Effects of Deployment Investment on the Growth of the Biofuels Industry: 2016 Update

Laura J. Vimmerstedt, Ethan S. Warner, and Dana Stright
National Renewable Energy Laboratory (NREL)

NREL is a national laboratory of the U.S. Department of Energy
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Technical Report
NREL/TP-6A20-65903
March 2016

Contract No. DE-AC36-08GO28308

NATIONAL RENEWABLE ENERGY LABORATORY

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Prepared under Task No. BZ14.1002

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Executive Summary

This report updates the 2013 report of the same title. Some text originally published in that report is retained and indicated in gray.

In support of the national goals for biofuel use in the United States, numerous technologies have been developed that convert biomass to biofuels. Some of these biomass to biofuel conversion technology pathways are operating at commercial scales, while others are in earlier stages of development. The advancement of a new pathway toward commercialization involves various types of progress, including yield improvements, process engineering, and financial performance. Actions of private investors and public programs can accelerate the demonstration and deployment of new conversion technology pathways. These investors (both private and public) will pursue a range of pilot, demonstration, and pioneer scale biorefinery investments; the most cost-effective set of investments for advancing the maturity of any given biomass to biofuel conversion technology pathway is unknown. In some cases, whether or not the pathway itself will ultimately be technically and financially successful is also unknown. This report presents results from the Biomass Scenario Model—a system dynamics model of the biomass to biofuels system—that estimate effects of investments in biorefineries at different maturity levels and operational scales. The report discusses challenges in estimating effects of such investments and explores the interaction between this deployment investment and a volumetric production incentive. Model results show that investments in demonstration and deployment have a substantial growth impact on the development of the biofuels industry. Results also show that other conditions, such as accompanying incentives, have major impacts on the effectiveness of such investments. Results from the 2013 report are compared to new results. This report does not advocate for or against investments, incentives, or policies, but analyzes simulations of their hypothetical effects.

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1 Introduction

This report updates the 2013 report of the same title (Vimmerstedt, Bush, and Peterson 2013), which will be referenced below as "the 2013 report." Some text originally published in that report is retained and indicated in gray. The Energy Independence and Security Act of 2007 (EISA) established a national goal of 36 billion gallons/year of renewable liquid transportation fuel in the United States by 2022 (U.S. Congress 2007). A variety of biomass resources can be converted to biofuels, including conversion of corn starch, sugar cane, cellulosic feedstocks, or other biomass to ethanol; biological oils to biodiesel; and cellulosic feedstocks or other biomass to hydrocarbons. Some biomass to biofuel conversion technology pathways are financially viable at commercial scales, while others face more uncertainty because they are in earlier stages of development. For example, ethanol from corn starch is a large-scale, fully commercial industry with 14.7 billion gallons annual production capacity (U.S. Energy Information Administration 2016), as is biodiesel, with a production capacity of 2.1 billion gallons per year (U.S. Energy Information Administration 2016). Other examples of commercially active biomass to biofuel conversion pathways include DuPont's Nevada, Iowa, 30-million-gallon-per-year capacity pioneer facility, which started production using a cellulosic feedstocks to ethanol pathway in October 2015 (DuPont 2015), and Diamond Green Diesel's Norco, Louisiana, pioneer facility with a 137-million-gallon-per-year capacity, which started production in 2014 using a biological oils to hydrocarbon conversion pathway (Honeywell 2014).

Commercialization of new biomass to biofuels conversion technology pathways may require improvements that include yield improvements, process engineering improvements, and financial performance developments that together drive down costs and reduce risks (Junginger, Sark, and Faaij 2010). Actions of both private investors and public programs contribute to the demonstration and deployment of new pathways. For example, the U.S. Department of Energy, Bioenergy Technologies Office, invests in research, development, demonstration, and deployment activities that aim to advance the commercialization of among other goals biofuels (U.S. Department of Energy 2015). The set of investments (both private and public) that will most cost-effectively advance the maturity of a new pathway is not known and is inherently uncertain. Deployment investments may take place at a variety of operational scales and levels of maturity ranging from investment in pilot, to demonstration, to pioneer scale biorefineries. This report estimates effects of investment in selected sets of biorefineries and discusses challenges in making such estimates. The estimates are based on results from the Biomass Scenario Model (BSM)—a system dynamics model of the biomass to biofuels system that can be used to understand system behavior and policy effects but is not intended for making precise predictions. Based on the results presented in this report, investments in demonstration and deployment of biomass to biofuels conversion technologies have a positive effect on the development of the biofuels industry, and supportive policies, among other conditions, have major impacts on the effectiveness of such investments. This report does not advocate for or against investments, incentives, or policies.

Steps toward deployment are made by proving various aspects of performance at different scales. Smaller-scale, less-costly, shorter-duration activities are completed first, on the theory that successful completion of these smaller-scale activities improves the chances of success of larger-scale facilities that follow, reducing financial risk. For purposes of this report, we discuss three biorefinery scales that are distinguished by throughput capacity and maturity of operations:

integrated pilot, demonstration, and commercial as defined in the Bioenergy Technology Office (BETO) Multiyear Program Plan (MYPP) (U.S. Department of Energy 2015). At the integrated pilot scale (typically greater than one dry tonne (one metric ton) of feedstock processed per day and less than one-fiftieth of commercial scale), integrated technical performance of technologies from feedstock through product output is a major emphasis. This may involve optimizing inputs, catalysts, micro-organisms, temperatures, pressures, residence times, and other process engineering parameters. Successful integrated pilot operations identify problems to be addressed before scale-up and provide essential data for demonstration scale design. At the demonstration scale (typically on the order of 50 tonnes of feedstock processed per day, or more than one-fiftieth of full commercial scale), proving total system operation during a period of continuous operations is a key challenge, especially maintaining process yield at this larger scale while proving the efficacy of process and material handling systems. Successful demonstration provides critical industrial-scale design information for the pioneer scale. At the pioneer scale (typically hundreds of tons of feedstock processed per day), maintaining performance at a larger scale on a continuous basis is again a focus, and the successful pioneer scale biorefinery will result in proof of all aspects of commercial scale system operations (e.g., feedstock supply and production distribution system), reducing risk and enabling future biorefineries to secure financing on better terms.[1] Pioneer scale is not always defined separately from commercial scale in the literature or in general usage, and is sometimes called first-of-a-kind. Distinguishing a pioneer scale from commercial scale is useful here because it highlights the higher costs and risks that are still present for biorefineries at early stages of commercialization. While pioneer facilities are generally considered too risky to receive regular project financing, successful pioneer operations could enable future full-scale commercial facilities to receive project financing at more favorable interest rates.

This report addresses the question, "What might be the effect of concerted investment in a set of biorefineries on advancing biomass to biofuels conversion technology pathways toward commercialization?" Answering this question could help either public or private investment portfolios by informing their design and potentially improving their cost-effectiveness.

Section 2 of the report describes how the BSM simulates the commercialization process, especially the effects of demonstration and deployment investment at different scales. Section 3 presents results, including a comparison for 2016 of baseline versus additional demonstration and deployment investment conditions with two oil price cases, as well as comparisons with results from the 2013 report. This section also discusses limitations of the results. Section 4 summarizes conclusions and possible next steps to further understand the role of investment in biorefineries (at all scales of operation) in advancing commercialization of conversion pathways.

[1] In 2013, the BSM used a definition of pioneer and commercial scales based on size, but now it includes pioneer within the commercial scale, with reduced cost and performance for pioneer plants as described below.

2 Modeling Commercialization of Biofuels in the BSM

The U.S. Department of Energy-Bioenergy Technologies Office and the National Renewable Energy Laboratory (NREL) developed the BSM to explore the development of a U.S. biofuels industry (Peterson et al. 2015). Using a system dynamics modeling approach, the BSM is built on the STELLA software platform (isee systems, n.d.). The model represents the dynamic interactions of the major sectors of the biofuels industry—feedstock production and logistics, feedstock conversion, and downstream elements (inventory, dispensing, distribution, fuel use, and vehicle fleet). The BSM represents contextual aspects of the developing biofuels industry, including investment in new biomass to biofuel conversion technologies, competition from petroleum fuels, vehicle demand for biofuels, and various government policies, using all of these to simulate the development of the industry. The purpose of the BSM is to generate and explore plausible scenarios for the evolution of a biofuels industry in the United States, and as a high-level system model it is not designed for precise, quantitative forecasting. Instead, it is best used to (1) analyze and evaluate alternate policies; (2) generate scenarios; (3) identify high-impact levers and bottlenecks to system evolution; and (4) seed focused discussion among policymakers, analysts, and stakeholders. In this report, the BSM will be used to explore how public or private investment at integrated pilot, demonstration, and early commercial biorefineries might affect biofuels industry development under different incentive conditions.

2.1 BSM Overview

The major sectors of the biofuel industry and the associated BSM modules are shown in Figure 1. Previous publications (Peterson et al. 2015; Newes, Inman, and Bush 2011; Lin et al. 2013; Inman et al. 2014; Bush 2011) offer a more detailed discussion of the BSM, including its geographic stratification, module logic and structure, and data sources. The part of the model most relevant to this report is the conversion module of the BSM, which simulates the conversion of biomass to biofuels, including the demonstration and deployment of new pathways.

Figure 2 shows the feedstocks, fuels or blendstocks, and biomass to biofuel conversion pathways in the BSM.

