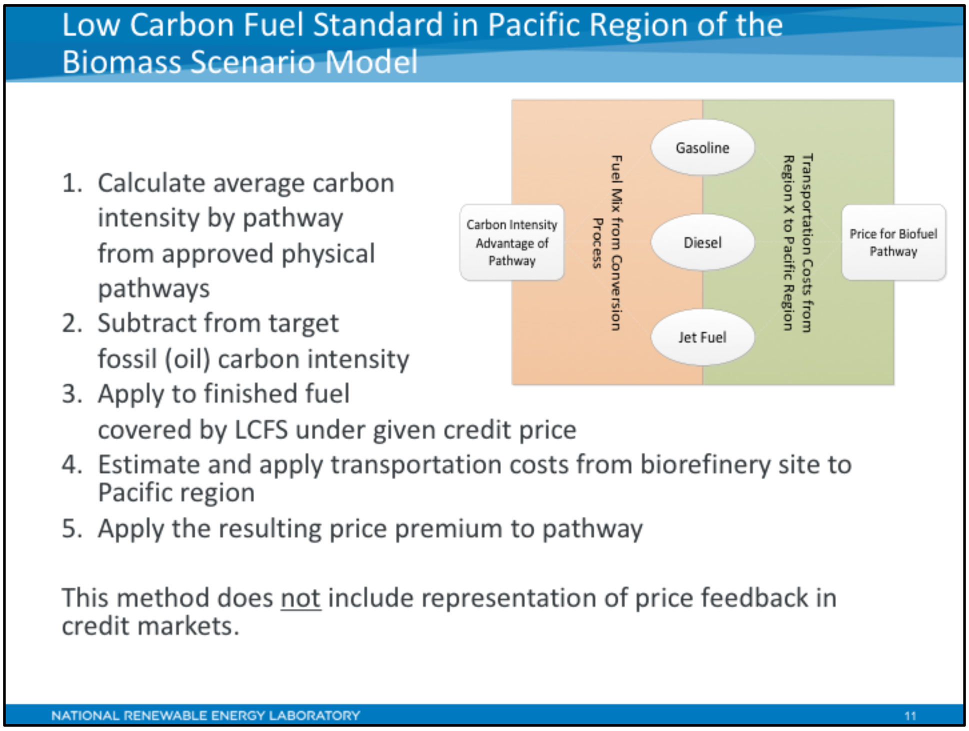
The BSM represents cellulosic, oil crop, algae, and starch resources and their conversion to hydrocarbons, ethanol, and butanol via the different processes illustrated here.



The Biomass Scenario Model Accounts for Use of Land in Contiguous United States by Region

The LCFS applies in the Pacific region.

The BSM resolves ten U.S. geographic regions.



Low Carbon Fuel Standard in Pacific Region of the Biomass Scenario Model

Carbon Intensity Advantage of Pathway

Fuel Mix from Conversion Process

Gasoline

Diesel

Jet Fuel

Transportation Costs from Region X to Pacific Region

Price for Biofuel Pathway

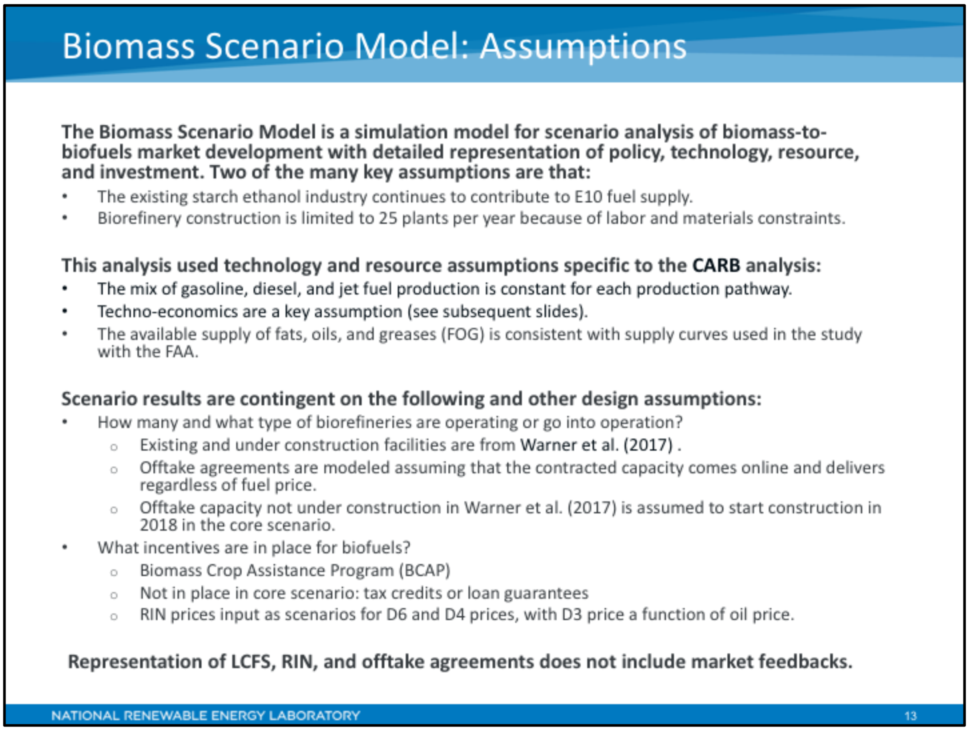
1. Calculate average carbon intensity by pathway from approved physical pathways
2. Subtract from target fossil (oil) carbon intensity
3. Apply to finished fuel covered by LCFS under given credit price
4. Estimate and apply transportation costs from biorefinery site to Pacific region
5. Apply the resulting price premium to pathway

This method does not include representation of price feedback in credit markets.

As part of this project, the NREL team modified the BSM to approximate an LCFS in the Pacific region (California, Oregon, Washington). Because of the geographic regions in the model, represent exclusively California is not possible.

This slide shows the methodology used to estimate the value of the LCFS to each biomass-to-biofuels conversion technology pathway and finished fuel.

Assumptions



Biomass Scenario Model: Assumptions

The Biomass Scenario Model is a simulation model for scenario analysis of biomass-to-biofuels market development with detailed representation of policy, technology, resource, and investment. Two of the many key assumptions are that:

- The existing starch ethanol industry continues to contribute to E10 fuel supply.
- Biorefinery construction is limited to 25 plants per year because of labor and materials constraints.

This analysis used technology and resource assumptions specific to the CARB analysis:

- The mix of gasoline, diesel, and jet fuel production is constant for each production pathway.
- Techno-economics are a key assumption (see subsequent slides).
- The available supply of fats, oils, and greases (FOG) is consistent with supply curves used in the study with the FAA.

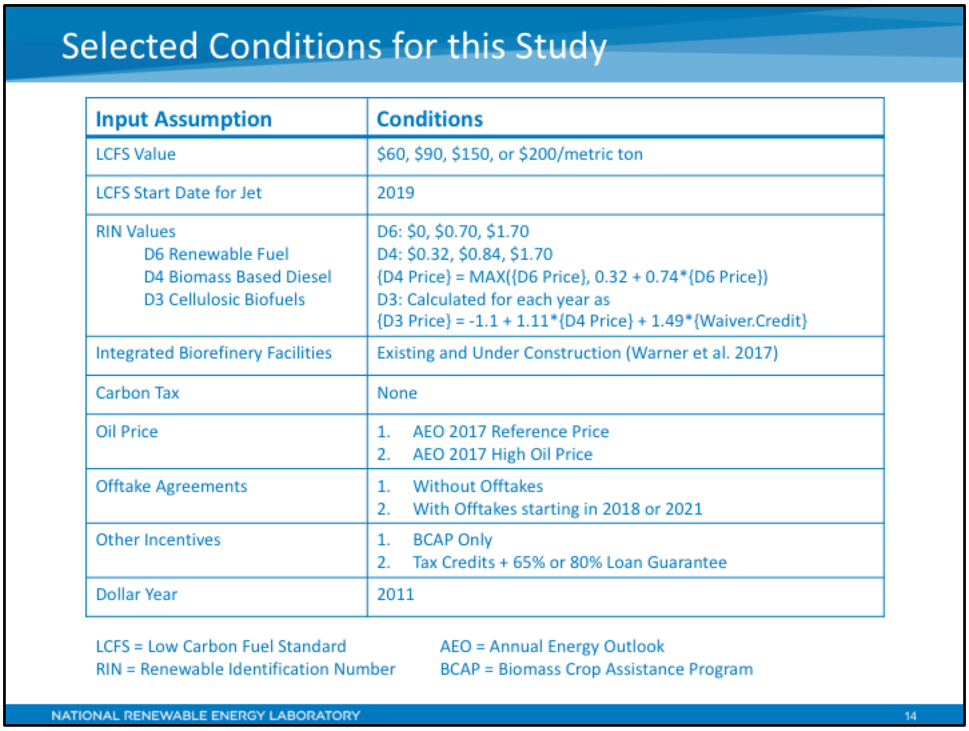
Scenario results are contingent on the following and other design assumptions:

- How many and what type of biorefineries are operating or go into operation?
    - Existing and under construction facilities are from Warner et al. (2017) .
    - Offtake agreements are modeled assuming that the contracted capacity comes online and delivers regardless of fuel price.
    - Offtake capacity not under construction in Warner et al. (2017) is assumed to start construction in 2018 in the core scenario.
- What incentives are in place for biofuels?
    - Biomass Crop Assistance Program (BCAP)
    - Not in place in core scenario: tax credits or loan guarantees
    - RIN prices input as scenarios for D6 and D4 prices, with D3 price a function of oil price.

Representation of LCFS, RIN, and offtake agreements does not include market feedbacks.

The BSM contains thousands of input values, constants, and equations, amounting to a set of assumptions about the biomass-to-biofuels industry and its potential growth.

Documentation is available in the references (Slide 35) and a public version of the model with documentation of assumptions is available at https://openei.org/wiki/Biomass_Scenario_Model. Some of the assumptions are highlighted here.

