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# Maturation of biomass-to-biofuels conversion technology pathways for rapid expansion of biofuels production: a system dynamics perspective

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Abstract: The Biomass Scenario Model (BSM) is a system-dynamics simulation model intended to explore the potential for rapid expansion of the biofuels industry. The model is not predictive — it uses scenario assumptions based on various types of data to simulate industry development, emphasizing how incentives and technological learning-by-doing might accelerate industry growth. The BSM simulates major sectors of the biofuels industry, including feedstock production and logistics, conversion, distribution, and end uses, as well as interactions among sectors. The model represents conversion of biomass to biofuels as a set of technology pathways, each of which has allowable feedstocks, capital and operating costs, allowable products, and other defined characteristics. This study and the BSM address bioenergy modeling analytic needs that were identified in recent literature reviews. Simulations indicate that investments are most effective at expanding biofuels production through learning-by-doing when they are coordinated with respect to timing, pathway, and target sector within the biofuels industry. Effectiveness metrics include timing and magnitude of increased production, incentive cost and cost effectiveness, and avoidance of windfall profits. Investment costs and optimal investment targets have inherent risks and uncertainties, such as the relative value of investment in more-mature versus less mature pathways. These can be explored through scenarios, but cannot be precisely predicted. Dynamic competition, including competition for cellulosic feedstocks and ethanol market shares, intensifies during times of rapid growth. Ethanol production increases rapidly, even up to Renewable Fuel Standards-targeted volumes of biofuel, in simulations that allow higher blending proportions of ethanol in gasoline-fueled vehicles. Published 2014. This article is a U.S. Government work and is in the public domain in the USA. Biofuels, Bioproducts and Biorefining published by John Wiley & Sons, Ltd on behalf of Society of Chemical Industry.

Keywords: biomass; biofuel; renewable fuels standard; system dynamics; learning; policy

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## Introduction

US public policy promotes biofuels to reduce dependence on imported energy and to decrease greenhouse gas (GHG) emissions.[1] The Energy Independence and Security Act of 2007 targets 36 billion gallons/year (136 billion liters/year) of renewable liquid transportation fuel in the United States by 2022.[2] This act established a Renewable Fuel Standard (RFS) with tradable credits (Renewable Identification Numbers, or RINs) for four categories of fuel, as shown in Table 1.

Commercially available fuels – biodiesel, imported cane-based ethanol, and corn-starch-based ethanol – are used to meet some of the RFS targets, and the corresponding RINs are actively traded. To reach the cellulosic biofuel target, new pathways for converting cellulosic feedstocks to biofuels are being developed and commercialized. Before 2014, market trading of associated cellulosic biofuel RINs had been limited to compliance RINs that the US Environmental Protection Agency (EPA) makes available at a fixed price; although private trades are anticipated as commercial sales of cellulosic fuels begin.

This study examines modeled scenarios about the rapid expansion of biofuels production, and addresses the following themes and associated questions:

1. Effective investment: How can investments in improving biomass-to-biofuels conversion technology pathways contribute to biofuels industry growth?
2. Risk and uncertainty: How do risks and uncertainties shape optimization of the magnitude and targeting of public and private investment?
3. Dynamics of rapid growth: If the biofuels industry grows rapidly, what barriers and system behaviors might emerge?

Improved answers to these questions could support faster growth in the biofuels industry and increase the effectiveness of the federal government's investment in policies to promote renewable fuels. This study uses the Biomass Scenario Model (BSM) to explore these questions and identify key incentives, bottlenecks, and points of leverage that may, given particular scenarios, facilitate industry development.

Recent literature reviews of bioenergy modeling identified numerous analytic needs, some of which the BSM addresses. Four of these are summarized here.

1. Some reviews[6,7] noted a need to address bioenergy risks and challenges – such as variability in policies, feedstock supply, and demand or competition for land – in a way that accounts for the multiple complex interactions between bioenergy and other sectors. They suggest that this need can be met by using *holistic models*, including system dynamics models, that provide an overall framework for simulating bioenergy supply chain development over time. These include bioenergy end use, distribution, biomass-to-bioenergy conversion, and resource production and transportation, as well as clear and consistent accounting for linkages with other sectors. Sharma[7] recommended greater use of simulation optimization modeling as a way to address uncertainty through exploration of large numbers of scenarios. Some surveys of the scope of model-based analyses[8,9]

**Table 1. Categories, volumes, RINs, and production of renewable fuels in the United States show implementation of the RFS.**

| | D3. Cellulosic Biofuel | D4. Biomass-based Diesel | D5. Advanced Biofuel | D6. Renewable Fuel |
|---|---|---|---|---|
| Volumetric target (2022) | ≥16 bgy (61 bly) | ≥1 bgy (4 bly) | 21 bgy (80 bly) target includes preceding categories [≤5 bgy (19 bly) from non-cellulosics] | 36 bgy (140 bly) target includes all other categories [≤15 bgy (57 bly) from corn starch] |
| Volumetric target (2013) | 0.006 bgy (0.02 bly) | 1.28 bgy (4.85 bly) | 2.75 bgy (9.73 bly) | 16.55 bgy (62.65 bly) |
| RIN price range (2008–2013) | Market trading not yet established; compliance credits available at fixed cost from EPA | \$0.05 – \$2.0/gal | \$0.3 – \$1.4/gal | \$0 – \$1.40/gal |
| Current and Predicted Production Sources | Conversion pathways under development | Various plant and waste-derived oils to biodiesel | Cane to ethanol | Corn starch to ethanol |

Notes: D3, D4, D5, and D6 are RIN categories. Bgy = billion gallons year$^{-1}$; bly = billion liters year$^{-1}$.
Sources: 2013 volumetric target;[3] 2022 volumetric target and current/predicted production;[4] RIN Price.[5]

noted an emphasis on tactical and operational levels of analysis, rather than strategic analysis. Others[9,10] focused on analysis of supply chain sustainability and include more holistic environmental analysis.

2. Other assessments[6,11] noted a need for models to estimate the effects of *coordinated decisions* to reach overall bioenergy supply chain goals.
3. Literature reviews call for models to support technology selection or *technology investment*. Most studies assume conversion technologies are available,[7] but offer no insight into the implications of various conversion technology pathway availability scenarios, and literature on strategic and tactical analysis of biomass-to-biofuel conversion technology pathways is limited.[8]
4. Literature reviews recommended more research to assess the *impacts of incentives* and policy choices, including a need for modeling that is readily adaptable to analyze many incentives and stakeholders' interests.[6,7]

The BSM's capabilities and the results of this study will be discussed in the context of these analytic needs.