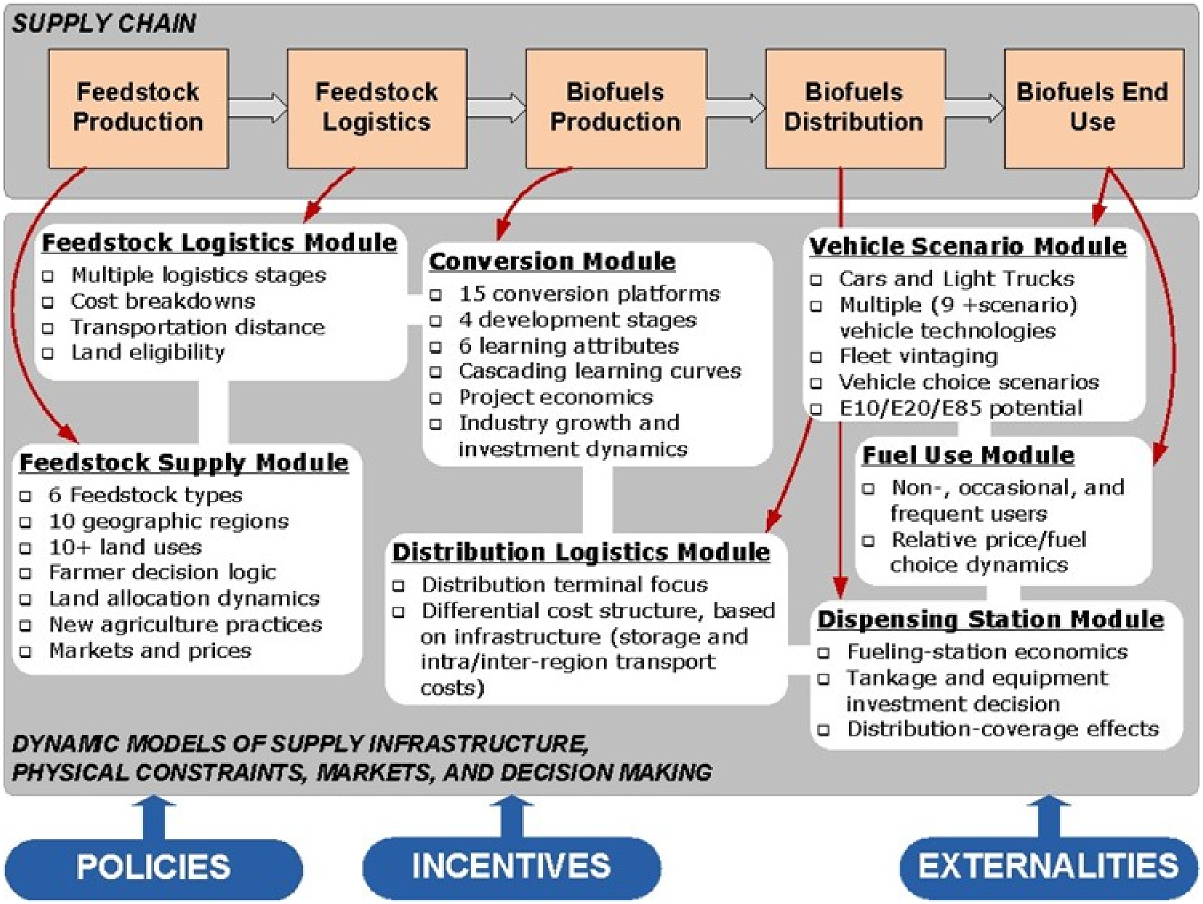

Figure 1. Major modules in the BSM represent major sectors of the biofuels industry (Vimmerstedt, Bush, and Peterson 2013)

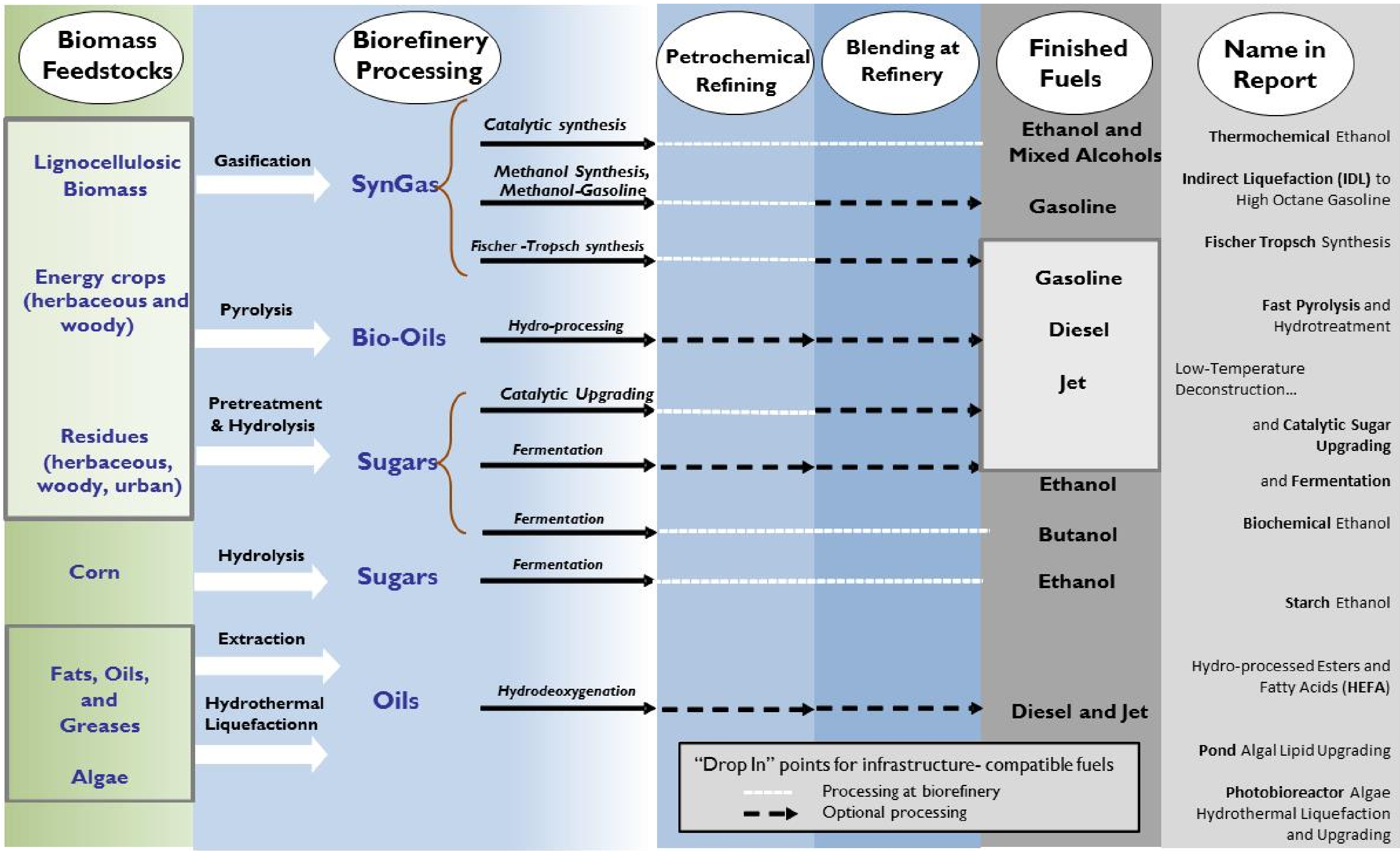

Figure 2. The BSM considers multiple conversion pathways

Note: Line formats show that there are multiple possibilities for integrating biomass-derived products.

Industrial learning (Junginger, Sark, and Faaij 2010) is central to the modeling of technology deployment. The BSM simulates the benefits of learning through experience (also called learning-by-doing or experiential learning)—separate from economies of scale (Vimmerstedt, Bush, and Peterson 2015). Learning through experience primarily addresses improvements to cost and performance metrics; while improvements in safety or environmental compliance may also occur through experience, adherence to safety and environmental standards is assumed at all scales, even in their immature states, because construction of biorefineries would rely on the established capability of the chemical industry to meet such standards. Learning through experience is also distinct from improvements that are made through research and development. In the BSM, research and development could improve expected performance of the mature commercial biorefinery and improve the initial state of a conversion technology pathway. A risk not explicit in the BSM is that commercial biorefineries might fail to perform at expected levels once fully mature.

Learning drives the major dynamic feature of the BSM conversion module through reinforcing feedback as shown in Figure 3. The model represents three scales of operation: integrated pilot, demonstration, and commercial (including pioneer, or first-of-a-kind, as well as full-scale commercial). Learning at all three scales impacts five performance metrics (yield of conversion process, input capacity for feedstocks, capital cost, risk premium that investors require to compensate for additional risk, and eligibility for debt financing) that are inputs to the model's estimated costs of construction of the next commercial biorefinery. In 2013, the BSM represented pioneer facilities separately from commercial facilities. In 2015, we eliminated the separate pioneer scale, but first-of-a-kind commercial facilities are assumed to have lower yield, less input capacity, higher capital cost, higher risk premium, and less eligibility for debt financing relative to those built later when a conversion pathway is more mature. These facility attributes continuously and endogenously improve with maturity.