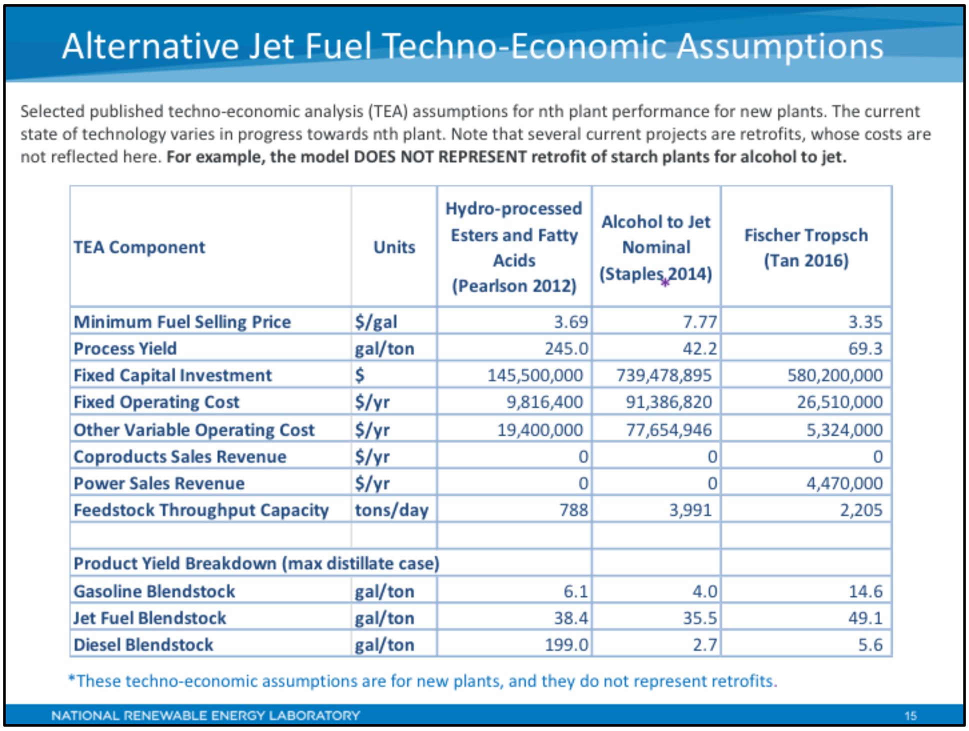


Selected Conditions for this Study

Input Assumption	Conditions
LCFS Value	\$60, \$90, \$150, or \$200/metric ton
LCFS Start Date for Jet	2019
RIN Values D6 Renewable Fuel D4 Biomass Based Diesel D3 Cellulosic Biofuels	D6: \$0, \$0.70, \$1.70 D4: \$0.32, \$0.84, \$1.70 {D4 Price} = MAX({D6 Price}, 0.32 + 0.74*{D6 Price}) D3: Calculated for each year as {D3 Price} = -1.1 + 1.11*{D4 Price} + 1.49*{Waiver.Credit}
Integrated Biorefinery Facilities	Existing and Under Construction (Warner et al. 2017)
Carbon Tax	None
Oil Price	1. AEO 2017 Reference Price 2. AEO 2017 High Oil Price
Offtake Agreements	1. Without Offtakes 2. With Offtakes starting in 2018 or 2021
Other Incentives	1. BCAP Only 2. Tax Credits + 65% or 80% Loan Guarantee
Dollar Year	2011

LCFS = Low Carbon Fuel Standard
RIN = Renewable Identification Number
AEO = Annual Energy Outlook
BCAP = Biomass Crop Assistance Program

This study simulated many different conditions in the BSM. These conditions are listed here. Where multiple conditions are listed, they were varied. All combinations were simulated.



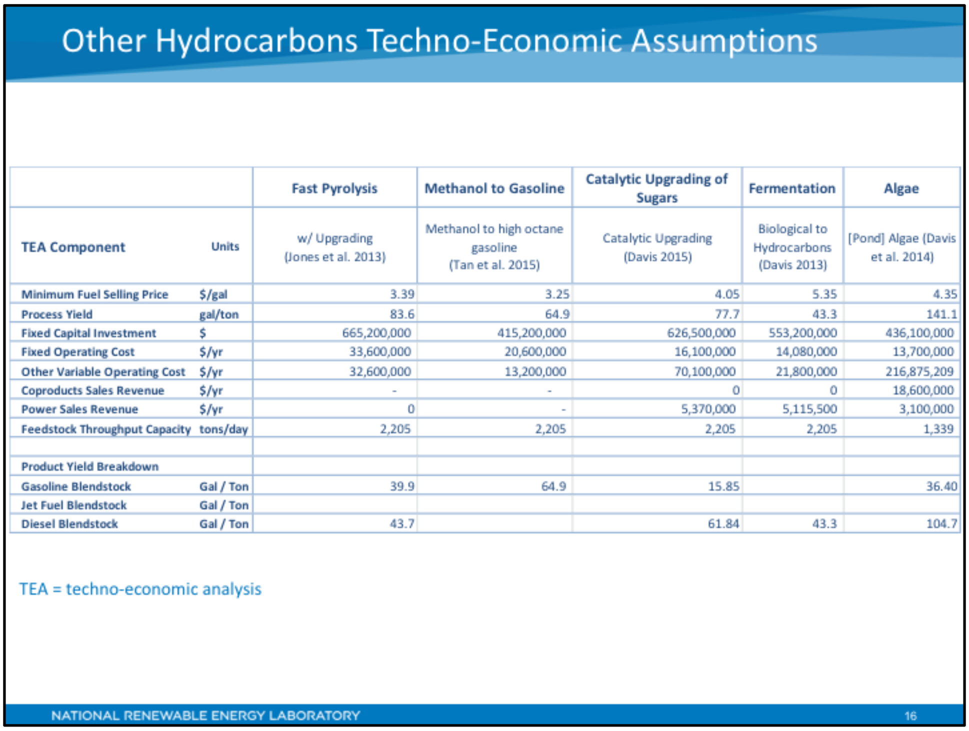
Alternative Jet Fuel Techno-Economic Assumptions

Selected published techno-economic analysis (TEA) assumptions for nth plant performance for new plants. The current state of technology varies in progress towards nth plant. Note that several current projects are retrofits, whose costs are not reflected here. **For example, the model DOES NOT REPRESENT retrofit of starch plants for alcohol to jet.**

TEA Component	Units	Hydro-processed Esters and Fatty Acids (Pearlson 2012)	Alcohol to Jet Nominal (Staples*2014)	Fischer Tropsch (Tan 2016)
Minimum Fuel Selling Price	**$/gal**	3.69	7.77	3.35
Process Yield	**gal/ton**	245.0	42.2	69.3
Fixed Capital Investment	**$**	145,500,000	739,478,895	580,200,000
Fixed Operating Cost	**$/yr**	9,816,400	91,386,820	26,510,000
Other Variable Operating Cost	**$/yr**	19,400,000	77,654,946	5,324,000
Coproducts Sales Revenue	**$/yr**	0	0	0
Power Sales Revenue	**$/yr**	0	0	4,470,000
Feedstock Throughput Capacity	**tons/day**	788	3,991	2,205
Product Yield Breakdown (max distillate case)				
Gasoline Blendstock	**gal/ton**	6.1	4.0	14.6
Jet Fuel Blendstock	**gal/ton**	38.4	35.5	49.1
Diesel Blendstock	**gal/ton**	199.0	2.7	5.6

*These techno-economic assumptions are for new plants, and they do not represent retrofits.

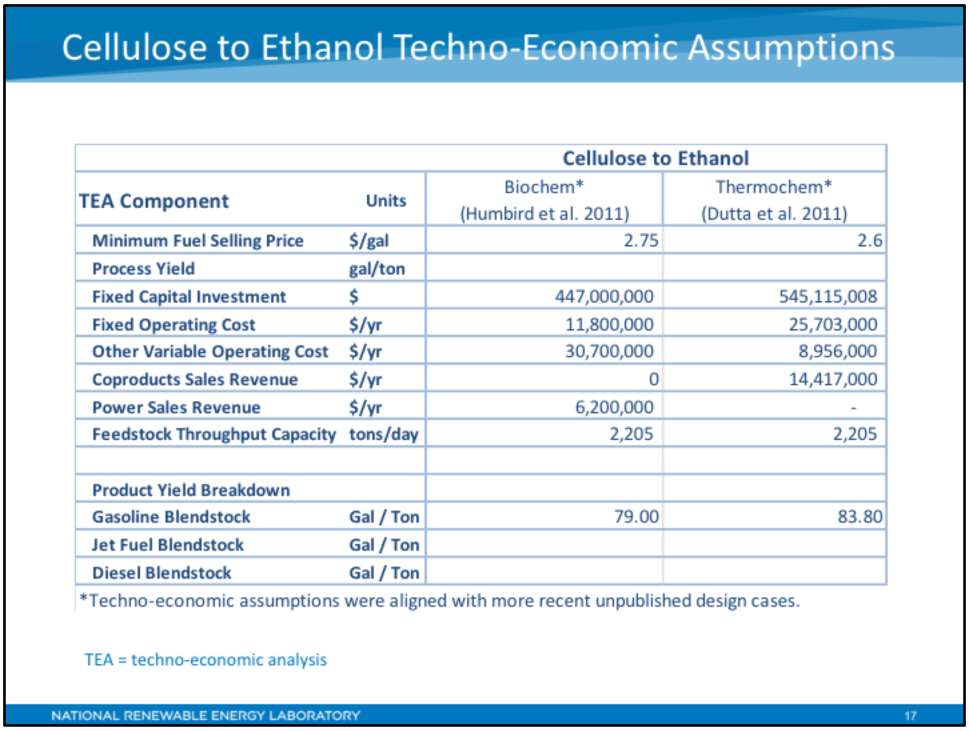
The BSM requires techno-economic input assumptions for the mature cost and performance of each technology that is included in a simulation. For technologies that are not mature, the model represents cost reductions from today's costs to mature costs as industrial learning-by-doing progresses. The preferred sources for the mature techno-economic assumptions are published design reports. The biomass-to-biofuels conversion technology pathways that are included are generally those targeted in BETO research, development, and deployment. Representing costs in these aggregate pathway categories necessarily simplifies the reality that there are distinct sub-categories and combinations of technologies and that each individual biorefinery will have its own costs and performance. The model has flexibility to input different techno-economic assumptions, but detailed subcategory or plant-level representation is currently beyond its resolution.