## Methodology: the Biomass Scenario Model

### Introduction to the Biomass Scenario Model

The US Department of Energy Bioenergy Technologies Office and the National Renewable Energy Laboratory developed the BSM to investigate the dynamics associated with the potential evolutionary trajectories of a US biofuels industry.[12] The model uses a system dynamics modeling approach, built on the STELLA software platform,[13] to represent the dynamic interactions among the major sectors that comprise the biomass-to-biofuel industry – feedstock production and logistics, feedstock conversion, and downstream elements (inventory, dispensing, distribution, fuel use, and vehicle fleet).[14] The model encodes a system of coupled ordinary differential equations that are integrated forward in time, thus establishing interdependence among rates of change of key parameters and feedbacks between variables representing physical, technical, economic, and behavioral aspects of the biofuels supply chain.[15] The BSM tracks the deployment of biofuels over time by representing investment in new technologies, competition from petroleum fuels, vehicle demand for biofuels, and various policies and incentives. Its intended use is to generate and explore scenarios for the evolution of a US biofuels industry. The bioenergy modeling literature review identified a need for such models:[6,7] holistic models, including models using system dynamics, that enable simulation and strategic analysis of the development of a bioenergy supply chain. The BSM is a holistic system-dynamics model for biofuels in the United States. In contrast to most of the bioenergy supply chain models reviewed in the literature, which tend to focus on shorter-term operational issues for specific processes and places,[8] the BSM represents the supply chain from end use to resource and can support longer-term, national analysis that may address strategic issues, such as incentive effects. This paper serves as one example of such analysis with an emphasis on conversion. Some of the literature on sustainability is holistic but less comprehensive of the bioenergy supply chain;[9,10,16,17] the BSM accounts for land use by crop in the United States and has a companion global land-use change model[18] that complements and potentially links to sustainability analysis. High-level system models such as the BSM are designed to estimate possibilities rather than to provide precise quantitative forecasts;[19] thus, the BSM is best suited for (i) analyzing and evaluating alternate policies; (ii) generating scenarios; (iii) identifying high-impact levers and bottlenecks to system evolution; and (iv) seeding focused discussion between policymakers, analysts, and stakeholders.

The BSM was developed as a set of modules, or submodels, for each major sector of the industry (feedstock supply and logistics, feedstock conversion, and downstream), allowing simulation of each sector in isolation or with dynamic connections to others. The major sectors of the biofuel supply chain and the associated BSM modules are shown in Fig. 1. Each module treats a single element of the biomass-to-biofuels supply chain, and each is further partitioned into sectors representing particular aspects (pricing, inventory, production, decision-making, investing, etc.) of that supply-chain element.[20] Systems of equations (both algebraic and integro-differential), within the sectors and spanning sectors and modules, specify the relationships between variables such as prices, costs, facilities, resources, and material. In some cases the equations represent physical or economic constraints or relationships, whereas others embody behavioral models such as investor decision-making and consumer choices.[21] Table 2 elucidates some of the key input parameters and areas of feedback in the BSM. In general, the BSM endogenizes the determination of prices, production, investment, and demand related to biomass and biofuel and relies on exogenously specified scenarios for boundary conditions such as petroleum prices and international trade.


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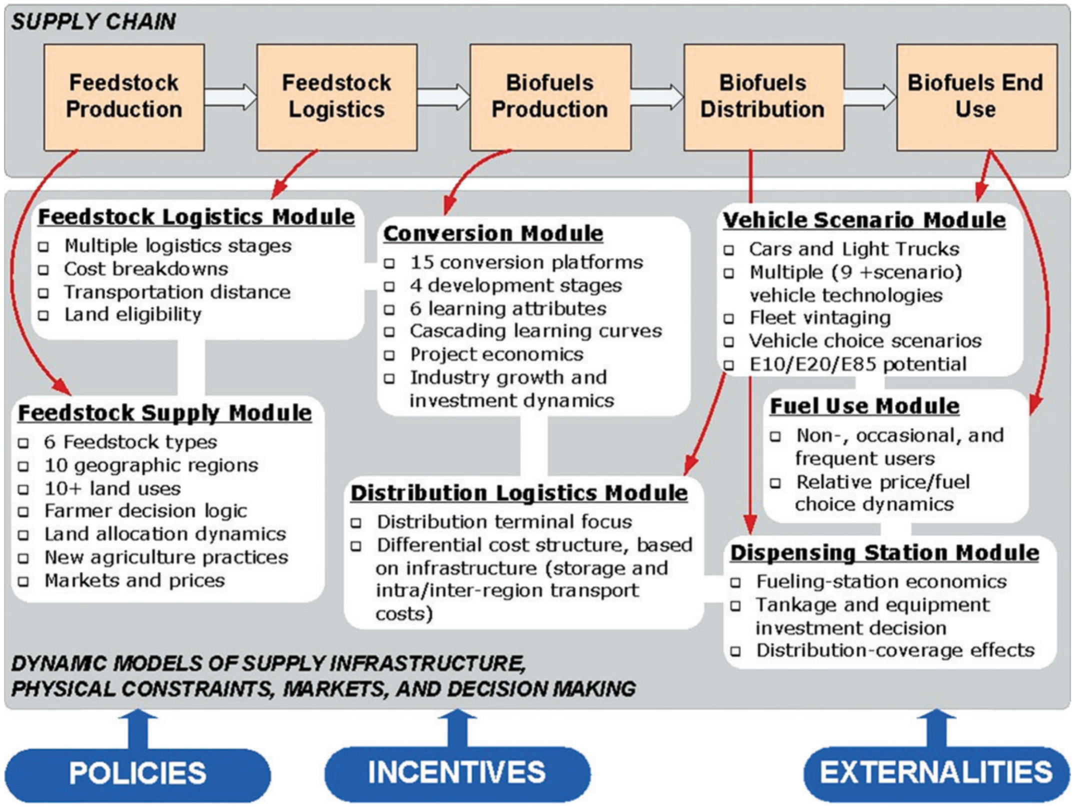