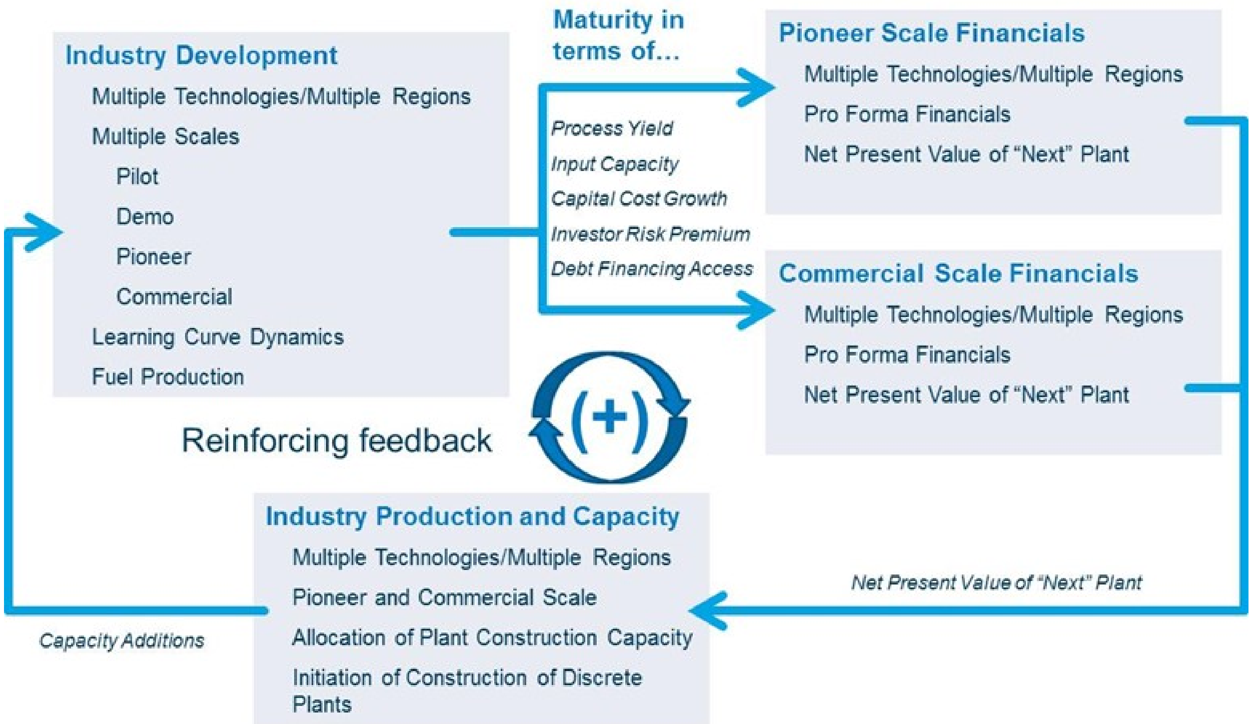

Figure 3. The BSM includes a reinforcing feedback around industrial development, financial performance, and industrial production and capacity (Vimmerstedt, Bush, and Peterson 2013)

In this study, assumptions about the rate of experiential learning impact results. The effectiveness of integrated pilot, demonstration, and commercial scale activities in advancing the maturity level of a pathway is an uncertain but highly influential assumption. This relationship determines the effect of deployment investment in the simulations, as described further below.

The attractiveness of an investment in a biorefinery is a key metric of the commercial maturity of a pathway and a critical driver of further deployment. The model approximates investors' considerations through calculation of the expected net present value of an investment in a new commercial biorefinery. A simplified schematic of these calculations is shown in Figure 4. As shown in Figure 3, the estimated net present value of a new biorefinery increases with industry maturity, improving the financial attractiveness of investing.

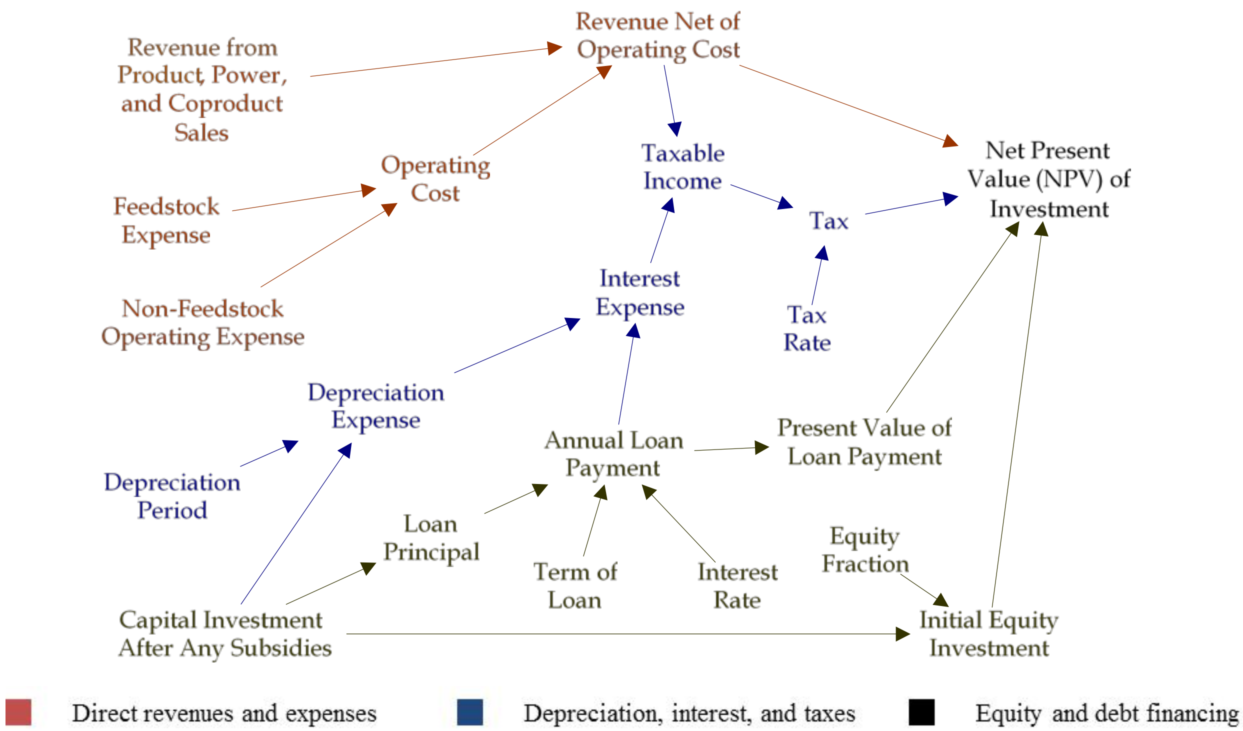

Figure 4. Computations of the financial characteristics of prospective new biorefineries in the BSM are used to estimate net present value; the figure above shows stages, types, and interrelationships among the financial computations (Newes, Inman, and Bush 2011)

Policy conditions can affect the attractiveness of investment, and incentive policies are important to biofuels industry development. The BSM can represent a wide variety of policies that provide incentives during conversion pathway start up or throughout its development, including point-of-production incentives; construction incentives (fixed capital investment, government loan guarantee); feedstock incentives; and downstream incentives (downstream point of use, distribution and storage, dispensing station fixed capital investment or capital expenditures for new equipment or repurposing, high-blend point of use). A library of incentive scenarios is available for BSM simulations, as described in Inman et al. (2014). For this study, we represented the status of policies as of 2015 with approximations of Renewable Identification Number (RIN) credit payments, tax credits, loan guarantees, and the Biomass Crop Assistance Program (BCAP).

The model represents biorefinery construction based on two different methods. First, biorefinery construction starts can be generated from within the model: if investment conditions are favorable and demand for biofuels is sufficient, the algorithm will initiate construction of a biorefinery. However, resources to build additional production capacity are constrained. The allocation choice distributes these resources among biorefinery construction projects by considering their characteristics—conversion pathway, technology maturity at commercial scale, and geographic region. Biorefineries also must compete for these construction resources with similar investments outside of the biofuels industry. Not all financially attractive biorefineries are assumed to be built because other investments might be more attractive (other biorefinery types or investments outside of biorefining) or there might not be available capacity for construction of large industrial facilities, such as design, materials, and skilled labor. These assumptions about competition for construction resources are critical, but challenging to substantiate, because they constrain the rate of growth once simulated biorefineries are estimated to be profitable.

Second, biorefinery starts can be scheduled: inputs to the model can specify the year, pathway, location, and size of new biorefineries. For this analysis, we specified two different schedules for planned biorefinery construction: one based on an assumed baseline industry and public deployment investment as of the end of 2015 and another based on an assumed additional public deployment investment after 2016. A comparison to the 2013 report shows how baseline investment has changed, and how these changes have been implemented in the model.

2.2 Study Design

We used BSM simulations to explore effects of a possible set of investments in advanced biorefineries, and to test these effects under a variety of conditions. The investments are scheduled operations of integrated pilot, demonstration, and commercial-scale biorefineries that represent possible effects of private and public investment. These scheduled biorefinery investments describe a subset of all possible investments and policies. Table 1 summarizes the scheduled biorefinery investments, incentive conditions, and background conditions that were varied in this 2016 report and in the 2013 report. The following subsections provide additional detail about these conditions that were varied in this study and conclude with an overview of differences in key inputs between this 2016 report and the 2013 report.

Table 1. Conditions Varied in the Studies

Category	2016 Study Conditions	2013 Study Conditions
Scheduled Biorefinery Investment	*Baseline (2016) (Appendix A) *Additional Deployment Investment (2016) (Appendix B)	Baseline (2013) Additional Deployment Investment (2013)
RIN Value	$0.00 RIN Value *$0.70 RIN Value $1.00 RIN Value	$0.00 RIN Value $0.45 RIN Value
Biofuels Tax Credit	With Biofuels Tax Credit	Without Biofuels Tax Credit
Loan Guarantee[†]	No Loan Guarantee *With Loan Guarantee of 65% With Loan Guarantee of 80%	No Loan Guarantee
Petroleum Price	*Reference Petroleum Price (AEO 2015)(U.S. Energy Information Administration 2015)* High Petroleum Price (AEO 2015)(U.S. Energy Information Administration 2015)	Reference Petroleum Price (AEO 2013)(U.S. Energy Information Administration 2013)

*Core cases in this study.