Other Hydrocarbons Techno-Economic Assumptions

		Fast Pyrolysis	Methanol to Gasoline	Catalytic Upgrading of Sugars	Fermentation	Algae
TEA Component	**Units**	w/ Upgrading (Jones et al. 2013)	Methanol to high octane gasoline (Tan et al. 2015)	Catalytic Upgrading (Davis 2015)	Biological to Hydrocarbons (Davis 2013)	[Pond] Algae (Davis et al. 2014)
Minimum Fuel Selling Price	**$/gal**	3.39	3.25	4.05	5.35	4.35
Process Yield	**gal/ton**	83.6	64.9	77.7	43.3	141.1
Fixed Capital Investment	**$**	665,200,000	415,200,000	626,500,000	553,200,000	436,100,000
Fixed Operating Cost	**$/yr**	33,600,000	20,600,000	16,100,000	14,080,000	13,700,000
Other Variable Operating Cost	**$/yr**	32,600,000	13,200,000	70,100,000	21,800,000	216,875,209
Coproducts Sales Revenue	**$/yr**	-	-	0	0	18,600,000
Power Sales Revenue	**$/yr**	0	-	5,370,000	5,115,500	3,100,000
Feedstock Throughput Capacity	**tons/day**	2,205	2,205	2,205	2,205	1,339
Product Yield Breakdown						
Gasoline Blendstock	**Gal / Ton**	39.9	64.9	15.85		36.40
Jet Fuel Blendstock	**Gal / Ton**					
Diesel Blendstock	**Gal / Ton**	43.7		61.84	43.3	104.7

TEA = techno-economic analysis

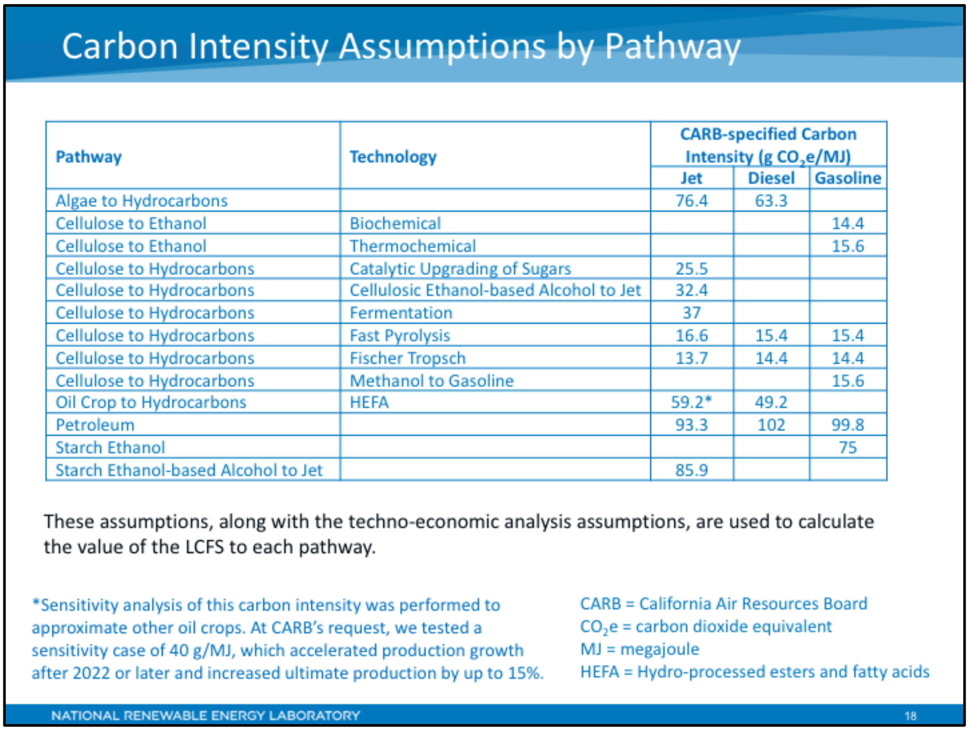


Cellulose to Ethanol Techno-Economic Assumptions

		Cellulose to Ethanol	
TEA Component	**Units**	Biochem* (Humbird et al. 2011)	Thermochem* (Dutta et al. 2011)
Minimum Fuel Selling Price	**$/gal**	2.75	2.6
Process Yield	**gal/ton**		
Fixed Capital Investment	**$**	447,000,000	545,115,008
Fixed Operating Cost	**$/yr**	11,800,000	25,703,000
Other Variable Operating Cost	**$/yr**	30,700,000	8,956,000
Coproducts Sales Revenue	**$/yr**	0	14,417,000
Power Sales Revenue	**$/yr**	6,200,000	-
Feedstock Throughput Capacity	**tons/day**	2,205	2,205
Product Yield Breakdown			
Gasoline Blendstock	**Gal / Ton**	79.00	83.80
Jet Fuel Blendstock	**Gal / Ton**		
Diesel Blendstock	**Gal / Ton**		

*Techno-economic assumptions were aligned with more recent unpublished design cases.

TEA = techno-economic analysis



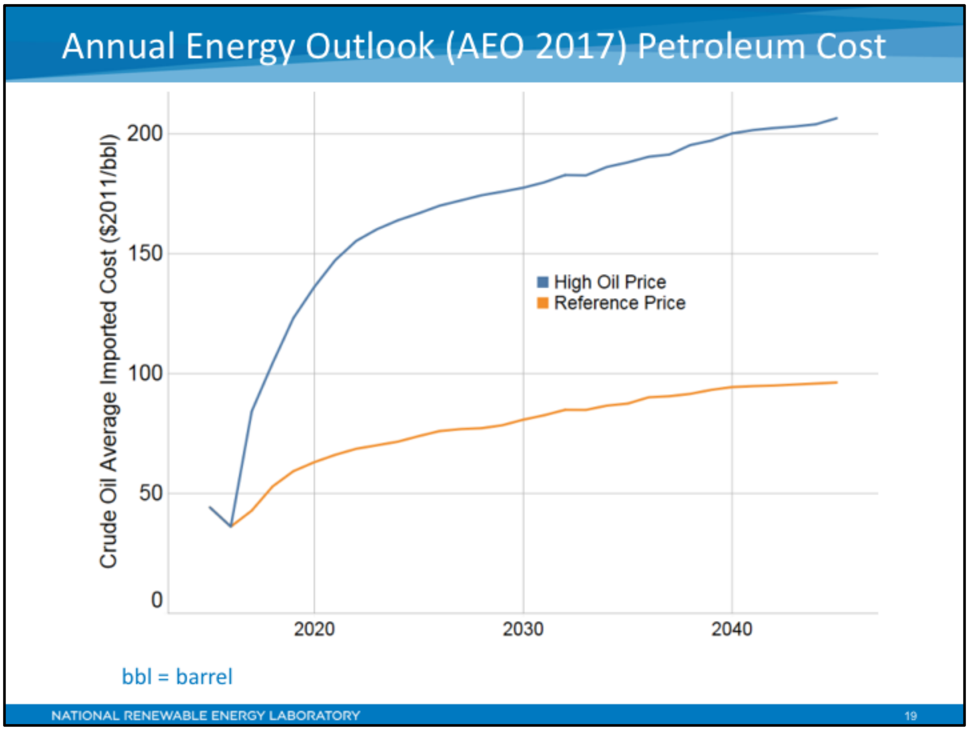
Carbon Intensity Assumptions by Pathway

Pathway	Technology	CARB-specified Carbon Intensity (g CO_2e/MJ)		
		Jet	Diesel	Gasoline
Algae to Hydrocarbons		76.4	63.3	
Cellulose to Ethanol	Biochemical			14.4
Cellulose to Ethanol	Thermochemical			15.6
Cellulose to Hydrocarbons	Catalytic Upgrading of Sugars	25.5		
Cellulose to Hydrocarbons	Cellulosic Ethanol-based Alcohol to Jet	32.4		
Cellulose to Hydrocarbons	Fermentation	37		
Cellulose to Hydrocarbons	Fast Pyrolysis	16.6	15.4	15.4
Cellulose to Hydrocarbons	Fischer Tropsch	13.7	14.4	14.4
Cellulose to Hydrocarbons	Methanol to Gasoline			15.6
Oil Crop to Hydrocarbons	HEFA	59.2*	49.2	
Petroleum		93.3	102	99.8
Starch Ethanol				75
Starch Ethanol-based Alcohol to Jet		85.9		

These assumptions, along with the techno-economic analysis assumptions, are used to calculate the value of the LCFS to each pathway.

*Sensitivity analysis of this carbon intensity was performed to approximate other oil crops. At CARB's request, we tested a sensitivity case of 40 g/MJ, which accelerated production growth after 2022 or later and increased ultimate production by up to 15%.

CARB = California Air Resources Board
CO_2e = carbon dioxide equivalent
MJ = megajoule
HEFA = Hydro-processed esters and fatty acids



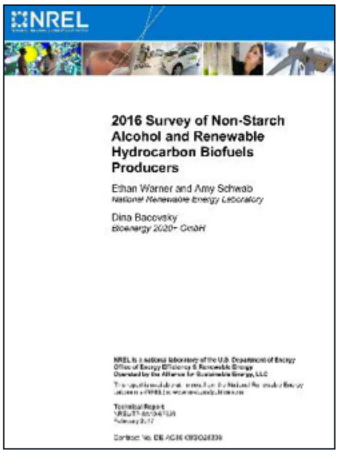
Annual Energy Outlook (AEO 2017) Petroleum Cost

bbl = barrel

Certain Biorefineries are Entered in the Biomass Scenario Model (from NREL *2016 Survey*)

- Biorefineries that are entered in the Biomass Scenario Model advance industrial learning in the model.
- Biorefineries that are …
  - Under Construction and Operating
  - In the United States

  … are entered in the model
- Quantities based on NREL *2016 Survey*
- Consistent with Environmental Protection Agency (U.S. EPA) data
- Includes cellulosic and oil feedstocks
- Does not include biorefineries that are in planning, are idle, or use Corn Kernel Cellulose