Figure 1. Major modules in the BSM represent major sectors of the biofuels industry.[22]

**Table 2. Key exogenous and endogenous variables in the BSM. Exogenous variables are typically represented as time series. Endogenous variables are computed dynamically and typically are influenced by feedbacks from other variables.**

| Exogenously Input Specified Data | Endogenously Determined via Feedback |
|---|---|
| • Petroleum prices | • Agricultural crop prices |
| • Prices of co-products from biorefineries | • Biofuel prices |
| • Electricity prices | • Crop and feedstock grower decisions |
| • International trade in biofuels | • Annual and perennial crop supply/production |
| • International agricultural trade | • Investment in biorefineries |
| • Domestic demand for agricultural crops | • Investment in refueling infrastructure |
| • Consumer purchases of light-duty vehicles | • Industry maturation (industrial learning) |
| • Construction of pilot- and demonstration-scale integrated biorefineries | • Construction of pioneer and full-scale commercial biorefineries |
| • RIN prices | • Biorefinery utilization |
| • Forest and urban residue supply curves | • Fuel choice by consumers |

The National Research Council[23] summarized economic models used in energy and agricultural policy analysis, including the Food and Agricultural Policy Research Institute (FAPRI) model, the Forest and Agricultural Sector Optimization (FASOM) model, the Global Trade Analysis Project (GTAP) model, and the Policy Analysis System (POLYSYS) model. These are all equilibrium models: GTAP is a general equilibrium model and the others are partial equilibrium models.[23] The BSM complements these models, offering a system dynamic rather than an economic equilibrium approach, which may facilitate detailed examination of transitions, such as the development of a larger biofuels market. Although many models can represent time delays during transition periods, these are readily incorporated into a system dynamics model. The BSM offers a different combination of economic

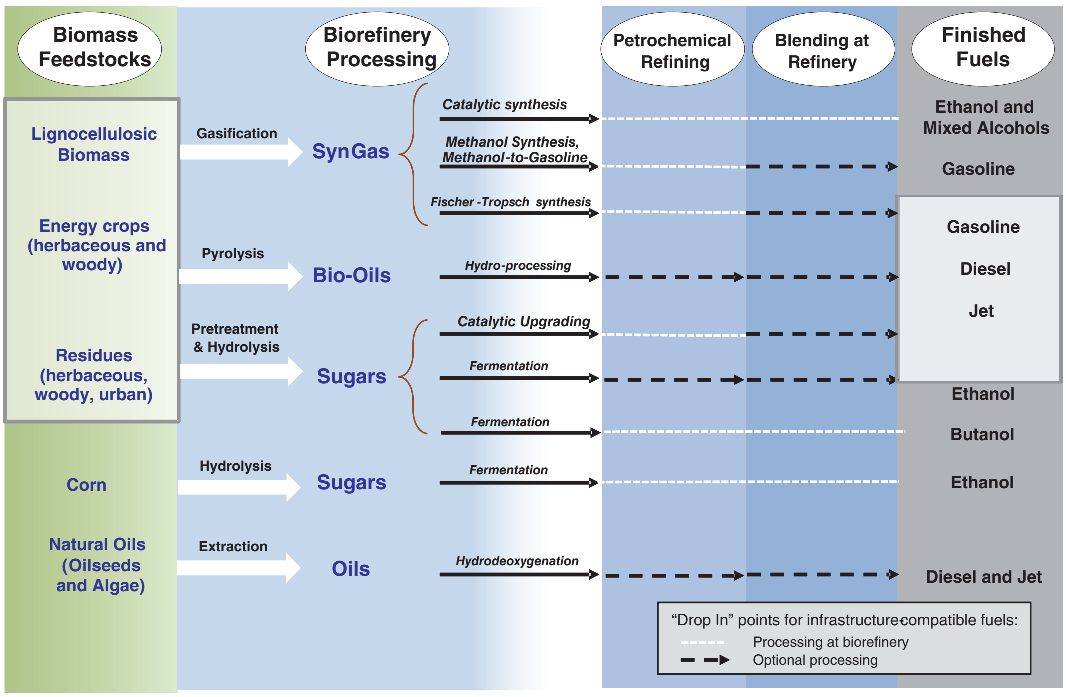


Figure 2. The BSM represents multiple biomass-to-biofuel conversion technology pathways.[22]

sector and geographic coverage relative to these and other models: some other models include more details on specific parts of the supply chain – notably agriculture; some offer more global coverage with more robust representation of trade; and general equilibrium models cover more economic sectors. Some BSM inputs use results of models that provide more detail for specific sectors, such as POLYSYS inputs for agricultural residue resources. The BSM can also use results of models that have broader scope, such as general equilibrium models, as scenarios to set boundary conditions.

## Biomass conversion to biofuels

The conversion sector – as it contributes to biofuels industry growth – is the focus of this study. For a more detailed discussion of other aspects of the BSM, such as its geographic stratification, other sectors, BSM logic, and data sources, see other BSM publications. Peterson *et al.*[21] and Newes *et al.*[24] provide overviews of the model, and Lin *et al.*[20] document model inputs. The feedstocks, intermediates, blendstocks, or fuels, and biomass-to-biofuels conversion technology pathways that are represented in BSM are shown in Fig. 2.

Learning-by-doing, also called *learning from experience* or *experiential learning*, is an observable feature of technological transitions from early development to commercial production,[25]* and the BSM explicitly represents learning-by-doing (distinguishing it from economies of scale and from background, economy-wide learning). Learning-by-doing is assumed to result in improved performance – from current to ultimate performance of each conversion pathway – as a function of process development through pilot- and demonstration-scale production and as a function of commercial production of biofuels. In general, learning-by-doing may be partially confined within firms, but in the BSM it is represented as occurring within a conversion pathway. This study explores the effects of different rates of learning transfer among related conversion pathways (spillover learning, measured as a percent of learning that is shared). Learning modes may include transfer of personnel, exchanges at professional meetings and conferences, formal sharing agreements,[26] and published research findings.

The major dynamic feature of the BSM that involves the conversion module is shown in Fig. 3. Industrial expansion is tracked at four operational scales (pilot, demonstration, pioneer-commercial,† and commercial) in terms of five

* Considering the biomass-to-biofuels conversion technology pathways, corn-starch-to-ethanol and biodiesel are well established; cellulose-to-ethanol and biomass-to-hydrocarbons pathways face early market challenges such as financing.
† 'Pioneer-commercial' is a category for early commercial-scale biorefineries within a pathway.