[†]A loan guarantee of either 65% or 80% is available for the initial 250 million gallons of cumulative production in each technology group.

Note: RIN = Renewable Identification Number; AEO = *Annual Energy Outlook*.

2.2.1 Scheduled Biorefinery Investment, Technology Maturity, and Industrial Learning

One possible strategy of deployment investment targets integrated pilot, demonstration, and commercial-scale activities sequentially so as to minimize capital at risk, such that later, larger investments do not proceed without prior success in smaller investments (Vimmerstedt, Bush, and Peterson 2013).

This study includes two different levels of advanced biorefinery deployment investment: (1) a baseline level of scheduled advanced biorefinery development based on the 2015 Integrated Biorefinery (IBR) survey (Schwab, Warner, and Lewis 2016) (see Appendix A) and (2) additional deployment investment beyond the baseline level for 2016. Table 2 summarizes the baseline and additional deployment investment scenarios for scheduled biorefineries. Appendix B includes additional details about the biomass to biofuels conversion pathways and timing of scheduled advanced biorefinery deployment investment. These baseline and additional deployment investment schedules are only two of many possible scenarios for planned construction and are used for analysis and discussion but are not forecasts. Future IBR surveys are planned, and these updates will provide further information on market developments.

The BSM also endogenously generates construction of commercial biorefineries (as described above) beyond those listed in Table 2, if and when conditions for industry growth are favorable.

In the 2013 report, the baseline level of scheduled advanced biorefinery development is based on professional judgment and informed by industry data (Biofuels Digest 2012; Bacovsky et al. 2013; Advanced Ethanol Council 2012). The 2013 baseline deployment scenario also includes scheduled advanced biorefineries that received public incentives from the U.S. Department of Energy.

Table 2. Scenarios for Scheduled Advanced Biorefinery Investment

	Baseline Investment Scenario	Additional Deployment Investment	Baseline Investment Scenario + Additional Deployment Investment
Integrated Pilot	2	9	11
Demonstration	1	6	7
Commercial [a]	7	3	10
Total Biorefineries	10	18	28

[a] Additional deployment investment is assumed to culminate in first-of-a-kind commercial biorefineries in each of three conversion pathways.

Note: See Appendix B for detailed scheduled biorefinery investment.

In addition to scheduled biorefinery investment, technology maturity and industrial learning are also critical determinants of BSM results. As described in Section 2.1, scheduled advanced biorefinery investment will contribute to industrial learning in the BSM. The BSM also assumes an initial 2015 maturity level for each technology at the integrated pilot, demonstration, and commercial scales. Both the initial maturity and the amount of deployment investment influence industrial learning and maturity in each modeled year over the course of a simulation.

The inputs used for baseline investment and initial maturity account for their combined effects differently than the 2013 report. Updated initial maturity accounts for many of the pre-commercial biorefineries that operated before 2015 and reflects newer expert assessment of the industry. For this 2016 report, the baseline investment scenario is based on the 2015 IBR survey (hereafter "2015 IBR survey") (Schwab, Warner, and Lewis 2016) (see Appendix A). Accounting for private sector investment at pre-commercial scales prior to 2015 within the initial technology maturities and not as scheduled biorefinery investments avoids double counting in the baseline investment scenario. In contrast, the 2013 report included these as scheduled biorefinery investments in its baseline.

Table 3 summarizes how the status of the 42 biorefineries included in the 2013 report changed in the 2015 IBR survey. In the former report, ten biorefineries were under construction and nine biorefineries were operating. In this 2016 report (based on status in 2015), of the 42 biorefineries, ten biorefineries are operating and four are under construction, and several others shifted to producing bioproducts. The 2015 IBR survey also documents 12 biorefineries that are operating or under construction and are either new or were not included in the 2013 report.

Table 3. Comparison of Advanced Biorefinery Status

Status in the 2015 Survey	Status in the 2013 Report			
	Planned	Under Construction	Operating	Idle
No change	5 (12%)	4 (9.5%)	5 (12%)	6 (14%)
Operating	1 (2.4%)	3 (7.1%)		1 (2.4%)
Idle	1 (2.4%)	3 (7.1%)	3 (7.1%)	
Cancelled	4 (9.5%)			
Now focused on other bioproducts	1 (2.4%)		1 (2.4%)	2 (4.8%)
Defunct*				2 (4.8%)
Total of 42 biorefineries from the 2013 report				

*Built, but subsequently dismantled.

Note: The table compares the status of advanced biorefineries in the 2015 IBR survey (Schwab, Warner, and Lewis 2016) with their status in the 2013 report.

Table 4 summarizes how the initial technology maturity assumptions changed between the 2013 report and this 2016 report in response to industry activity that has occurred since the 2013 report and based on more recent expert judgement. The table shows that the commercial maturity of the hydro-processed esters and fatty acids (HEFA) pathway has advanced since the 2013 report. Biomass to biofuels conversion technologies for cellulosic feedstocks to ethanol technologies and hydrocarbons from Fischer Tropsch synthesis are approaching full pre-commercial maturity with the first pioneer scale plants being built. Other cellulosic feedstocks to hydrocarbon technologies are near the beginning stages of integrated piloting. Algae technologies are mostly operating at the small pilot scale that is outside the scope of BSM.

Table 4. Changes in Technology Maturity Assumptions Since the 2013 Report

Feedstock/Fuel	Technology Group	Industry Maturity in this 2016 Report Relative to the 2013 Report
Fats, Oils, and Greases to Hydrocarbons	HEFA	Improvements in commercial maturity. Commercial plants (TRL 9-10) are being built and operated globally. HEFA is approaching full commercial maturity similar to starch ethanol and biodiesel.
Cellulosic Feedstocks to Ethanol	Biochemical	Pre-commercial maturity has increased. Integrated piloting (TRL 7) is mostly completed. Demonstration-scale (TRL 8) is nearing completion. First pioneer scale commercial plant (TRL 9) is being built and operated.
	Thermochemical	
Cellulosic Feedstocks to Hydrocarbons	Fischer Tropsch	
	Indirect Liquefaction	Little change since the 2013 report. Maturity at all scales remains low. Integrated pilots (TRL 7) using cellulosic feedstocks are beginning to be built and operated
	Fast Pyrolysis	
	Fermentation	
	Catalytic Sugar Upgrading	
Algae to Hydrocarbons	Pond	No change: Low industry maturity at the pre-commercial-scale. Currently, the industry is beginning small non-integrated pilots (TRL level 6) that are not applicable to BSM.
	Photobioreactor	

Note: HEFA = hydro-processed esters and fatty acids; TRL = Technology Readiness Level

Along with scheduled investment and initial technology maturity assumptions, learning rate is an assumption that contributes to determining how rapidly the performance of a technology improves. The 2013 report explored learning rates of 35%, 25%, and 15% (corresponding to progress ratios of 65%, 75%, and 85%). The core cases for this study use a learning rate of 25% (or progress ratio of 75%), which we considered most representative of historical performance of related industries. As shown in the 2013 report, a given amount of experience advances technological maturity more with a higher learning rate than with a lower one.

2.2.2 Incentives

Table 5 summarizes the incentives that were applied in the simulations and describes their rationale.

Table 5. Incentive Conditions in Simulations

Scenario Name	Incentives	Rationale
RIN **$0.00** ***$0.70** **$1.00**	RIN value ($/gal)	$0.00 RIN: a lower bound $0.70 RIN: published projection (Foody 2015) $1.00 RIN: in market range (OPIS 2016)
***With Biofuels Tax Credit**	For first 1 billion gallons produced: • $0.46/gal for cellulosic feedstocks to ethanol • $1.01/gal for cellulosic feedstocks to hydrocarbons • $1.00/gal for oil crops to hydrocarbons • $1.00/gal for algae to hydrocarbons	Reauthorized (Public Law 114-113 (Dent 2015) 26 U.S. Code 40 ("26 U.S.C. § 40" 2016)
No Loan Guarantee ***With Loan Guarantee of 65%** **With Loan Guarantee of 80%**	For first 250 million cumulative gallons for cellulosic feedstocks to ethanol, cellulosic feedstocks to hydrocarbons, oil crops to hydrocarbons, and algae to hydrocarbons	Loan guarantees may be awarded for up to 90% of the principal and interest under 7 U.S. Code 8103(d)(2)(B)(iii)("7 U.S.C. § 8103" 2016)
***With BCAP until 2016**	Incentives to growers for feedstock establishment, annual payments, and collection, harvesting, storage, and transport [7 U.S. Code 8111]	Reauthorized (Public Law 113-79 ("Agricultural Act of 2014" 2014); 7 U.S. Code 8111 ("7 U.S.C. § 8111" 2016))

Note: RIN = Renewable Identification Number; BCAP = Biomass Crop Assistance Program

2.2.2.1 Renewable Identification Numbers

The study examines the effects of a RIN incentive value, but does not model the RIN market. The model approximates the effective value of a RIN for the fuel producer. This value is automatically distributed among various parties over the course of a simulation. The RIN value is modeled as a point-of-production payment per gallon of fuel produced. The value applies to fuels on an energy-content basis; one RIN is the energy equivalent of one gallon of ethanol. Core cases have a RIN value of $0.70, based on an industry projection (Foody 2015), and variations in this value include $0—a lower bound on potential changes in RIN markets—and $1.00—a higher value within the range of cellulosic RIN market values in 2015–2016 (OPIS 2016).