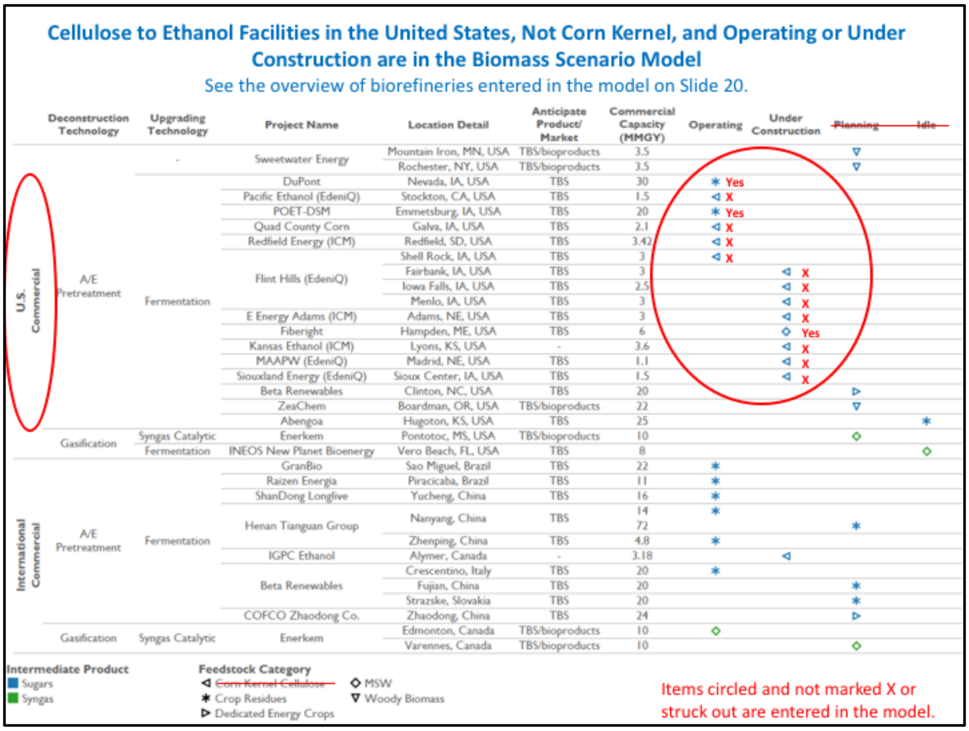
2016 Survey of Non-Starch Alcohol and Renewable Hydrocarbon Biofuels Producers

Ethan Warner and Amy Schwab
National Renewable Energy Laboratory

Dina Bacovsky
Bioenergy 2020+ GmbH

http://www.nrel.gov/docs/fy17osti/67539.pdf

The next two slides show selected biorefineries.



Cellulose to Ethanol Facilities in the United States, Not Corn Kernel, and Operating or Under Construction are in the Biomass Scenario Model

See the overview of biorefineries entered in the model on Slide 20.

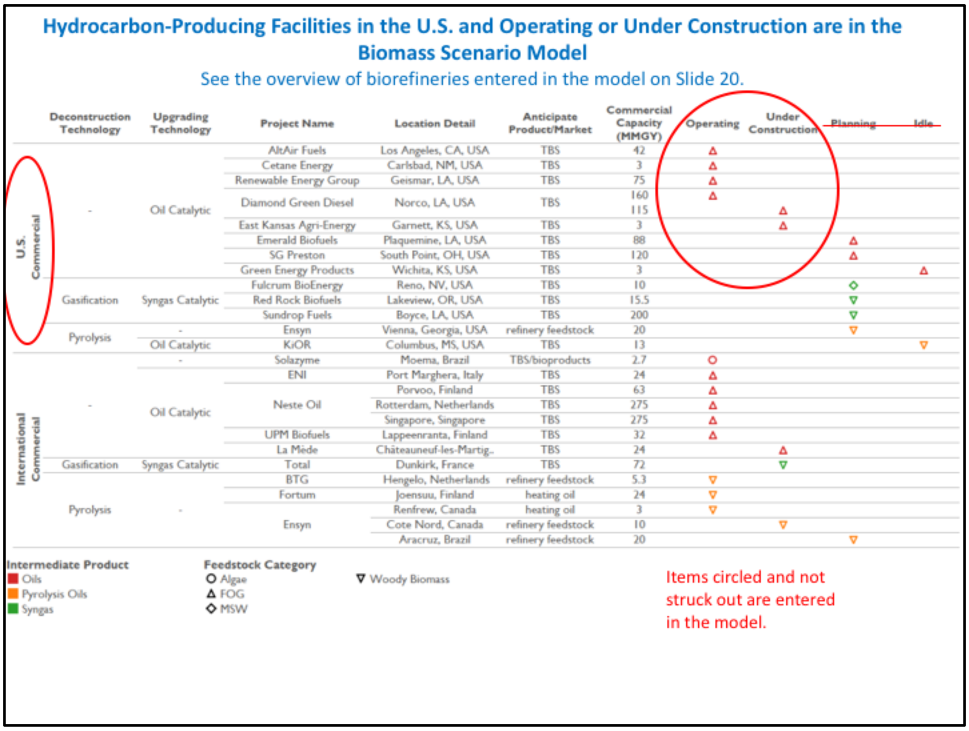
	Deconstruction Technology	Upgrading Technology	Project Name	Location Detail	Anticipate Product/ Market	Commercial Capacity (MMGY)	Operating	Under Construction	~~Planning~~	~~Idle~~
U.S. Commercial	A/E Pretreatment	-	Sweetwater Energy	Mountain Iron, MN, USA	TBS/bioproducts	3.5			▽	
				Rochester, NY, USA	TBS/bioproducts	3.5			▽	
		Fermentation	DuPont	Nevada, IA, USA	TBS	30	✱ Yes			
			Pacific Ethanol (EdeniQ)	Stockton, CA, USA	TBS	1.5	◁ X			
			POET-DSM	Emmetsburg, IA, USA	TBS	20	✱ Yes			
			Quad County Corn	Galva, IA, USA	TBS	2.1	◁ X			
			Redfield Energy (ICM)	Redfield, SD, USA	TBS	3.42	◁ X			
			Flint Hills (EdeniQ)	Shell Rock, IA, USA	TBS	3	◁ X			
				Fairbank, IA, USA	TBS	3		◁ X		
				Iowa Falls, IA, USA	TBS	2.5		◁ X		
				Menlo, IA, USA	TBS	3		◁ X		
			E Energy Adams (ICM)	Adams, NE, USA	TBS	3		◁ X		
			Fiberight	Hampden, ME, USA	TBS	6		◇ Yes		
			Kansas Ethanol (ICM)	Lyons, KS, USA	-	3.6		◁ X		
			MAAPW (EdeniQ)	Madrid, NE, USA	TBS	1.1		◁ X		
			Siouxland Energy (EdeniQ)	Sioux Center, IA, USA	TBS	1.5		◁ X		
			Beta Renewables	Clinton, NC, USA	TBS	20			▷	
			ZeaChem	Boardman, OR, USA	TBS/bioproducts	22			▽	
			Abengoa	Hugoton, KS, USA	TBS	25				✱
	Gasification	Syngas Catalytic	Enerkem	Pontotoc, MS, USA	TBS/bioproducts	10			◇	
		Fermentation	INEOS New Planet Bioenergy	Vero Beach, FL, USA	TBS	8				◇
International Commercial	A/E Pretreatment	Fermentation	GranBio	Sao Miguel, Brazil	TBS	22	✱			
			Raizen Energia	Piracicaba, Brazil	TBS	11	✱			
			ShanDong Longlive	Yucheng, China	TBS	16	✱			
			Henan Tianguan Group	Nanyang, China	TBS	14	✱			
						72			✱	
				Zhenping, China	TBS	4.8	✱			
			IGPC Ethanol	Alymer, Canada	-	3.18		◁		
			Beta Renewables	Crescentino, Italy	TBS	20	✱			
				Fujian, China	TBS	20			✱	
				Strazske, Slovakia	TBS	20			✱	
			COFCO Zhaodong Co.	Zhaodong, China	TBS	24			▷	
	Gasification	Syngas Catalytic	Enerkem	Edmonton, Canada	TBS/bioproducts	10	◇			
				Varennes, Canada	TBS/bioproducts	10			◇	

Intermediate Product
🟦 Sugars
🟩 Syngas

Feedstock Category
◁ ~~Corn Kernel Cellulose~~
✱ Crop Residues
▷ Dedicated Energy Crops
◇ MSW
▽ Woody Biomass

Items circled and not marked X or struck out are entered in the model.

This slide shows a table from the *2016 Survey*, with annotations. The table lists cellulose to ethanol facilities, and the red annotations indicate that the biorefineries that are entered in the model must be domestic, operating, or under construction, and not using corn kernel cellulose.



Hydrocarbon-Producing Facilities in the U.S. and Operating or Under Construction are in the Biomass Scenario Model

See the overview of biorefineries entered in the model on Slide 20.