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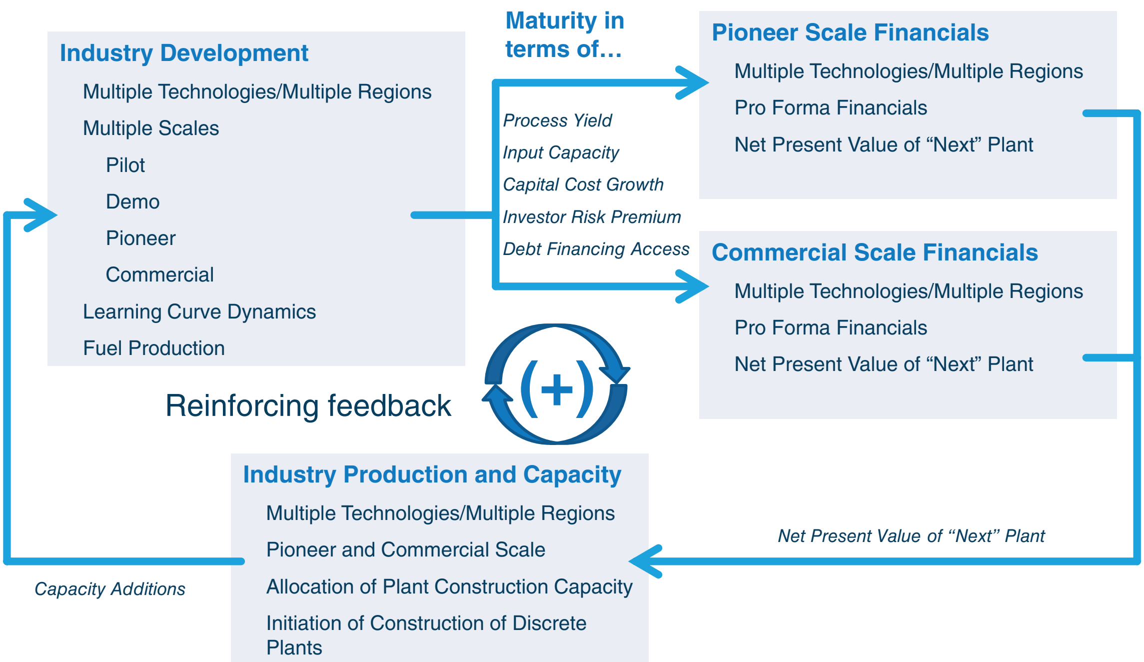


Figure 3. The BSM includes reinforcing feedbacks around industrial development, financial performance, and industrial production and capacity.[22]

**Table 3. Information is exchanged to and from the conversion module and other modules of the BSM.**

| Module Name | …Feedstock Supply and Logistics | …Oil Industry | …Downstream |
|---|---|---|---|
| to Conversion from… | Feedstock consumption<br>Feedstock price (plant gate) | Module-specific price input | Ethanol point of production price<br>Butanol point of production price |
| from Conversion to… | Feedstock demand<br>Cost to price ratios<br>Output capacity | Infrastructure-compatible fuel production by pathway | Ethanol Production<br>Butanol Production |

types of performance improvement (conversion-process yield, feedstock-input capacity, capital cost, investor risk premium,[‡] and access to debt financing). Reinforcing feedback[§] occurs as industrial development improves the financial performance of pioneer-commercial and commercial-scale biorefineries, attracting investment in capacity expansion. Calculations of expected economic value of investment, learning-by-doing, and utilization are used to estimate production capacity development and production volume. This reinforcing feedback may enable technologies with higher initial maturity to receive most of the available investment under certain circumstances; it also shapes the timing and rates of capacity expansion.

This reinforcing feedback is implemented within the BSM through connections that include information exchange between its modules, as shown in Table 3.

## Investment in biorefineries

The BSM calculates the expected net present value (NPV) of investment in a new pioneer-commercial or commercial biorefinery to approximate the financial decision-making of investors. (Opinions differ about actual investor behavior: some literature supports the view that investors tend to assume current prices will persist. The BSM, for the purposes of this study, uses this assumption.**)

‡ Investor risk premium is the additional return that investors require to compensate for additional risk.
§ Reinforcing, or positive, feedback encourages a trend in one direction (growth or decline) in contrast to balancing feedback, which encourages stability.

** Prevailing prices persist and are discounted in the NPV calculation at the specified discount rate.

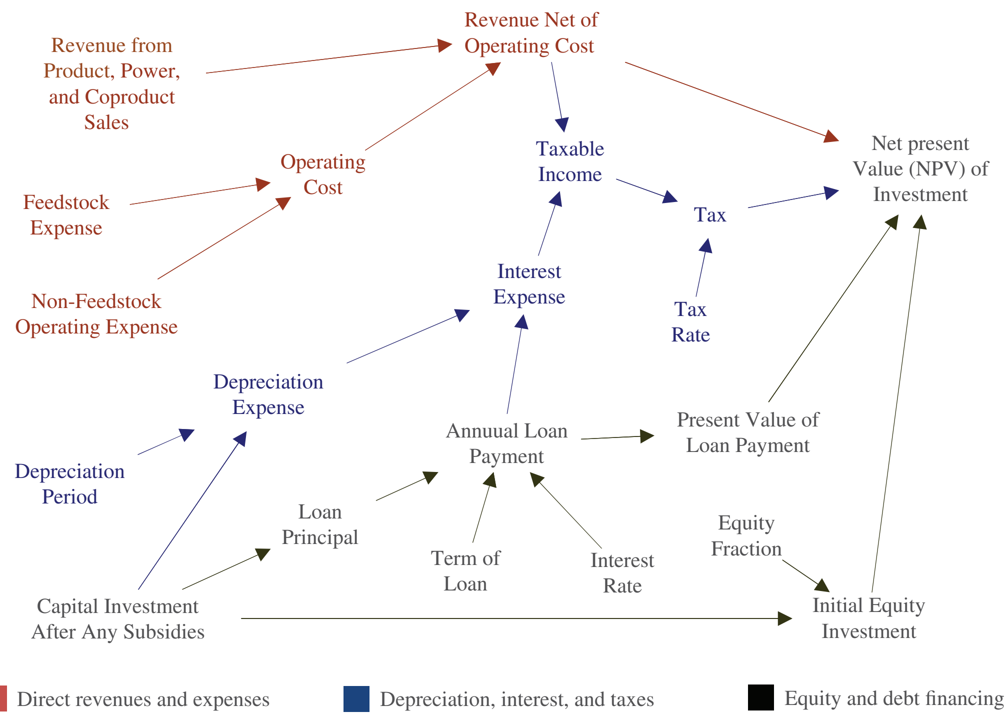


Figure 4. This schematic outlines the project financial computations in the BSM estimate of the net present value (NPV). Note that the NPV calculation includes required rate of return on investment. 