2.2.2.2 Biofuels Tax Credit

This study shows results with a biofuels tax credit. A biofuels tax credit for producers has been available under 26 USC 40 ("26 U.S.C. § 40" 2016) since 2008 in the amount of $1.01/gallon for non-alcohol-based cellulosic biofuels and $0.46/gallon for alcohol-based cellulosic biofuels. Since 2005, HEFA has been eligible for $1.00/gallon from either the Biodiesel Income Tax Credit or Biodiesel Mixture Excise Tax Credit, depending on how the fuel is sold, under 26 USC 6426 (Alternative Fuels Data Center 2014; "Biodiesel Mixture Excise Tax Credit" 2014). Biofuel tax credits were extended until January 1, 2017 in Public Law 114-113 (Dent 2015). This study assumes that tax credits of these amounts will be available for the first one billion gallons of cumulative production within each technology group (cellulosic feedstocks to ethanol, cellulosic feedstocks to hydrocarbons, oil crops to hydrocarbons, algae to hydrocarbons).

2.2.2.3 Loan Guarantee

The study shows results without a loan guarantee and with loan guarantees of 65% and 80% of the fixed capital investment cost. Loan guarantees up to 90% are allowed under 7 USC 8103(d)(2)(B)(iii) ("7 U.S.C. § 8103" 2016), but the "no loan guarantee" and "65% loan guarantee" cases are typical of recent historical conditions. The study included a loan guarantee of 80% because that level has been found in simulations to prompt industry growth under a wide variety of simulated conditions. We assume the loan guarantees are offered for biorefineries in each technology group until the associated cumulative production reaches 250 million gallons (for cellulosic feedstocks to ethanol, cellulosic feedstocks to hydrocarbons, oil crops to hydrocarbons, and algae to hydrocarbons). A loan guarantee of 65% was used in the core cases.

2.2.2.4 BCAP

We present results with BCAP through 2016. BCAP provides incentives to growers for feedstock establishment, annual payments, and collection, harvesting, storage, and transport. First established in 2008, BCAP was reauthorized in 2014 through fiscal year 2018 ("Agricultural Act of 2014" 2014; Dent 2015; "7 U.S.C. § 8111" 2016). The core case, BCAP through 2016, reflects appropriations to date, not the extension through 2018.

2.2.3 Petroleum Prices

Two projections of petroleum prices were used in the simulations: the AEO 2015 Reference Case and the AEO 2015 High Oil Price Case (U.S. Energy Information Administration 2015). The core cases include both of these, shown in Figure 5. Figure 5 also shows petroleum prices from the AEO 2013 Reference Case that was used in the 2013 report (U.S. Energy Information Administration 2013), which has higher prices than the AEO 2015 Reference Case.

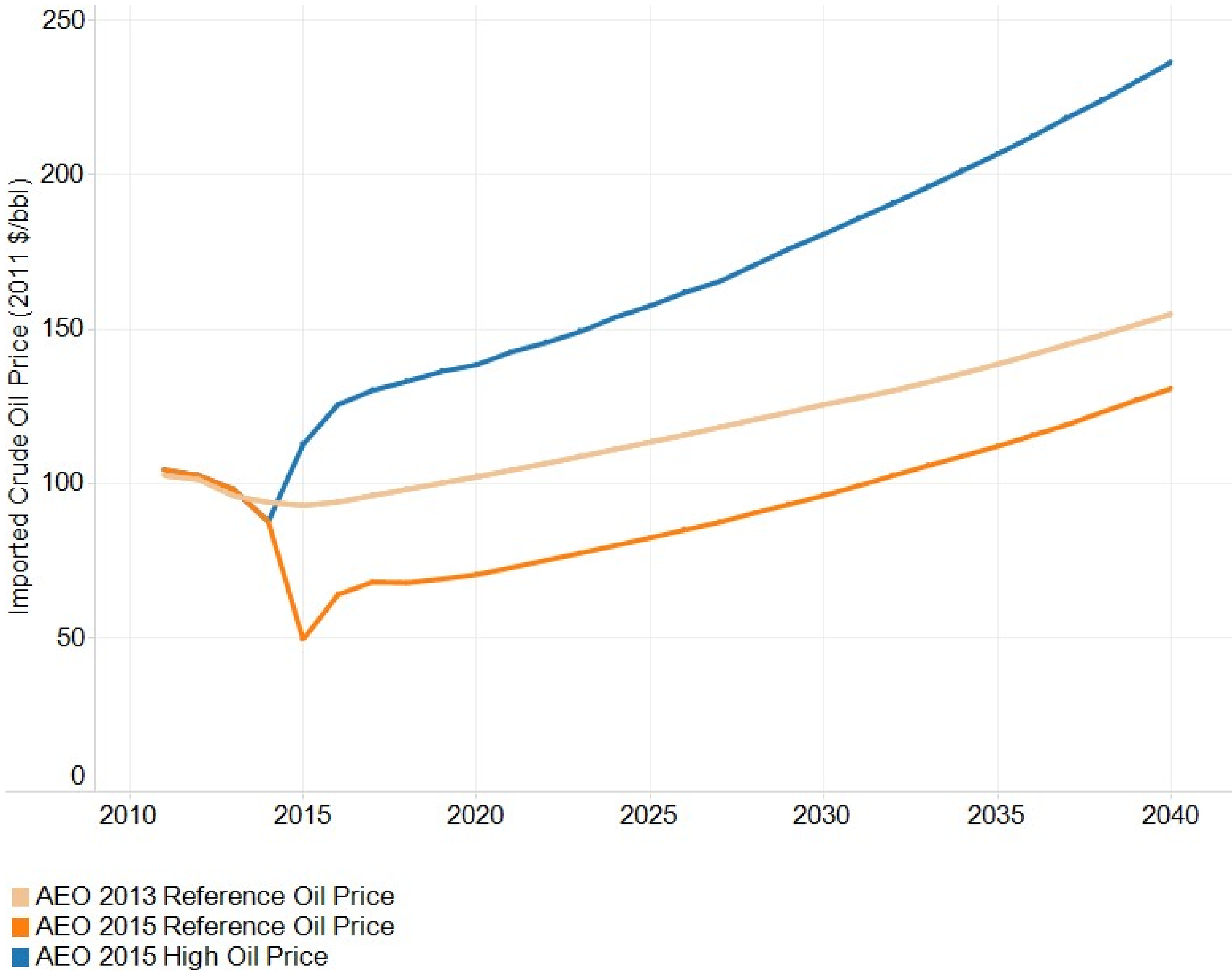

Figure 5. AEO oil price scenarios (U.S. Energy Information Administration 2015; U.S. Energy Information Administration 2013)

2.2.4 Other Key Assumptions: 2016 vs. 2013 Comparison

Beyond the conditions that were varied within this 2016 report—scheduled biorefinery investment, incentive, and background petroleum price assumptions—two categories of important assumptions were not varied within this 2016 report but differed between 2013 and 2016: biorefinery techno-economics and feedstock availability.

2.2.4.1 Biorefinery Techno-economics

Techno-economic assumptions about biorefinery cost and performance are key inputs to the BSM. These inputs include both mature techno-economic performance assumptions and current performance assumptions. Based mostly on published design reports, the mature technology assumptions for 2016 are shown in Table 6. The assumptions about current techno-economics are based on the mature technology assumptions and expert assessment of the status of industry maturity for each technology group.

In general, mature techno-economics changed significantly for all technologies between the 2013 report to the 2016 report, as shown in Table 6. Increases in design case estimated costs, as well as some improvements in estimated yields, influenced BSM results. Some changes include:

1. A decrease in HEFA's estimated throughput capacity and an increase in its biofuel production yields
2. Updates to assumptions for the cellulosic feedstocks to ethanol technology group
3. Increases in fixed capital investment assumptions (the largest were for indirect liquefaction and fast pyrolysis technology groups)
4. Algae technologies now include feedstock costs in their operating costs.

Table 6. Comparison of Techno-economic Assumptions, 2013 vs. 2016

Feedstock/Fuel	Technology Pathway	Biofuel Yield		Max Throughput Capacity		Fixed Capital Costs (mil 2011$)		Operating Costs (mil 2011$)		Co-Product Revenue (mil 2011$)		Data Source	
		2013	2016	2013	2016	2013	2016	2013	2016	2013	2016	2013	2016
Fats, Oils, and Greases to Hydrocarbons	HEFA	43	245	2,200	840	39	71	15	16	7.9	7.9	a	a
Cellulosic Ethanol	Biochemical	79	79	2,200	2,200	400	450	37	43	6.6	6.2	(Humbird et al. 2011)	(Humbird et al. 2011)*
	Thermochemical	84	84	2,200	2,200	490	550	30	35	15	14	(Dutta et al. 2011)	(Dutta et al. 2011)*
Cellulosic Hydrocarbons	Fischer Tropsch	62	69	2,200	2,200	350	580	20	32	0	4.5	b	(Zhang et al., n.d.)
	Indirect Liquefaction	51	65	2,200	2,200	190	420	29	34	21	0	(Phillips et al. 2011)(Jones and Zhu 2009)	(Tan et al. 2015)
	Fast Pyrolysis	100	84	2,200	2,200	300	670	66	66	0	0	(Jones et al. 2009)	(Jones et al. 2013)
	Fermentation	42	43	2,200	2,200	400	550	20	36	0	5.1	(Rude and Schirmer 2009)	(Davis et al. 2013)
	Catalytic Sugar Upgrading	50	78	2,200	2,200	490	630	31	86	0	5.4	(Huber 2005)	(Davis et al. 2015)
Algae to Hydrocarbons	Pond	95	140	1,300	1,300	150	440	8.7	230	1.7	22	(Davis et al. 2012)	(Davis et al. 2014)
	Photobioreactor	95	150	1,300	1,300	320	450	15	230	2.2	36	(Davis et al. 2012)	(Jones et al. 2014)

[a] Unpublished NREL modeling based (M. N. Pearlson 2011; M. Pearlson, Wollersheim, and Hileman 2013).