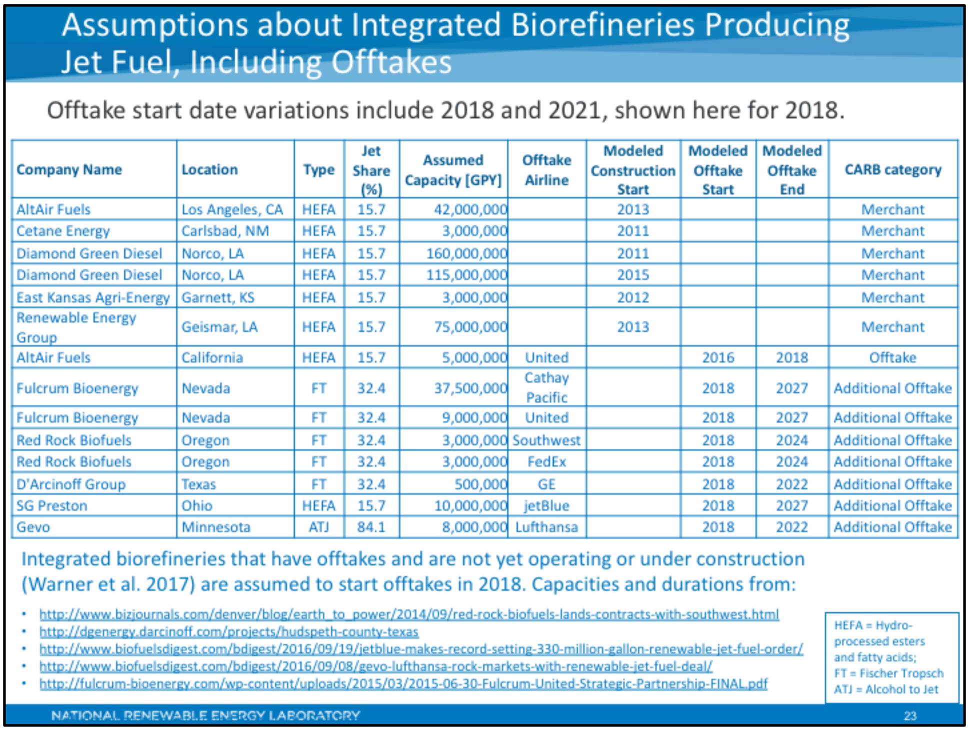
	Deconstruction Technology	Upgrading Technology	Project Name	Location Detail	Anticipate Product/Market	Commercial Capacity (MMGY)	Operating	Under Construction	~~Planning~~	~~Idle~~
U.S. Commercial	-	Oil Catalytic	AltAir Fuels	Los Angeles, CA, USA	TBS	42	△			
			Cetane Energy	Carlsbad, NM, USA	TBS	3	△			
			Renewable Energy Group	Geismar, LA, USA	TBS	75	△			
			Diamond Green Diesel	Norco, LA, USA	TBS	160	△			
						115		△		
			East Kansas Agri-Energy	Garnett, KS, USA	TBS	3		△		
			Emerald Biofuels	Plaquemine, LA, USA	TBS	88			△	
			SG Preston	South Point, OH, USA	TBS	120			△	
			Green Energy Products	Wichita, KS, USA	TBS	3				△
	Gasification	Syngas Catalytic	Fulcrum BioEnergy	Reno, NV, USA	TBS	10			◇	
			Red Rock Biofuels	Lakeview, OR, USA	TBS	15.5			▽	
			Sundrop Fuels	Boyce, LA, USA	TBS	200			▽	
	Pyrolysis	-	Ensyn	Vienna, Georgia, USA	refinery feedstock	20			▽	
		Oil Catalytic	KiOR	Columbus, MS, USA	TBS	13				▽
International Commercial	-	-	Solazyme	Moema, Brazil	TBS/bioproducts	2.7	○			
		Oil Catalytic	ENI	Port Marghera, Italy	TBS	24	△			
			Neste Oil	Porvoo, Finland	TBS	63	△			
				Rotterdam, Netherlands	TBS	275	△			
				Singapore, Singapore	TBS	275	△			
			UPM Biofuels	Lappeenranta, Finland	TBS	32	△			
			La Mède	Châteauneuf-les-Martig..	TBS	24		△		
	Gasification	Syngas Catalytic	Total	Dunkirk, France	TBS	72		▽		
	Pyrolysis	-	BTG	Hengelo, Netherlands	refinery feedstock	5.3	▽			
			Fortum	Joensuu, Finland	heating oil	24	▽			
			Ensyn	Renfrew, Canada	heating oil	3	▽			
				Cote Nord, Canada	refinery feedstock	10		▽		
				Aracruz, Brazil	refinery feedstock	20			▽	

Intermediate Product
- 🟥 Oils
- 🟧 Pyrolysis Oils
- 🟩 Syngas

Feedstock Category
- ○ Algae
- △ FOG
- ◇ MSW
- ▽ Woody Biomass

Items circled and not struck out are entered in the model.

This slide shows a table from the *2016 Survey*, with annotations. The table lists hydrocarbon-producing facilities, and the red annotations indicate that the biorefineries that are entered in the model must be domestic and operating or under construction.



Assumptions about Integrated Biorefineries Producing Jet Fuel, Including Offtakes

Offtake start date variations include 2018 and 2021, shown here for 2018.

Company Name	Location	Type	Jet Share (%)	Assumed Capacity [GPY]	Offtake Airline	Modeled Construction Start	Modeled Offtake Start	Modeled Offtake End	CARB category
AltAir Fuels	Los Angeles, CA	HEFA	15.7	42,000,000		2013			Merchant
Cetane Energy	Carlsbad, NM	HEFA	15.7	3,000,000		2011			Merchant
Diamond Green Diesel	Norco, LA	HEFA	15.7	160,000,000		2011			Merchant
Diamond Green Diesel	Norco, LA	HEFA	15.7	115,000,000		2015			Merchant
East Kansas Agri-Energy	Garnett, KS	HEFA	15.7	3,000,000		2012			Merchant
Renewable Energy Group	Geismar, LA	HEFA	15.7	75,000,000		2013			Merchant
AltAir Fuels	California	HEFA	15.7	5,000,000	United		2016	2018	Offtake
Fulcrum Bioenergy	Nevada	FT	32.4	37,500,000	Cathay Pacific		2018	2027	Additional Offtake
Fulcrum Bioenergy	Nevada	FT	32.4	9,000,000	United		2018	2027	Additional Offtake
Red Rock Biofuels	Oregon	FT	32.4	3,000,000	Southwest		2018	2024	Additional Offtake
Red Rock Biofuels	Oregon	FT	32.4	3,000,000	FedEx		2018	2024	Additional Offtake
D'Arcinoff Group	Texas	FT	32.4	500,000	GE		2018	2022	Additional Offtake
SG Preston	Ohio	HEFA	15.7	10,000,000	jetBlue		2018	2027	Additional Offtake
Gevo	Minnesota	ATJ	84.1	8,000,000	Lufthansa		2018	2022	Additional Offtake

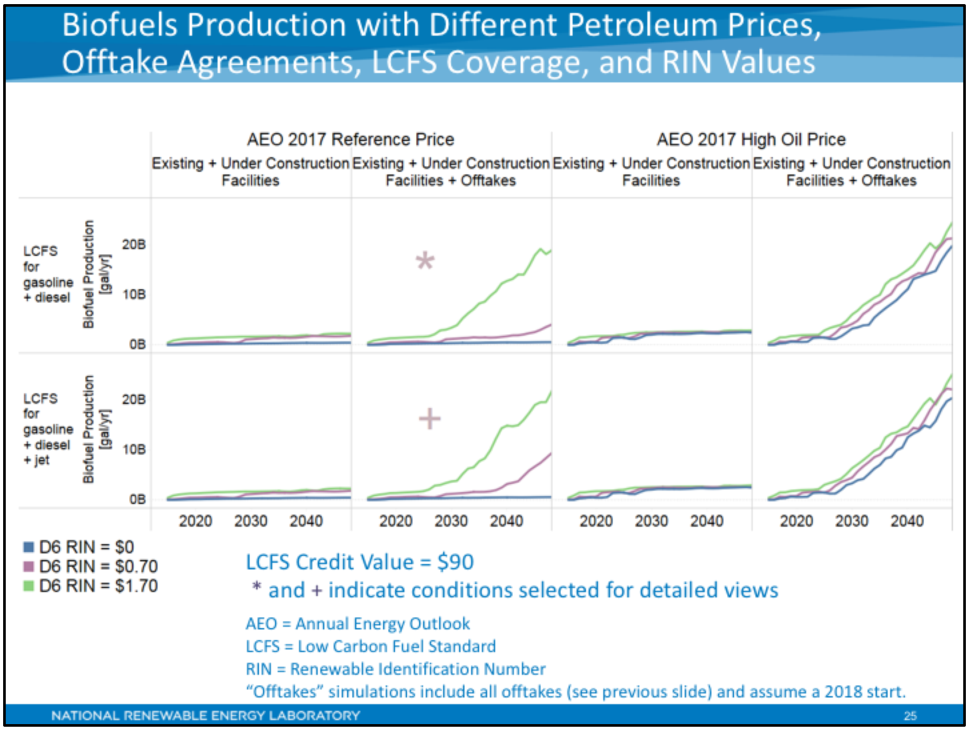
Integrated biorefineries that have offtakes and are not yet operating or under construction (Warner et al. 2017) are assumed to start offtakes in 2018. Capacities and durations from:

- http://www.bizjournals.com/denver/blog/earth_to_power/2014/09/red-rock-biofuels-lands-contracts-with-southwest.html
- http://dgenergy.darcinoff.com/projects/hudspeth-county-texas
- http://www.biofuelsdigest.com/bdigest/2016/09/19/jetblue-makes-record-setting-330-million-gallon-renewable-jet-fuel-order/
- http://www.biofuelsdigest.com/bdigest/2016/09/08/gevo-lufthansa-rock-markets-with-renewable-jet-fuel-deal/
- http://fulcrum-bioenergy.com/wp-content/uploads/2015/03/2015-06-30-Fulcrum-United-Strategic-Partnership-FINAL.pdf

HEFA = Hydro-processed esters and fatty acids;
FT = Fischer Tropsch
ATJ = Alcohol to Jet

Several firms are producing or have expressed an intention to produce alternative jet fuel, sometimes with an agreement to supply a specific airline (i.e., an offtake agreement). The table shows the data used in the BSM for this study. The final column ("CARB category") shows the production that is included in all of the simulations (labeled "Merchant" and "Offtake") and the production that is added to some of the simulations in either 2018 or 2021 (labeled "Additional Offtake").