These calculations use major categories of revenue and expenses, straight-line depreciation, constant tax and interest rates, and maturity-based capital costs and access to credit, as shown in the simplified schematic of Fig. 4. Because of learning-curve dynamics, the estimated NPV of a new biorefinery increases with industry maturity and improved financial attractiveness.

The BSM represents a competition between potential facilities for scarce financial and construction resources. It allocates constrained capacity to produce facilities and characterizes the construction and location decisions as choices among (i) the several conversion pathways, (ii) the pioneer-commercial and full-commercial scales, (iii) the 10 geographic regions, and (iv) other uses of facility-construction capacity outside the biofuels industry. It also calculates the utilization of commercial biorefineries as a function of product cost relative to product price.[24]

## Conversion pathways

The BSM represents biomass-to-biofuels conversion technology pathways that include corn-starch-based ethanol, ethanol from lignocellulosic biomass via biochemical conversion ('biochemical ethanol'), ethanol from lignocellulosic biomass via thermochemical conversion ('thermochemical ethanol'),[24] methanol-to-gasoline (MTG), Fischer-Tropsch synthesis, fast pyrolysis followed by hydroprocessing, aqueous phase reforming), sugar fermentation to hydrocarbons, butanol synthesis through a fermentation pathway, and hydrodeoxygenation of oils ('green diesel') (Fig. 2).

The BSM representation of each conversion pathway includes a set of assumptions about the five types of performance improvements identified in Fig. 3. The level of performance is tied to the maturity of the pathway, which is characterized as initial, state-of-technology, or mature. Performance levels for initial and mature industry conditions are externally specified inputs. The model estimates a state-of-technology based on its learning algorithm, which accounts for learning within each operational scale (pilot, demonstration, pioneer commercial, and full-scale commercial). As learning increases, performance approaches mature industry conditions. The learning rate and progress ratio[††] govern the rate of this approach, and progress ratios of 65%, 75%, and 85% were explored in this study.

[††] Learning Rate = 1 – Progress Ratio; Progress Ratio is the relative cost after production doubles, or Progress Ratio = $2^{-b}$ where b is the slope of logarithm cost vs. logarithm cumulative production.


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Newes *et al.*[24] describe the BSM learning algorithm. A more detailed BSM learning analysis is in development. The sources and levels of analytic development underlying these assumptions and calculations vary considerably by pathway and include operating data from mature biorefineries (currently only corn starch to ethanol), analogous industries, published literature based on conceptual process designs, and assumptions for biomass-to-biofuel conversion technology pathways that do not have conceptual process models. For example, the current techno-economic estimates for the biochemical pathway for cellulose-to-ethanol conversion are based on more than a decade of research, whereas the estimates for aqueous phase reforming and sugar fermentation are coarser. Techno-economic estimates are frequently revised, as are the techno-economic input data for the BSM. This study assumes that, with sufficient learning-by-doing, all conversion pathways would reach mature technology performance. This assumption, as well as the variation in the quality of techno-economic data, limits the robustness of the conclusions that can be drawn about comparisons among conversion pathways or about portfolios of different conversion pathways. Additional analysis would be needed to explore scenarios in which conversion pathways might face unexpected barriers, such as performance that falls short of the mature technology assumptions.

The BSM assumptions about technology performance at various states of maturity incorporate information gathered from consultation with biofuels analysts and peer reviewers. The sensitivity of the model results to these parameters is a topic for further exploration beyond this study. Table 4 presents assumptions about conversion pathway characteristics for each BSM conversion pathway.

**Table 4. The BSM uses input assumptions about conversion pathway characteristics. Values are shown in 2007 dollars.**

| | Feedstock Throughput | Capital Expenditure | Fixed Operating Costs | Variable Operating Costs | Revenue from Power Sales | Revenue from Coproduct Sales | Gasoline | Diesel | Butanol | Ethanol | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel Pathway | Mg day$^{-1}$ | million 2007 USD | | | | | Fuel Yield L Mg$^{-1}$ | | | | Days yr$^{-1}$ |
| Algae open pond[1] | 1154 | 139 | 8.16 | 29.4 | 0 | 1.22 | 17 | 484 | | | |
| Algae PBR[1,2] | 270 | 321 | 15.1 | 13.0 | 1.33 | 0.916 | 0 | 396 | 0 | 0 | 330 |
| APR[3,4] | 2000 | 490 | 23.2 | 7.28 | 0 | 0 | 0 | 208 | 0 | 0 | 350 |
| Butanol[1] | 2000 | 464 | 11.6 | 31.5 | 2.31 | 0 | 0 | 0 | 138 | 0 | 350 |
| Fast pyrolysis[29] | 2000 | 303 | 16.7 | 49.4 | 0 | 0 | 184 | 234 | 0 | 0 | 329 |
| Fischer-Tropsch[1] | 2000 | 461 | 18.3 | 2.84 | 0 | 0 | 19 | 175 | 0 | 0 | 350 |
| Green diesel[1] | 2000 | 64.3 | 5.36 | 27.5 | 0 | 18.0 | 8 | 367 | 0 | 0 | 350 |
| MTG[30,7] | 2000 | 316 | 18.0 | 4.8 | 0 | 11.7 | 196 | 0 | 0 | 0 | 350 |
| FHC[31,9] | 2000 | 400 | 10.7 | 20.1 | 0 | 0 | 0 | 175 | 0 | 0 | 350 |
| Corn starch to ethanol[32] | 1112 | 57.0 | 5.14 | 19.5 | 0 | 14.0 | 0 | 0 | 0 | 488 | |
| BC ethanol[33] | 2000 | 401 | 10.7 | 26.7 | 6.60 | 0 | 0 | 0 | 0 | 330 | 350 |
| TC ethanol[34] | 2000 | 490 | 23.2 | 7.28 | 0 | 15.4 | 0 | 0 | 0 | 351 | 350 |

[1]Unpublished NREL data. [2]PBR = photo bioreactor, [3],[27]data modified from Huber.[28] [4]APR = aqueous phase reforming, [7]MTG= methanol to gasoline, [9]FHC = fermentation of sugars to hydrocarbons. (Dollar values will not match references exactly because they are updated here to 2007 dollars and rounded to 3 significant figures).