[b] Unpublished NREL data.

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

Note: HEFA = hydro-processed esters and fatty acids.

2.2.4.2 Feedstock Availability

The 2013 BSM analysis assumed that all feedstock types are equally available to all pathway types, without cost penalty. However, we revised this assumption because of the growing consensus that specific biomass to biofuel conversion technology pathways require distinct feedstock specifications to avoid excess costs. For example, thermochemical processes generally have higher performance and lower costs when using woody feedstocks (Humbird et al. 2011; Rude and Schirmer 2009; Davis et al. 2013; Huber 2005; Davis et al. 2015; Staples et al. 2014), and biochemical processes generally have higher performance and lower costs when using herbaceous feedstocks (Dutta et al. 2011; Zhang et al., n.d.; Phillips et al. 2011; Jones and Zhu 2009; Tan et al. 2015; Jones et al. 2009; Jones et al. 2013). The changes in the model allow it to represent a variety of assumptions about flexibility or targeting of feedstock by pathway. In the 2016 report, targeted feedstock is the core assumption: woody feedstocks are used in thermochemical processes, and herbaceous feedstocks are used in biochemical processes.

2.3 Estimating Potential Life Cycle Greenhouse Gas Emissions of Study Results

Reducing greenhouse gas (GHG) emissions is one of the objectives of public investment in research, development, demonstration, and deployment of advanced biofuels technologies. Accordingly, we estimated life cycle GHG emissions reductions. The potential reduction in life cycle GHG emissions of cellulosic feedstocks to ethanol and hydrocarbon fuels are estimated in this study using BSM results for fuel output and GREET life cycle emission factors (EFs), shown in Table 7. Sources of GHG emissions include feedstock cultivation, harvest, collection, transportation, conversion, fuel distribution, and fuel use. GHG EFs include carbon dioxide, methane, and nitrous oxide. GHG EFs do not change over time to reflect technology improvements such as in energy efficiency and yields typically seen in a maturing industry.

In the BSM, the mix of feedstocks used to produce fuel in a given year is dynamically changing over time. For simplicity, the feedstocks assumed for the generation of EFs are static. EFs for varying cellulosic feedstocks only differ around ±10-20%, so change in life cycle GHG emissions estimates would be small.

Life cycle GHG emissions presented in this report are from a simplified analysis of potential GHG emission reductions that could be achieved in each scenario. The GHG emission analysis only compares GHG emissions from the production and use of biofuels with GHG emissions from an energy-equivalent volume of petroleum fuel, even though there is also displacement of one biofuel by another in the results. The GHG emissions analysis does not estimate the direct market displacement effects of biofuel. We established this scope due to time constraints and the constraints of the BSM, such as limited modeling of international trade in biofuels, which would improve the realism of a market displacement assessment.

Table 7. Life Cycle GHG Emission Factors

Fuel	Feedstock	Life Cycle EF ($g\ CO_2e\ MJ^{-1}$)
Gasoline	Crude Oil	94
Diesel Fuel	Crude Oil	93
Fischer-Tropsch	Corn Stover	14
Fast Pyrolysis	Corn Stover	15
Biochemical Ethanol	Corn Stover	14
Thermochemical Ethanol	Corn Stover	16
Advanced Fermentation	Switchgrass	37 (Staples et al. 2014)

Source: "Energy Systems: GREET Model" 2016 except as noted.

3 Results and Discussion

In BSM simulations, additional deployment investment results in increased growth of advanced biofuel production. The magnitude of this result is highly dependent on petroleum price, as shown in the core cases, and also on RIN value and loan guarantee, as shown in the additional cases.

3.1 Baseline and Additional Deployment Investment

The BSM was used to perform simulations to explore the effects of demonstration and deployment investment under different incentive and investment scenarios. Results for the core cases are shown in Figure 6. As described, the assumptions made in these simulations include updated techno-economics, targeted feedstock use, medium learning rate, updated initial maturity levels, and incentives that included \$0.70 RIN value, \$1.01/gal biofuel tax credit, 65% loan guarantee, and BCAP through 2016. Both Reference and High Oil Price Cases from AEO 2015 are shown in the core cases. Rapid growth of cellulosic feedstocks to hydrocarbons production occurs when the model estimates competitive return on investment for that technology.

Additional results from cases with \$0 and \$1 RIN values are shown in Figure 7. With additional deployment investment, the higher RIN value makes a greater difference in cellulosic feedstocks to hydrocarbons production in the scenario with AEO Reference Case oil prices than it does in the High Oil Price Case; without deployment investment, the opposite relationship occurs. This is an example of the inter-relatedness of different inputs within the model.

Figure 8 shows additional results without loan guarantees and with an 80% loan guarantee. As with RIN value, the effect of a change in the loan guarantee differs with differing conditions of other inputs. Its effect is greatest when other conditions provide a moderately but not overwhelmingly favorable environment for biofuels investment, as in the High Oil Price Case without additional deployment investment or with the oil prices from the Reference Case with additional deployment investment.

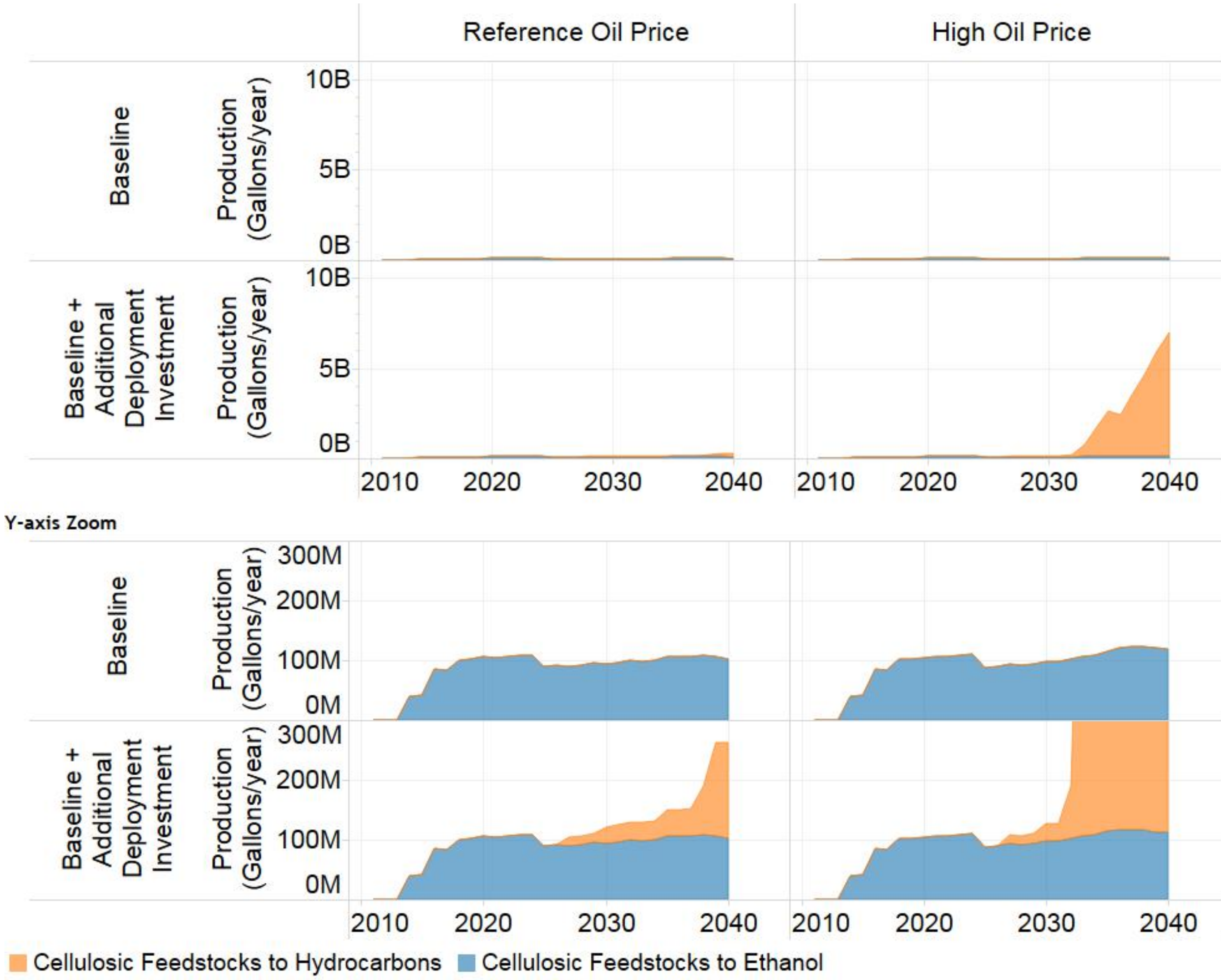

Figure 6. Annual biofuel production in core cases: with and without additional deployment investment (rows); reference and high oil prices (columns)

Note: RIN Value = $0.70 and Loan Guarantee = 65%.