Results



Biofuels Production with Different Petroleum Prices, Offtake Agreements, LCFS Coverage, and RIN Values

LCFS Credit Value = $90

* and + indicate conditions selected for detailed views

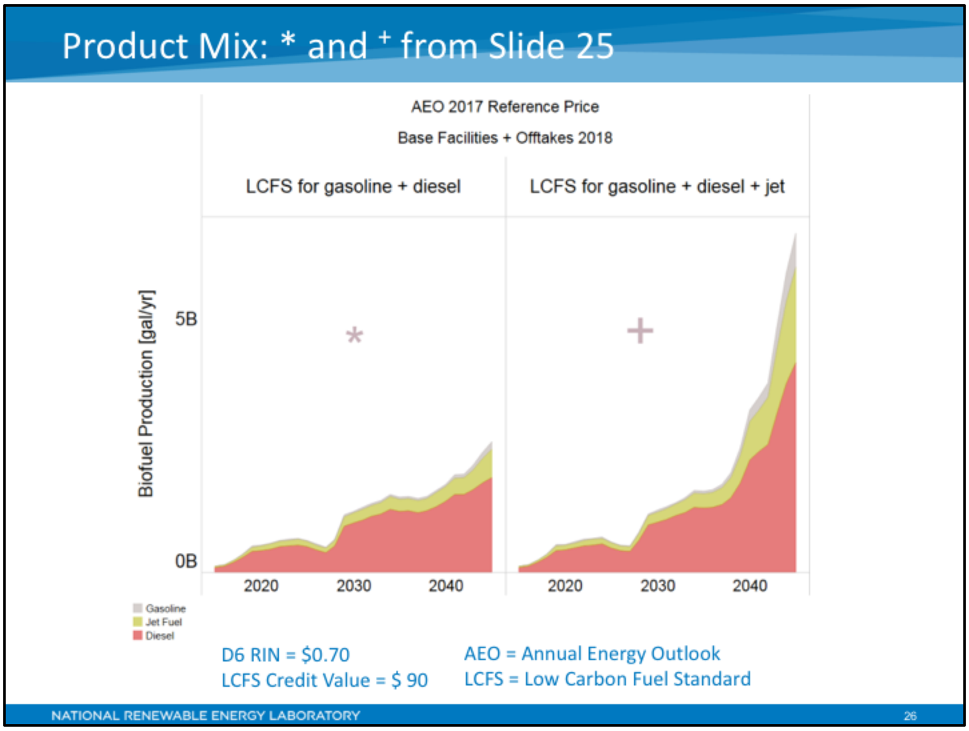
AEO = Annual Energy Outlook
LCFS = Low Carbon Fuel Standard
RIN = Renewable Identification Number
"Offtakes" simulations include all offtakes (see previous slide) and assume a 2018 start.

NATIONAL RENEWABLE ENERGY LABORATORY 25

This figure shows results for biofuels production (gal/yr) versus time, with each of the eight panels representing different input conditions for the simulation. Columns 1–2 use AEO 2017 Reference oil prices, and Columns 3–4 use AEO 2017 High oil prices, shown in Slide 19. Columns 2 and 4 add the additional offtake agreements shown in Slide 23.

The rows show simulation results for the policy difference that is the subject of this study. The top row excludes alternative jet fuel from receiving LCFS credit; the bottom row allows alternative jet fuel to receive LCFS credit, according to the methodology described in Slide 11.

The simulations with additional offtake agreements exhibit increased biofuels industry growth, except under reference oil prices and $0 RIN value. The two marked panels show the circumstances among these eight simulations under which the effect of LCFS credit for alternative jet fuel is greatest. Subsequent slides explore these two conditions in detail.



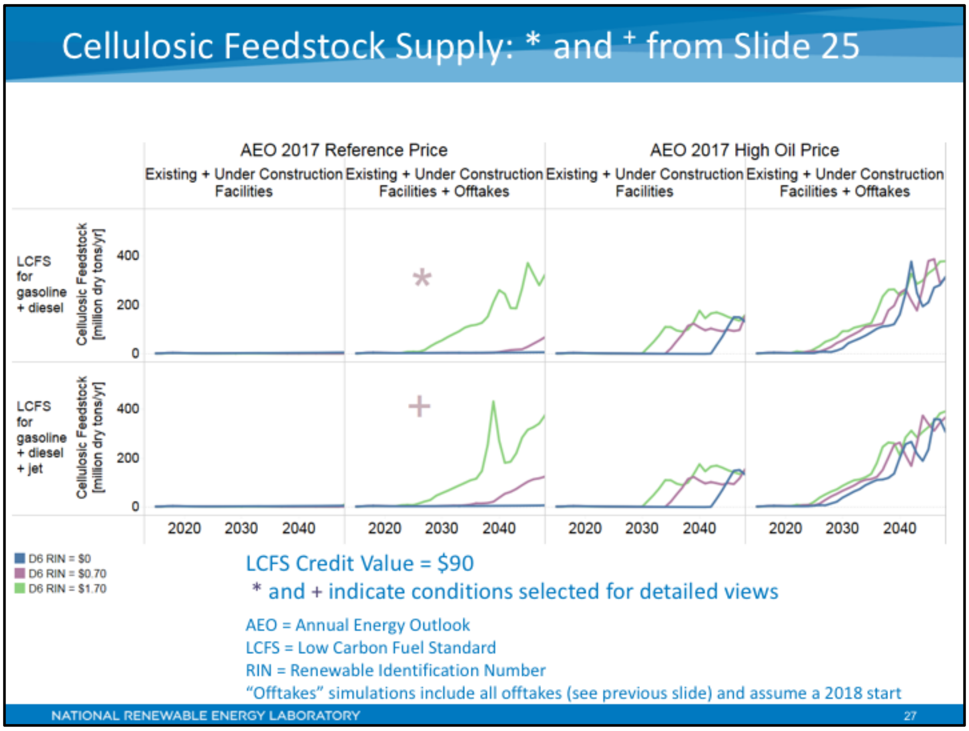
Product Mix: * and + from Slide 25

D6 RIN = $0.70
LCFS Credit Value = $ 90

AEO = Annual Energy Outlook
LCFS = Low Carbon Fuel Standard

NATIONAL RENEWABLE ENERGY LABORATORY 26

This figure shows results for biofuels production (gal/yr) by type in the two marked panels from Slide 25 (purple line) for the $0.70 D6 RIN value. The product mix of gasoline, jet, and diesel is fixed for each pathway—not dynamically determined based on profitability.



Cellulosic Feedstock Supply: * and + from Slide 25

LCFS Credit Value = $90

* and + indicate conditions selected for detailed views

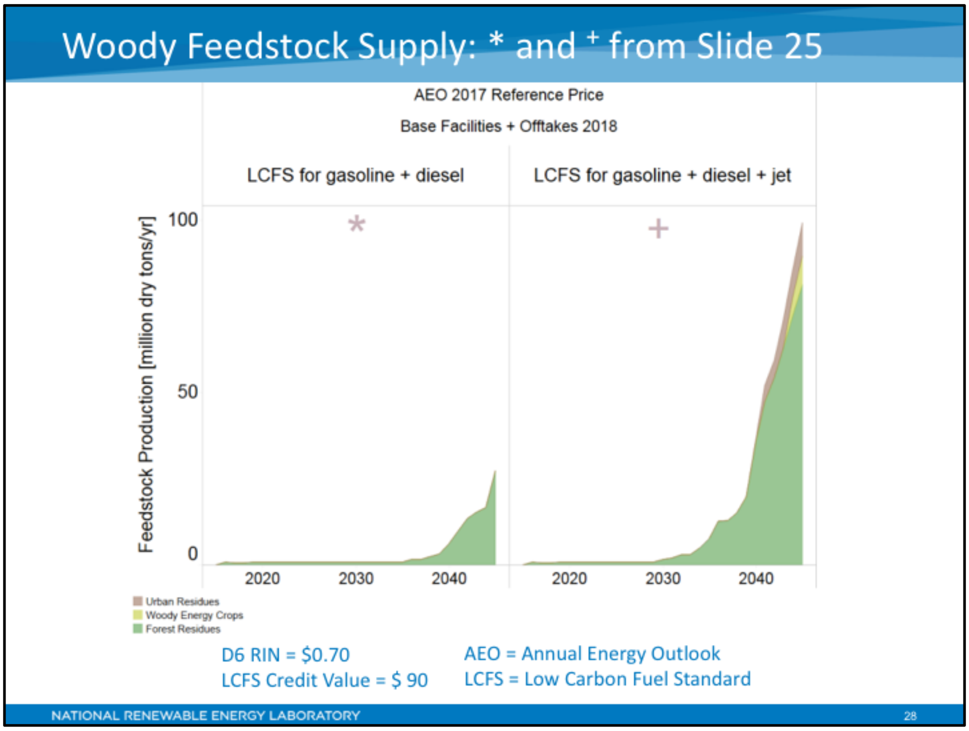
AEO = Annual Energy Outlook

LCFS = Low Carbon Fuel Standard

RIN = Renewable Identification Number

"Offtakes" simulations include all offtakes (see previous slide) and assume a 2018 start

This figure shows results for cellulosic feedstock production (million dry tons/yr) versus time, with each of the eight panels representing different input conditions as on Slide 25. Cellulosic feedstocks in the BSM include herbaceous and woody energy crops. Variability in an output is common in system dynamics models such as the BSM, because they are expressly designed to represent feedbacks that create these cycles, as may be empirically observed in many commodity markets.



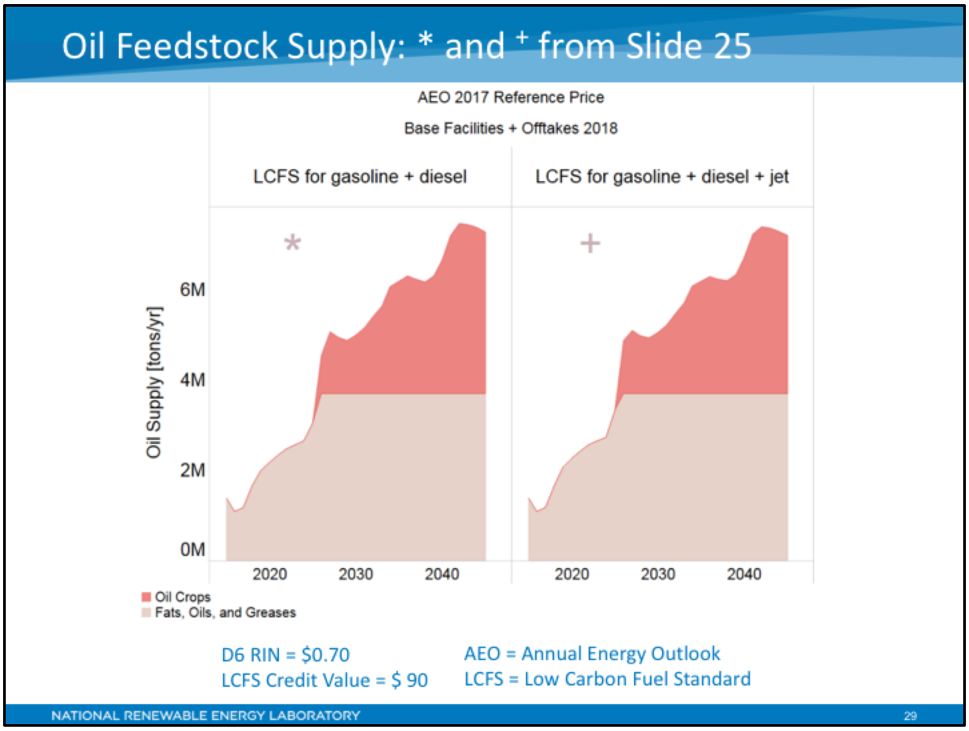
Woody Feedstock Supply: * and + from Slide 25

D6 RIN = $0.70
LCFS Credit Value = $ 90

AEO = Annual Energy Outlook
LCFS = Low Carbon Fuel Standard

This figure shows results for woody feedstock production (million dry tons/yr) by type in the two marked panels from Slide 25 (purple line) for the $0.70 D6 RIN value. The mix of urban residues, woody energy crops, and forest residues is determined by the supply curves of the resources and their desirability as feedstocks for the producing biorefineries.