## Study design: exploration of incentives, capacity expansion, ethanol use, and technological learning

A set of BSM simulations was developed to explore a variety of biofuel industry development scenarios. These scenarios are defined along four dimensions: incentive policies, facility expansion limits, ethanol use, and learning-by-doing assumptions, described below. As shown in Table 5, model simulations for this study included four incentive conditions, three capacity expansion limit conditions, three ethanol use conditions, and two spillover learning conditions. All combinations were simulated, although not all are discussed here.

### Incentives

Representing incentives is a key dimension of a BSM simulation. Comparison of the results of simulations that differ

**Table 5. BSM simulations used numerous combinations of conditions that were simulated, including four different incentives (represented by the four different vertical columns), three different capacity expansion limits on annual plant starts (12, 25, and 75), three different ethanol policy conditions (E10, E15, and E25), and two different spillover learning conditions (0% and 30%). All the combinations shown were simulated at three different progress ratios (65%, 75%, and 85%).**

| Learning | 0% Spillover Learning | | | | 30% Spillover Learning | | | |
|---|---|---|---|---|---|---|---|---|
| Incentives | Point of Production Incentive | Ethanol Focused | Output Focused | Pathway Diversity | Point of Production Incentive | Ethanol Focused | Output Focused | Pathway Diversity |
| E10 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 |
| | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 |
| E15 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 |
| | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 |
| E25 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 |
| | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 |

on the incentive dimension can provide important insights into biofuels industry system behavior. Some incentive directly impact biorefinery financials; others affect the conversion module less directly. The BSM represents incentives that can target a technology during startup or throughout its development (point of production); incentives for construction of biorefineries (fixed capital investment, government loan guarantee); feedstock incentives; and downstream incentives (downstream point of use, distribution and storage, dispensing station fixed capital investment, dispensing station repurposing, high-blend point of use). Scenarios are defined by selecting quantitative characteristics, such as value and duration, of each type of incentive. A library of scenarios is available for BSM simulations, as described in Inman *et al.*[35] This study selects from the BSM incentive scenario library to explore a range of policies that influence biofuel volumetric outputs, as shown in Table 6.

### Capacity expansion

Three limits on annual facility construction were tested in the BSM: initiation of construction of 12, 25, and 75 facilities per year. The low end of this range approximates historical construction rates in the corn-starch-to-ethanol industry. Higher levels model possible effects if market pressures spur development of greater construction capacity during a period of rapid growth.

### Ethanol use

The study explored three levels of ethanol use: E10, E15, and E25. The approximation of the baseline conditions is E10, or 10% by volume ethanol blended into all gasoline. The E15 level represents a phase-in that starts in 2013 and reaches 15% ethanol in all gasoline by 2018. The E25 level has a phase-in that starts in 2013 and reaches 25% ethanol in gasoline by 2025. Limits on ethanol use are a key near-term constraint on biofuels industry growth.

### Technological learning-by-doing

The BSM can simulate learning across conversion pathways that contain similar processes. We explored two assumptions about this spillover learning: (i) it occurs only within a given technological pathway, and (ii) it occurs across similar conversion pathways.

## Limitations of the input data, model features, and scenario design

The results and insights of the BSM are limited by data inputs, model features, and scenario design. The BSM was


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**Table 6. BSM cases for this study included four scenarios from the BSM scenario library.**

| Full Scenario Name | Short Name | Strategy | Incentives |
|---|---|---|---|
| Point-of-production focused incentives scenario | Point of Production Incentive | Mimic a moderate RIN value of $0.45/gal | Point-of-production payment for all biofuels |
| Ethanol-focused incentives scenario | Ethanol Focused | Subsidize ethanol pathways only | Provide support for ethanol only |
| Output-focused incentives scenario | Output Focused | Maximize growth, without exceeding $10 billion per year in incentive costs | Target most promising technology and withhold most incentives from other pathways |
| Pathway-diversity-focused incentives scenario | Pathway Diversity | Maximize pathways, without exceeding $10 billion per year in incentive costs | Design incentive timeline to enable take-off of multiple fuel pathways by staggering incentive start and end dates based on pathway progress and potential |

developed to provide insights about the possible evolution of the biomass-based fuels system. It is not intended to be a precise forecasting tool or a predictive model. All the limitations identified here could be addressed; some are being addressed in ongoing development efforts.

While the BSM results depend on many input data assumptions, the techno-economic input data are particularly important for the conversion module. Earlier we noted the issue of variation in techno-economic data sources. The BSM compensates somewhat for these variations by assigning different technology maturity levels to different pathways. The BSM results should thus not be interpreted to support strong conclusions about specific pathways, such as relative market prospects or the number of pathways to pursue initially to ensure eventual achievement of particular goals.

The BSM conversion module features specific technology pathways and neglects others. In particular, potential feedstock inputs from various waste streams, such as municipal solid wastes or waste oils, are not represented, nor are products such as sugar, biopolymers, and other bioproducts. Exploring these pathways would require a different set of assumptions and different data.

The scenario design used in this study could be expanded to include additional key sensitivity analyses such as techno-economics or investment decision calculations.

## Results

The BSM results, based on the selected scenarios, illustrate the crucial role of coordinated investment, management of risk and uncertainty, and conversion sector barriers during periods of rapid growth in scenarios that approach RFS-level volumes of biofuels sales.

### Coordination of investment

Reaching the targets of the RFS would involve overcoming the initial immaturity of some biomass-to-biofuels conversion pathways through publicly funded incentives and private investments.