Source: "Core Cases in Biomass Scenario Model, Revision 6018, 178981, 178984,178987, 178990" 2016

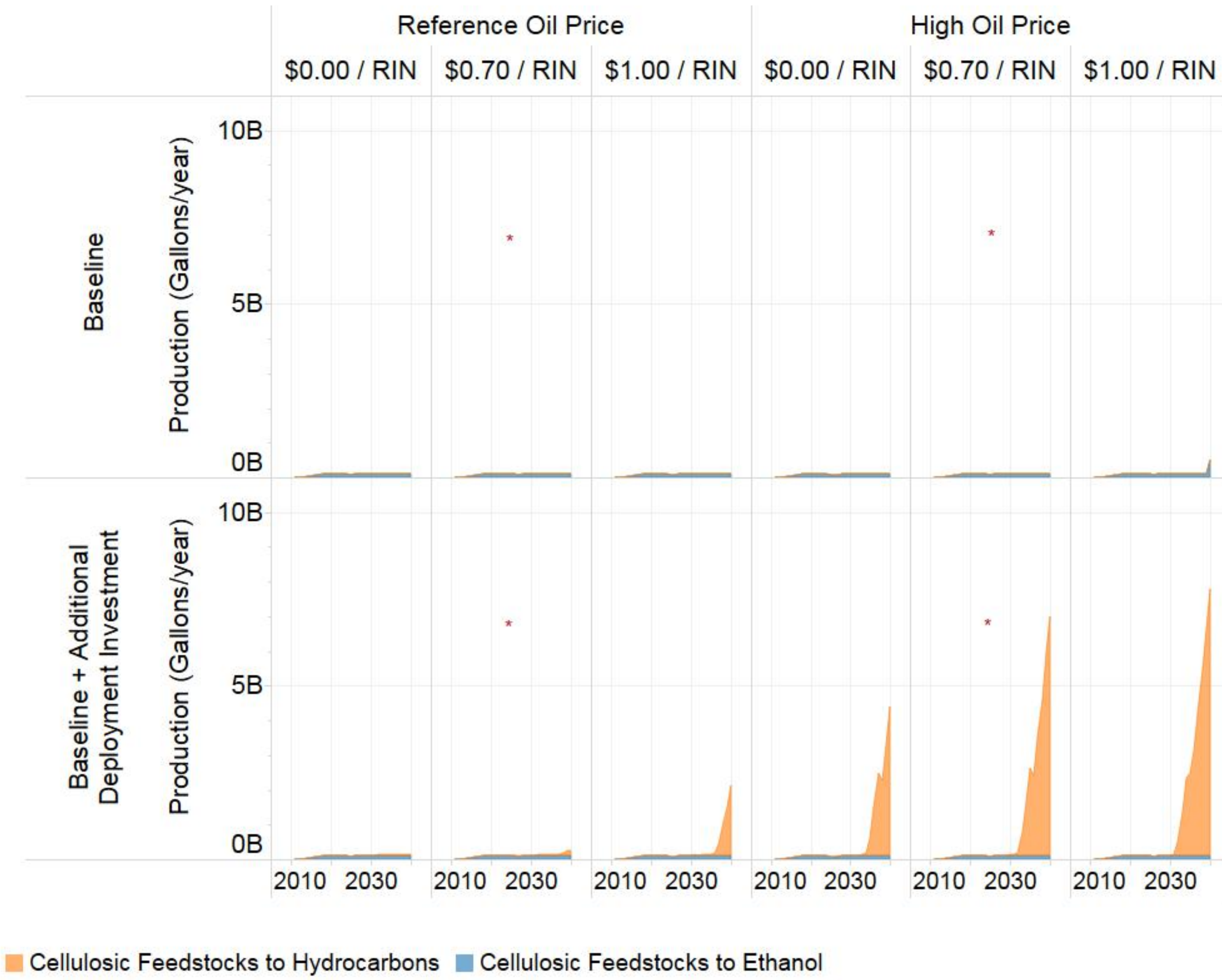

Figure 7. Annual biofuel production showing effect of RIN value

Note: * indicates core cases.
Source: “RIN Variations in Biomass Scenario Model, Revision 6018, Runs 178957, 178981, 178969, 178960, 178984, 178972, 178963,178987, 178975,178966, 178990, 178978” 2016

Figure 8. Annual biofuel production showing effect of loan guarantee

Note: * indicates core cases.
Source: "Loan Guarantee Variations in Biomass Scenario Model, Revision 6018, Runs 178980-178982, 178983-178985,178986-178988, 178989-178991" 2016

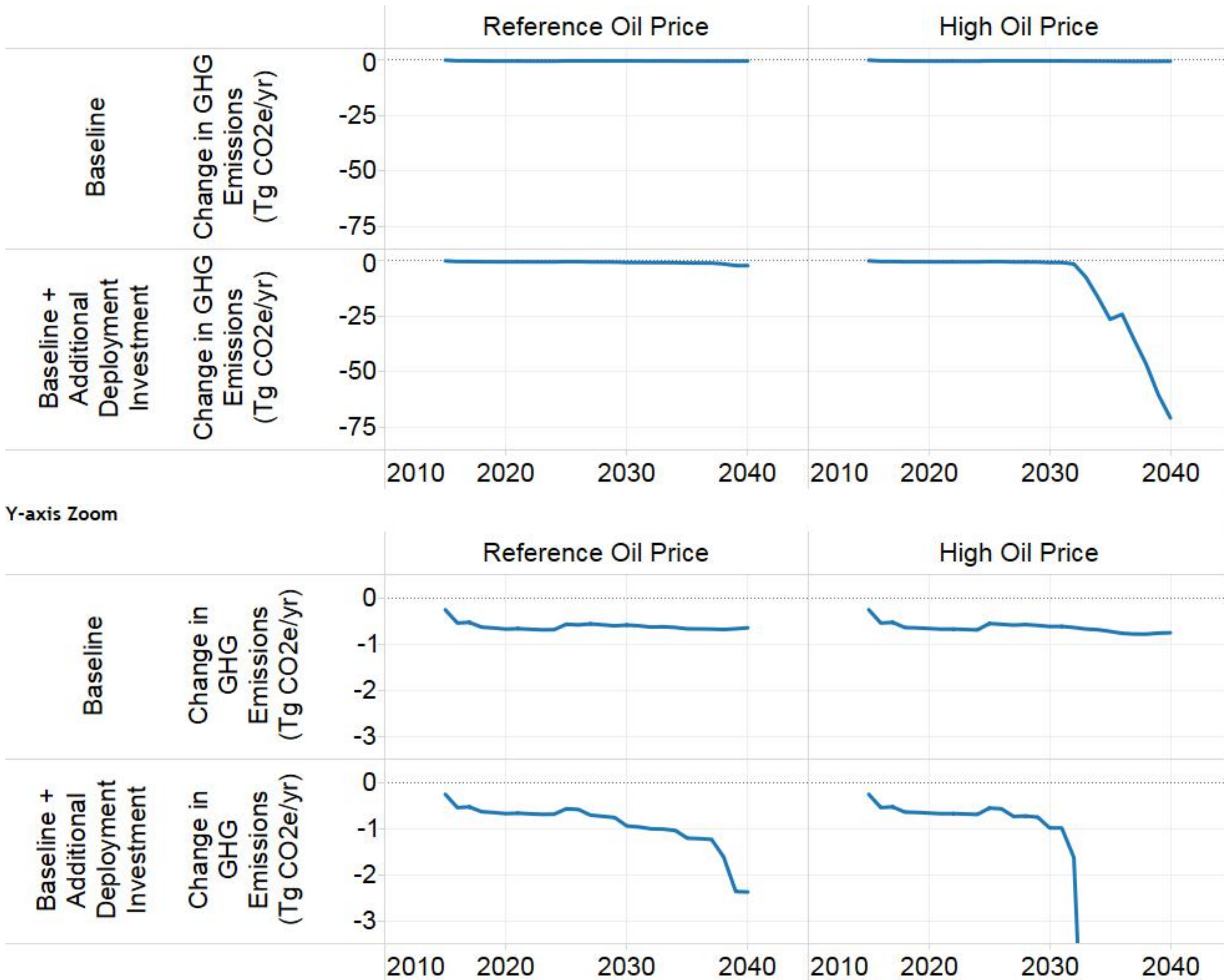

Figure 9. Greenhouse gas emissions reductions results

Note: Reductions are the difference in emissions associated with replacing an energy equivalent volume of petroleum fuels with the simulated biofuels production from cellulosic feedstocks.

Figure 9 shows the associated potential life cycle GHG emissions reductions from ethanol and hydrocarbons from cellulosic feedstocks in the core cases. Emission reductions in each core case represent the difference between emissions from the biofuel produced and the emissions if the biofuel were replaced with an energy equivalent volume of fossil fuel. If the biofuel were displacing another biofuel, such as cellulosic feedstocks to ethanol replacing starch to ethanol, the results would be lower than these estimates.

In the reference and high oil price cases with baseline investment, life cycle GHG emission reductions are around 0.5 terragrams (Tg) CO_2e per year by 2040. In the reference oil price case with additional deployment investment, GHG emission reductions increase to over 2 Tg CO_2e per year by 2040. In the high oil price case with additional deployment investment, GHG emissions are around 70 Tg CO_2e per year. When comparing the baseline investment cases to the additional deployment investment cases, the cumulative changes in GHG emissions by 2040 are about 8.3 Tg CO_2e under reference oil prices and about 280Tg CO_2e under high oil prices.

3.2 Comparison with 2013 Results

Previous results found earlier growth of production from cellulosic feedstocks-to-hydrocarbon pathways, which may be attributed to:

1. More favorable techno-economic and industrial learning assumptions.
2. Higher projected oil prices.
3. More favorable deployment assumptions.
4. Assumed availability of all feedstocks to all conversion pathways without penalty; current results target feedstocks by pathway.

These modified assumptions change the timing of production growth, affirming the previous finding that the effect of deployment investment depends heavily on other conditions.

The changes in production from cellulosic feedstocks to hydrocarbon pathways do not change the conclusions of the 2013 report. Consistent with previous findings, these results show that the modeled deployment investment accelerates modeled cellulosic feedstocks to biofuels production. The precise quantity and timing of production is sensitive to a variety of assumptions, including those that varied between 2013 and 2016, as well as many others.