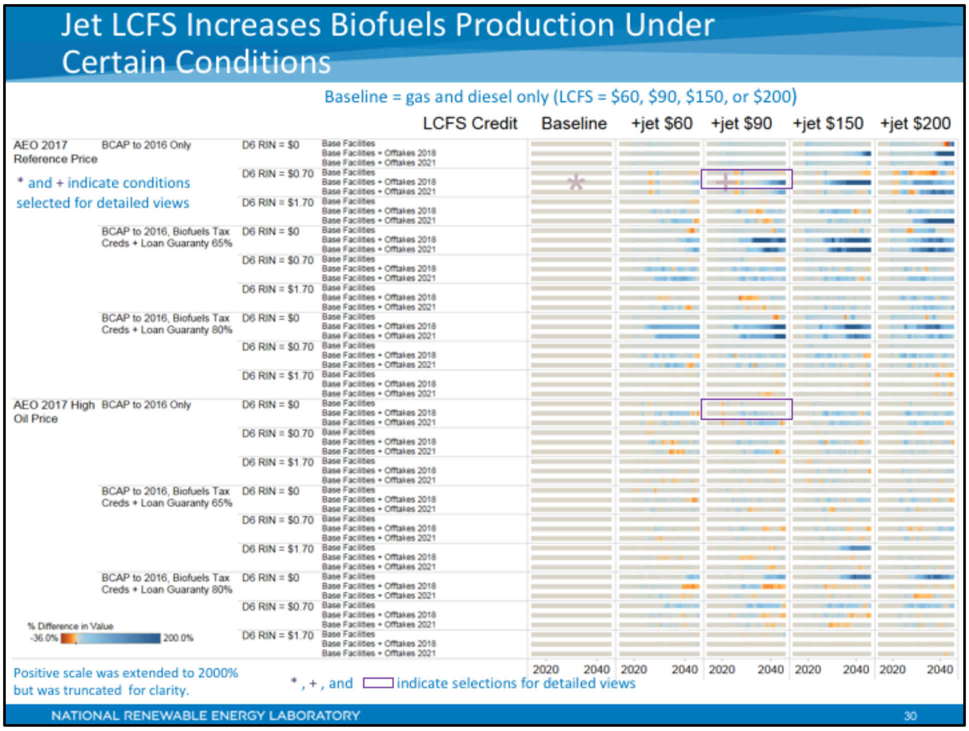
Oil Feedstock Supply: * and $^{+}$ from Slide 25



D6 RIN = $0.70
LCFS Credit Value = $ 90

AEO = Annual Energy Outlook
LCFS = Low Carbon Fuel Standard

This figure shows results for oil feedstock production (tons/yr) by type in the two marked panels from Slide 25 (purple line) for the $0.70 D6 RIN value. The mix of oil crops and fats oils and greases is determined by the supply curves of the resources and their desirability as feedstocks for the producing biorefineries. As a waste product, the supply of fats, oils, and greases is likely to face some upper limit, indicated here by the horizontal line at approximately 3.5 million tons, although growth in producing industries might lead to increased supply. The oil crop producing here is soy oil, which is also assumed to be limited to avoid potential for competition with its use in food industries. The limit in these simulations is at approximately 4.6 million tons.



Jet LCFS Increases Biofuels Production Under Certain Conditions

Baseline = gas and diesel only (LCFS = $60, $90, $150, or $200)

* and + indicate conditions selected for detailed views

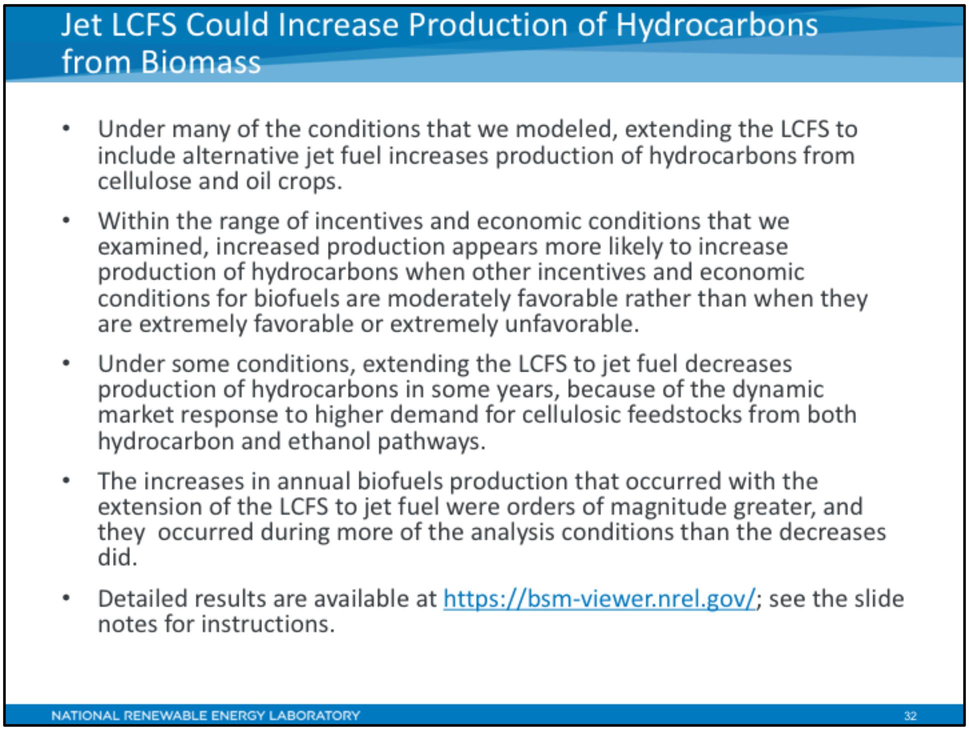
Positive scale was extended to 2000% but was truncated for clarity.

* , + , and ▭ indicate selections for detailed views

NATIONAL RENEWABLE ENERGY LABORATORY 30

This figure shows results for the difference in biofuels production (%) with the LCFS for alternative jet fuel, relative to baseline without LCFS for jet, versus time for 270 of the simulations performed for this study. The color scale ranges from dark orange for reductions in biofuels production with the LCFS to dark blue for increases in biofuels production with the LCFS. The scale is not centered on zero because the simulations extended farther in the positive than in the negative. Conclusions about the prevalence of increases and decreases are described on the next slide and placed in context the preceding results of the few selected detailed views.

Conclusions and Limitations



Jet LCFS Could Increase Production of Hydrocarbons from Biomass

- Under many of the conditions that we modeled, extending the LCFS to include alternative jet fuel increases production of hydrocarbons from cellulose and oil crops.
- Within the range of incentives and economic conditions that we examined, increased production appears more likely to increase production of hydrocarbons when other incentives and economic conditions for biofuels are moderately favorable rather than when they are extremely favorable or extremely unfavorable.
- Under some conditions, extending the LCFS to jet fuel decreases production of hydrocarbons in some years, because of the dynamic market response to higher demand for cellulosic feedstocks from both hydrocarbon and ethanol pathways.
- The increases in annual biofuels production that occurred with the extension of the LCFS to jet fuel were orders of magnitude greater, and they occurred during more of the analysis conditions than the decreases did.
- Detailed results are available at https://bsm-viewer.nrel.gov/; see the slide notes for instructions.

This website (https://bsm-viewer.nrel.gov/) contains the underlying data that were used to make the charts in this presentation; it does not contain the charts themselves. After you navigate to the website, you can find the data for biofuel production by pathway by selecting the check boxes for “Output by Technology and Region” AND “Cellulosic Hydrocarbons” OR “Oil Hydrocarbons” Conversion Pathways. Note that the “Oil Hydrocarbons” Conversion Pathway is not currently available on a regional level. Once the data are displayed, you can select a download option.

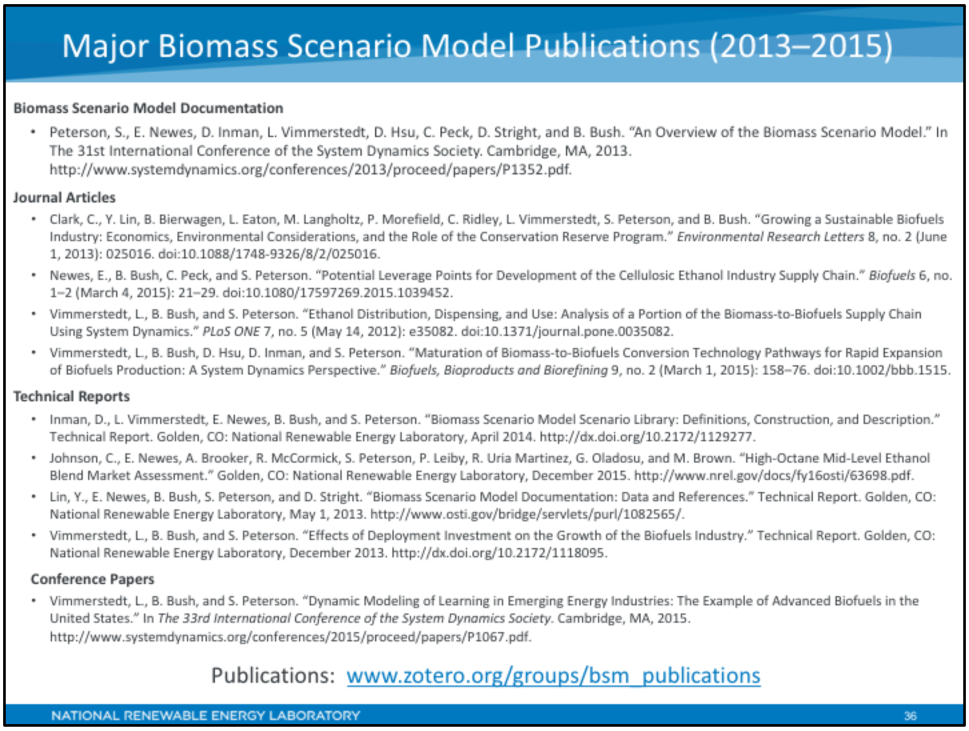
Limitations

- Results depend on many assumptions.
    - Input assumptions may not reflect future conditions.
    - Model algorithms are necessarily a simplified representation of reality.
- Not all relevant alternative jet fuel or other pathways are represented. In particular, retrofit pathways and unpublished techno-economics are not included.
- The simplified representation of LCFS credit applies to the Pacific region, one of the 10 regions in the Biomass Scenario Model.
- Price feedback is not included in fuel mix, LCFS credit markets, RIN markets, or representation of offtake agreements.
- Offtakes are modeled as fixed scenarios of **guaranteed** production, strongly driving industrial learning.
- Results show that system behaviors are more robust than specific quantitative results.