#### Coordination of investments with respect to timing, pathway, and targeted biofuels industry sector promotes biofuels industry development

The biofuels industry is an interdependent system; its overall growth requires coordinated expansion of various parts of the system from feedstock production to vehicle consumption of biomass-based fuels.

Overall industry growth is the greatest when (i) the least amount of effort is wasted in removing any single barrier, and (ii) when barriers across the entire system are removed in an orchestrated manner that considers timing, pathway, and sector. Waste metrics include delays in reaching production targets, total incentive cost, windfall profits, and cost-effectiveness metrics such as cost per volume of installed production capacity. Investment in incentives in any single part of the system will influence overall industry growth only under certain conditions, such as when that part is the constraint. BSM results show that investments in incentives that remove barriers across the entire system are more effective than investments that target some parts of the system and neglect others. Previous studies[24] use BSM results to illustrate the value of balanced incentives in reaching RFS levels of biofuels production. These results illustrate the application of the BSM to the second analytic need: the need for coordinated supply chain decisions, which was identified in the bioenergy modeling review. Although much of the literature on supply chain emphasizes tactical or operational coordination, as might occur among firms through contracts,[6,11] the BSM estimate of effects of coordination of incentives across the supply chain highlights the value of coordination at a strategic, national level, as might be achieved through coordinated or linked policies. The BSM analysis locates bottlenecks in the supply chain and identifies the magnitude of incentives required to overcome these bottlenecks under modeled assumptions.

## Risk and uncertainty

The maturation and techno-economics of conversion pathways are uncertain; thus, the size of the public and private investment needed to develop a self-sustaining industry is difficult to estimate. Public incentives for the biofuels industry can support diverse conversion pathways as an explicit goal, and may mitigate the risk that a technology will not perform as expected. Alternatively, they can target a narrower set of conversion pathways, by design or by default, and possibly reduce the cost, and increase the probability of success of the selected pathways by concentrating resources. This comes at a higher risk that technology performance issues would have overall negative impacts on timing and magnitude of production. Ease of learning within pathways and sharing of learning across pathways are major uncertainties in modeling these issues, and these assumptions shape simulation results.

### Potential trade-offs exist between pathway diversity (risk mitigation) and direct incentive cost because of uncertainty in maturation and techno-economics

Incentives allocate resources towards biomass-to-biofuels conversion technology pathways that are at different stages of development. A pathway could have relatively attractive financial performance in the nearer term, but could someday be surpassed by pathways that are now at earlier stages of development. The design choices about allocation of incentives to more-mature or less-mature pathways are important because (i) future development is uncertain; (ii) less attractive but early-maturing technology pathways can lock out others, making their market entry all but impossible; and (iii) incentives can influence conversion technology development. The results from the BSM illustrate these insights. The Pathway Diversity scenario features deliberate allocation of incentives to encourage maturation of multiple conversion pathways. This approach places greater value on fostering diversity to reduce technology risk. The Output Focused scenario allocates incentives to encourage rapid expansion of commercial-scale biofuel-production capacity. The Output Focused scenario favors the pathway with the most competitive performance under mature technology assumptions, and the Pathway Diversity scenario favors the development of multiple pathways.

The BSM includes assumptions about the initial maturity of each conversion pathway, as shown in Table 4. Assumptions about maturity and costs are such that Fischer-Tropsch has the highest initial NPV of the biomass-based hydrocarbon pathways; its initial settings for pilot- and demonstration-scale maturity are at least equal to all other pathways, except those for corn starch and cellulosic ethanol. The pathway with the best NPV attracts more investment, increasing its maturity and investment attractiveness in the reinforcing feedback (Fig. 3). However, in these assumptions the financial performance of a mature commercial biorefinery is better for fast pyrolysis than for Fischer-Tropsch, based on the cited process design publications. Actual long-term performance is, of course, uncertain.

In the model, a more mature conversion pathway that is more expensive in the long run can lock out a less-mature conversion pathway that is less expensive in the long run, due to investment and learning dynamics.[25] Significant uncertainty also remains about the ultimate cost and performance of many pathways. In the Point of Production Incentive scenario, Fischer-Tropsch tends to lock out other biomass-based hydrocarbon pathways. To counteract the risk of lockout and to diversify pathways for technology risk management, policies could be designed to overcome the low initial maturity of promising pathways, as in the Output Focused scenario, or promote even greater pathway diversity, as in the Pathway Diversity scenario. Figure 5 illustrates this trade-off between pathway diversity and incentive costs (not adjusted for risk).

Model results suggest greater cost effectiveness for the Output Focused scenario than for the Pathway Diversity scenario. For example, in the Output Focused scenario in 2026, a cumulative $20 billion investment in incentives for the biomass-to-hydrocarbons pathway has an established production capacity of about 7 billion gallons per year. The Pathway Diversity scenario reaches this level of cumulative cost in 2027, with a 4-billion gallon per year industry. However, these do not include the cost of technology risk or the value of the option to use more pathways. Instead, model results indicate that encouraging more diversity may have a higher cost (the difference in estimated cost effectiveness between the Output Focused and Pathway Diversity scenarios). These scenarios are not fully optimized, so the costs are approximate, but this kind of relative scenario cost could be compared with estimates of the expected benefits of additional technology options. For example, estimates of probabilities of reaching mature conversion technology pathway performance could be used to compare risk-adjusted costs