4 Conclusions and Possible Next Steps

Deployment investments substantially accelerate industrial development under certain conditions, as modeled in the BSM. The model can detect effects of different amounts of investment in integrated pilot, demonstration, and commercial-scale biorefineries. Results show that the impact of deployment investment depends heavily on other conditions, such as baseline scheduled biorefinery investments, techno-economics, industrial learning assumptions, and incentives. Results also show deployment investment effects that include accelerated industrial learning, biorefinery construction, biofuel production, and associated reductions in GHG emissions. The results of this study showed sharply increasing biorefinery construction and biofuels production when additional deployment investment was combined with favorable conditions, either from incentives, petroleum prices, industrial learning, or their combinations. While simulation results cannot precisely predict real-world events, these results suggest that deployment investments can accelerate industrial development if conditions are sufficiently favorable.

Future analyses of deployment investment can take advantage of any further updates of market analyses and techno-economic estimates. Future analysis can also assess how deployment investment interacts with other conditions that affect the growth of the biofuels industry, similar to the explorations of oil price and incentive effects in this study. These other conditions may include overall economic growth, growth of transportation fuels other than petroleum, labor and materials capacity for construction of biorefineries and other chemical industry facilities, industrial learning rates within and among biomass to biofuels conversion technology pathways, ethanol blending policy, and other incentive assumptions. Exploration of how these many other conditions interact with various types of deployment investment could reveal bottlenecks and synergies that could help target incremental investment where it is most effective. A key next step within this exploration would be to understand in greater detail the synergies between production incentives and deployment investment in biorefineries and to evaluate the impact of investment levels in each category.

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Appendix A. Constructing the Baseline Advanced Biorefinery Investment Scenario

This appendix documents how the baseline advanced biorefinery investment scenario was constructed.

The BSM simulations in this study use a subset of the biorefineries from the 2015 IBR survey for the baseline investment scenario. The IBR survey covered non-starch ethanol or renewable hydrocarbon biofuels producers with commercial intentions in the United States. The baseline investment scenario excludes the biorefineries from the survey that used a feedstock (e.g., corn kernel cellulose) or technology not in the BSM. Also excluded were biorefineries in the planning stages rather than operating or under construction.

This study used a set of technological maturity assumptions at each scale (i.e., integrated pilot, demonstration, and commercial) as of 2015 to indicate the level of industrial learning that has been completed. To avoid double counting the biorefineries that were already considered in the development of the technological maturity assumptions, the biorefineries from the 2015 IBR survey were screened for those whose effects on technology maturity were not included—those relevant in the timeframe of 2015 or later.

Biorefineries at the pre-commercial scale were included in the baseline investment scenario if they were operating or under construction at the beginning of 2015. Pilot and demonstration-scale biorefineries that began operating before 2015 were included in the technology maturity assumptions and not directly used in the baseline scenario.

Biorefineries at the commercial scale were included in the baseline investment scenario if they were operating or under construction at the end of 2015. Commercial-scale biorefineries that were idle before 2015 and are not expected to resume operations after 2015 were included in the technology maturity assumptions and not directly used in the baseline investment scenario.

Three pre-commercial and seven commercial-scale biorefineries met the criteria for inclusion in the scenario. Appendix B summarizes how these 10 biorefineries were implemented in scheduled advanced biorefinery scenarios.

Appendix B. Scheduled Advanced Biorefinery Scenarios

This appendix documents the pathways, scale, and timing of facilities that comprise the deployment investment scenarios. This report uses two scenarios for scheduled biorefinery construction: a baseline investment scenario based on the 2015 IBR survey and a scenario that also includes additional deployment investment. Scenarios are shown in two formats: Table B-1 and Figure B-1. This is not a forecast.

Table B-1. Scheduled Advanced Biorefineries, by Pathway, Year Operations Begin, and Scale

Technology Group	Scale	Technology Pathway	Region in BSM	Year Operations Start	Baseline Investment Scenario	Baseline Investment + Additional Deployment Investment Scenario
Fats, Oils, and Greases to Hydrocarbons	Commercial	HEFA	N/A	2014	1	1
			N/A	2015	1	1
			N/A	2016	1	1
Cellulosic Feedstocks to Ethanol	Integrated Pilot	Thermochemical	N/A	2015	1	1
	Demonstration	Biochemical	N/A	2015	1	1
	Commercial	Biochemical	Corn Belt	2015	2	2
			Appalachia	2017	1	1
		Thermochemical	Southeast	2016	1	1
Cellulosic Feedstocks to Hydrocarbons	Integrated Pilot	Indirect Liquefaction	N/A	2021	0	2
		Fast Pyrolysis	N/A	2021	0	2
			N/A	2024	0	1
		Fermentation	N/A	2021	0	1
			N/A	2024	0	1
		Sugar Catalytic Upgrading	N/A	2024	0	1
	Demonstration	Fischer Tropsch	N/A	2021	0	1
		Indirect Liquefaction Gasoline	N/A	2021	0	1
			N/A	2024	0	1
		Fast Pyrolysis	N/A	2024	0	1
			N/A	2029	0	1
		Fermentation	N/A	2029	0	1
	Commercial	Fischer Tropsch	Northeast	2026	0	1
		Indirect Liquefaction	Delta States	2029	0	1
		Fast Pyrolysis	Delta States	2034	0	1
Algae to Hydrocarbons	Integrated Pilot	Pond	N/A	2029	0	1
		Photobioreactor	N/A	2015	1	1

Note: HEFA = hydro-processed esters and fatty acids.

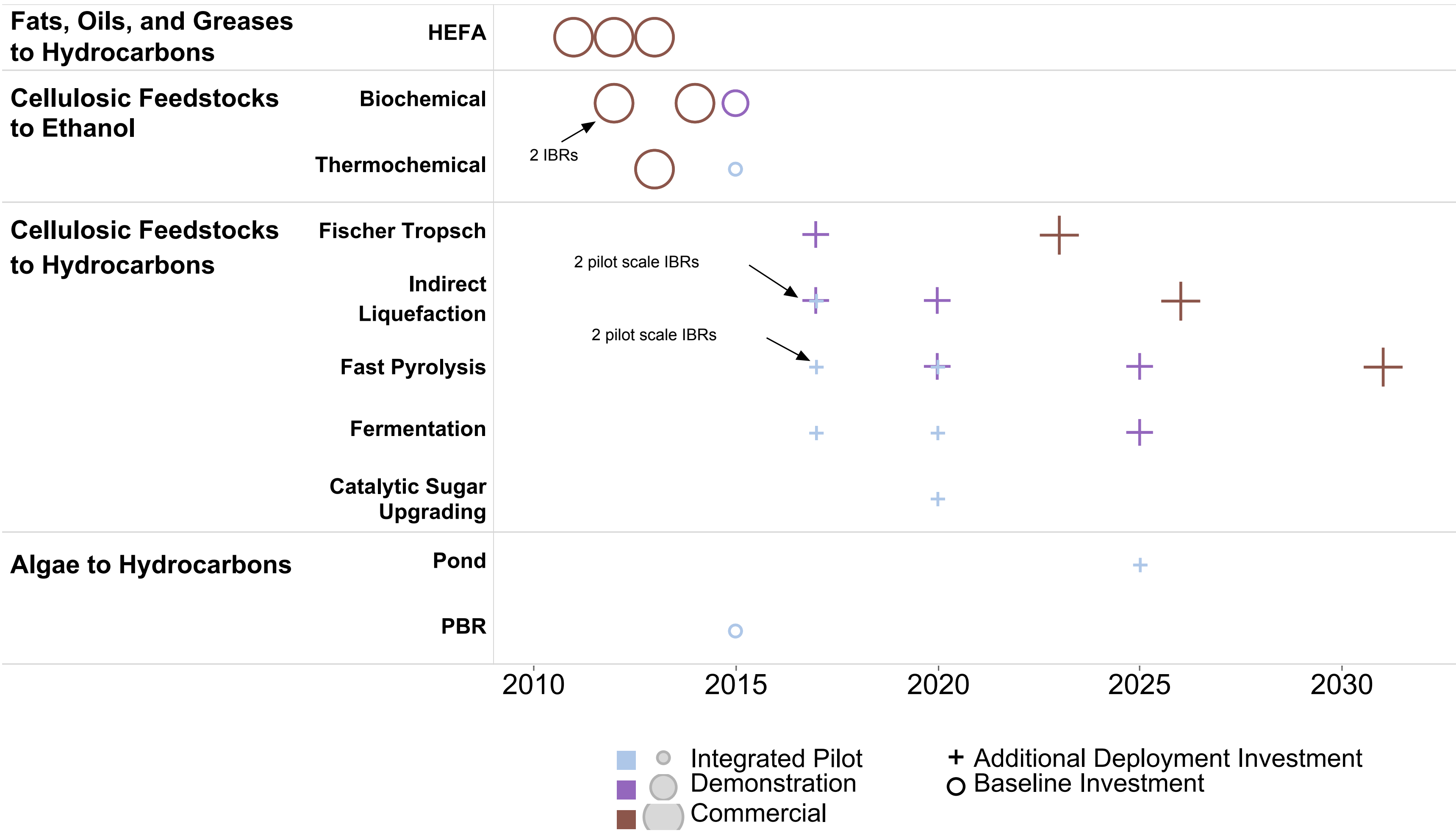

Figure B-1. Scheduled advanced biorefinery baseline and additional deployment investment, by pathway, operating year, and scale

Note: HEFA = hydro-processed esters and fatty acids; PBR = Photobioreactor.