References

References

- **References for Techno-Economic Assumptions**
  - Davis, R.; Tao, L.; Tan, E. C. D.; Biddy, M. J.; Beckham, G. T.; Scarlata, C.; Jacobson, J.; Cafferty, K.; Ross, J.; Lukas, J.; Knorr, D.; Schoen, P. (2013). Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Biological Conversion of Sugars to Hydrocarbons. NREL/TP-5100-60223. Golden, CO: National Renewable Energy Laboratory. Available from: http://www.nrel.gov/docs/fy14osti/60223.pdf.
  - Davis, R., L. Tao, C. Scarlata, E.C.D. Tan, J. Ross, J. Lukas, and D. Sexton. 2015. Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Catalytic Conversion of Sugars to Hydrocarbons. NREL/TP-5100-62498. Golden, CO: NREL. http://www.nrel.gov/docs/fy15osti/62498.pdf.
  - Dutta, A.; Talmadge, M.; Hensley, J.; Worley, M.; Dudgeon. D.; Barton, D.; Groenendijk, P.; Ferrari, D.; Stears, B.; Searcy, E.M.; Wright, C.T.; Hess, J.R. (2011). *Process Design and Economics for Conversion of Lignocellulosic Biomass to Ethanol Thermochemical Pathway by Indirect Gasification and Mixed Alcohol Synthesis.* NREL/TP-5100-51400. Golden, CO: National Renewable Energy Laboratory. Accessed May 12, 2014: http://www.nrel.gov/biomass/pdfs/51400.pdf.
  - Jones, S.B., P.A. Meyer, L.J. Snowden-Swan, A.B. Padmaperuma, E. Tan, A. Dutta, J. Jacobson, and K. Cafferty. 2013. Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Fast Pyrolysis and Hydrotreating Bio-Oil Pathway. PNNL-23053; NREL/TP-5100-61178. Pacific Northwest National Laboratory, NREL. http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23053.pdf.
  - Humbird, D.; Davis, R.; Tao, L.; Kinchin, C.; Hsu, D.; Aden, A.; Schoen, P.; Lukas, J.; Olthof, B.; Worley, M.; Sexton, D.; Dudgeon, D. (2011). Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover. NREL/TP-5100-47764. Golden, CO: National Renewable Energy Laboratory. Accessed May 12, 2014: http://www.nrel.gov/biomass/pdfs/47764.pdf.
  - Pearlson, M., Wollersheim, C., Hileman, J. "A techno-economic review of hydroprocessed renewable esters and fatty acids for jet fuel production." *Biofuels, Bioproducts and Biorefining* 7 (2013). DOI: 10.1002/bbb.1378.
  - Staples, M.D., Malina, R., Olcay, H., Pearlson, M.N., Hileman, J.I., Boies, A., Barrett, S.R.H. "Lifecycle greenhouse gas footprint and minimum selling price of renewable diesel and jet fuel from fermentation and advanced fermentation production technologies." *Energy Environmental Science* 7 (2014). DOI: 10.1039/C3EE43655A.
  - Tan, E.C.D., Snowden-Swan, L.J., Talmadge, M., Dutta, A., Jones, S., Ramasamy, K.K., Gray, M., Dagle, R. Padmaperuma, A., Gerber, M., Sahir, A.H., Tao, L., Zhang, Y. "Comparative Techno-Economic Analysis and Process Design for Indirect Liquefaction Pathways to Distillate-Range Fuels via Biomass-Derived Oxygenated Intermediates Upgrading." *Biofuels, Bioproducts and Biorefining* 11 (2016). DOI:10.1002/bbb.1710.
  - Tan, E.C.D., Talmadge, M., Dutta, A., Hensley, J., Schaidle, J., Biddy, M., Humbird, D., Snowden-Swan, L.J., Ross, J., Sexton, D., Yap, R., Lukas, J. "Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons via Indirect Liquefaction Comparative Techno-Economic Analysis and Process Design for Indirect Liquefaction." NREL/TP-5100-62402. Golden, CO: NREL. http://www.nrel.gov/docs/fy15osti/62402.pdf.
  - Tao and Aden (2011)
- **Integrated Biorefinery Survey**
  - Warner, E., Schwab, A., Bacovsky, D. "2016 Survey of Non-Starch Alcohol and Renewable Hydrocarbon Biofuels Producers." Golden, CO: National Renewable Energy Laboratory (2017). NREL/TP-6A10-67539.
- **Websites for Offtake Agreements**
  - http://www.bizjournals.com/denver/blog/earth_to_power/2014/09/red-rock-biofuels-lands-contracts-with-southwest.html
  - http://dgenergy.darcinoff.com/projects/hudspeth-county-texas
  - http://www.biofuelsdigest.com/bdigest/2016/09/19/jetblue-makes-record-setting-330-million-gallon-renewable-jet-fuel-order/
  - http://www.biofuelsdigest.com/bdigest/2016/09/08/gevo-lufthansa-rock-markets-with-renewable-jet-fuel-deal/
  - http://fulcrum-bioenergy.com/wp-content/uploads/2015/03/2015-06-30-Fulcrum-United-Strategic-Partnership-FINAL.pdf
- **References for Carbon Intensities**
  - California Air Resources Board, personal communication with James Duffy.



Major Biomass Scenario Model Publications (2013–2015)

Biomass Scenario Model Documentation

- Peterson, S., E. Newes, D. Inman, L. Vimmerstedt, D. Hsu, C. Peck, D. Stright, and B. Bush. "An Overview of the Biomass Scenario Model." In The 31st International Conference of the System Dynamics Society. Cambridge, MA, 2013. http://www.systemdynamics.org/conferences/2013/proceed/papers/P1352.pdf.

Journal Articles

- Clark, C., Y. Lin, B. Bierwagen, L. Eaton, M. Langholtz, P. Morefield, C. Ridley, L. Vimmerstedt, S. Peterson, and B. Bush. "Growing a Sustainable Biofuels Industry: Economics, Environmental Considerations, and the Role of the Conservation Reserve Program." *Environmental Research Letters* 8, no. 2 (June 1, 2013): 025016. doi:10.1088/1748-9326/8/2/025016.
- Newes, E., B. Bush, C. Peck, and S. Peterson. "Potential Leverage Points for Development of the Cellulosic Ethanol Industry Supply Chain." *Biofuels* 6, no. 1–2 (March 4, 2015): 21–29. doi:10.1080/17597269.2015.1039452.
- Vimmerstedt, L., B. Bush, and S. Peterson. "Ethanol Distribution, Dispensing, and Use: Analysis of a Portion of the Biomass-to-Biofuels Supply Chain Using System Dynamics." *PLoS ONE* 7, no. 5 (May 14, 2012): e35082. doi:10.1371/journal.pone.0035082.
- Vimmerstedt, L., B. Bush, D. Hsu, D. Inman, and S. Peterson. "Maturation of Biomass-to-Biofuels Conversion Technology Pathways for Rapid Expansion of Biofuels Production: A System Dynamics Perspective." *Biofuels, Bioproducts and Biorefining* 9, no. 2 (March 1, 2015): 158–76. doi:10.1002/bbb.1515.

Technical Reports

- Inman, D., L. Vimmerstedt, E. Newes, B. Bush, and S. Peterson. "Biomass Scenario Model Scenario Library: Definitions, Construction, and Description." Technical Report. Golden, CO: National Renewable Energy Laboratory, April 2014. http://dx.doi.org/10.2172/1129277.
- Johnson, C., E. Newes, A. Brooker, R. McCormick, S. Peterson, P. Leiby, R. Uria Martinez, G. Oladosu, and M. Brown. "High-Octane Mid-Level Ethanol Blend Market Assessment." Golden, CO: National Renewable Energy Laboratory, December 2015. http://www.nrel.gov/docs/fy16osti/63698.pdf.
- Lin, Y., E. Newes, B. Bush, S. Peterson, and D. Stright. "Biomass Scenario Model Documentation: Data and References." Technical Report. Golden, CO: National Renewable Energy Laboratory, May 1, 2013. http://www.osti.gov/bridge/servlets/purl/1082565/.
- Vimmerstedt, L., B. Bush, and S. Peterson. "Effects of Deployment Investment on the Growth of the Biofuels Industry." Technical Report. Golden, CO: National Renewable Energy Laboratory, December 2013. http://dx.doi.org/10.2172/1118095.

Conference Papers

- Vimmerstedt, L., B. Bush, and S. Peterson. "Dynamic Modeling of Learning in Emerging Energy Industries: The Example of Advanced Biofuels in the United States." In *The 33rd International Conference of the System Dynamics Society*. Cambridge, MA, 2015. http://www.systemdynamics.org/conferences/2015/proceed/papers/P1067.pdf.

Publications: www.zotero.org/groups/bsm_publications

Thank you!

emily.newes@nrel.gov

laura.vimmerstedt@nrel.gov

www.nrel.gov

NREL
NATIONAL RENEWABLE ENERGY LABORATORY