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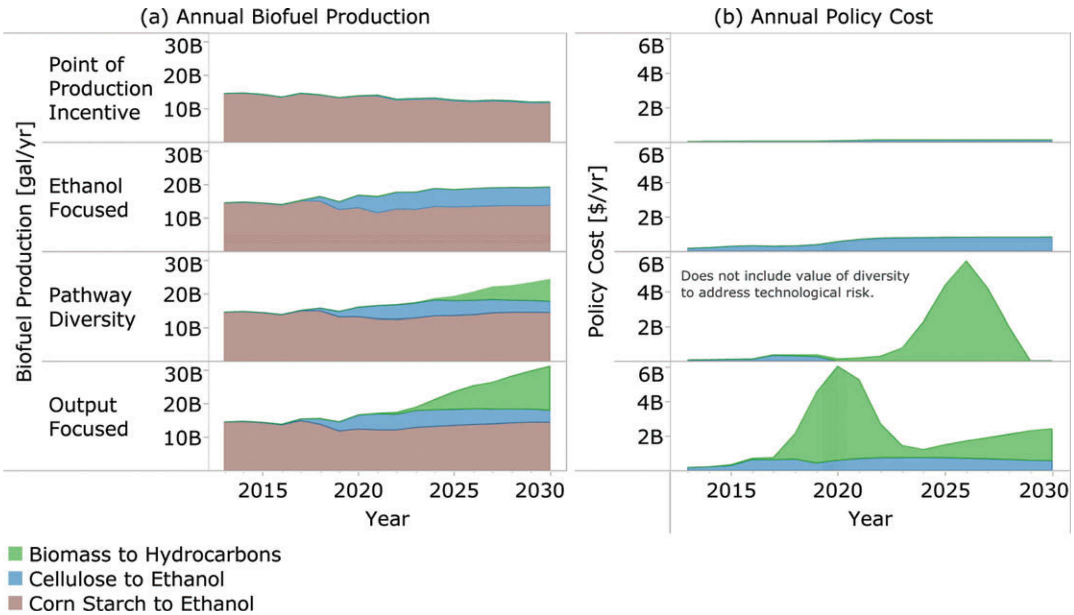


Figure 5. Assuming mature technology performance will be reached with sufficient learning, the Output Focused scenario reaches higher production levels than the Pathway Diversity scenario, with a similar annual limit on incentive cost.

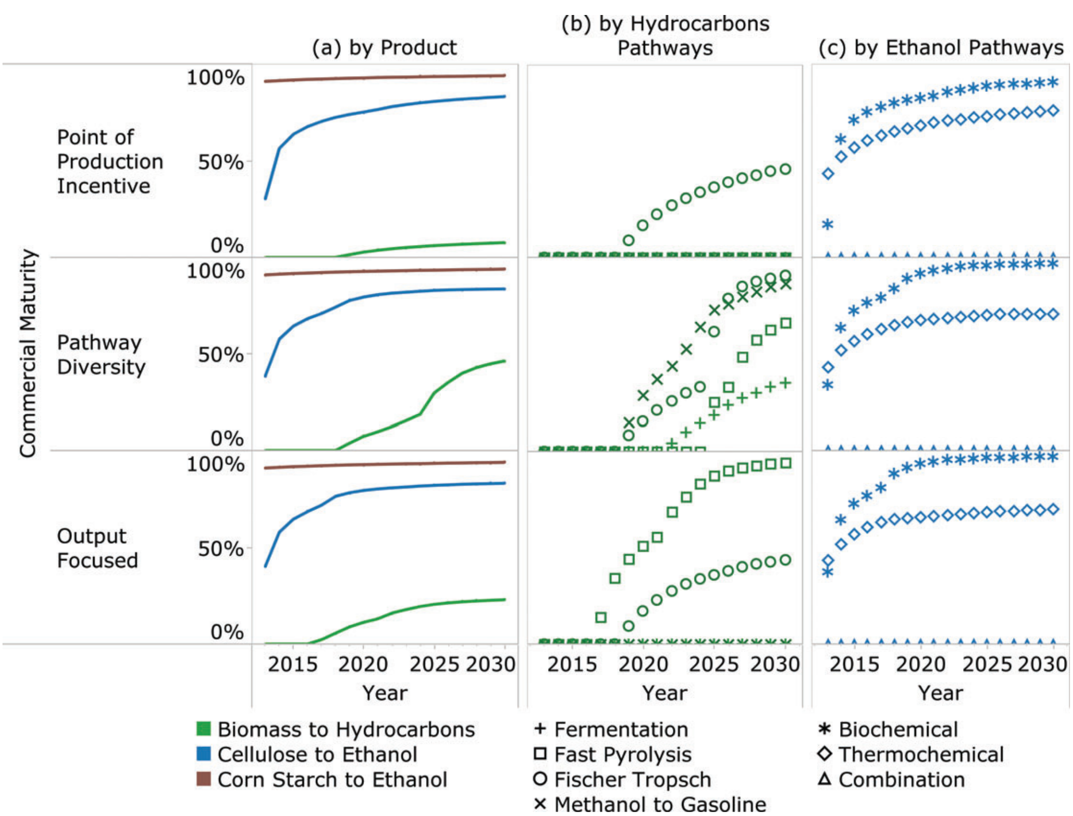


Figure 6. Maturity levels by technology in the Output Focused and Pathway Diversity scenarios.

of investment in more or less diverse sets of conversion technology pathways.

Technologies with favorable long-term economic cost structures can succeed if incentives are designed to overcome initial maturity deficiencies. The Pathway Diversity and Output Focused scenarios represent incentives that are designed to overcome lockout of less-mature conversion pathways, in hopes of realizing their long-term advantages over more-mature pathways. The BSM results suggest that incentives can effectively overcome an initial maturity deficit. The difference in commercial maturity levels over time between an Output Focused and a Pathway Diversity scenario is apparent in Fig. 6. The first panel shows the relative maturity of the corn-starch-to-ethanol pathway, the cellulose-to-ethanol pathway, and the biomass-to-hydrocarbons pathway over time. The second panel shows detail for selected biomass-based hydrocarbon pathways. Deliberately targeting incentives towards multiple pathways, as in the Pathway Diversity scenario, causes more pathways to mature than in the Output Focused scenario. Once mature, the additional pathways may or may not become competitive with the dominant pathway, either in general or in specific niches.

A challenge in policy design is distinguishing incentives that are overcoming initial maturity differences, which may enable healthy competition of financially attractive pathways, from incentives that are attempting to maintain diversity in the face of unfavorable long-term financial performance. Some pathways may not become competitive in the long term, and different pathways may dominate in different market segments characterized by feedstock or product, which the BSM may not resolve in sufficient detail to reveal niche advantages for particular conversion technologies. These considerations complicate assessment of incentive effectiveness.

## Characteristics of learning, such as its rate and sharing across pathways, can dramatically influence pathway competition timing and results

The BSM can represent learning as occurring within and across pathways (each row of Table 4 represents a pathway). Research has documented spillover learning from one technology to another in other industries.[26] To the extent that learning occurs across biomass-to-biofuels conversion technology pathways, learning will be accelerated, the transition time to mature commercial-scale biorefinery performance will be reduced, and pathways with favorable mature financial performance will lock in sooner. Figure 7

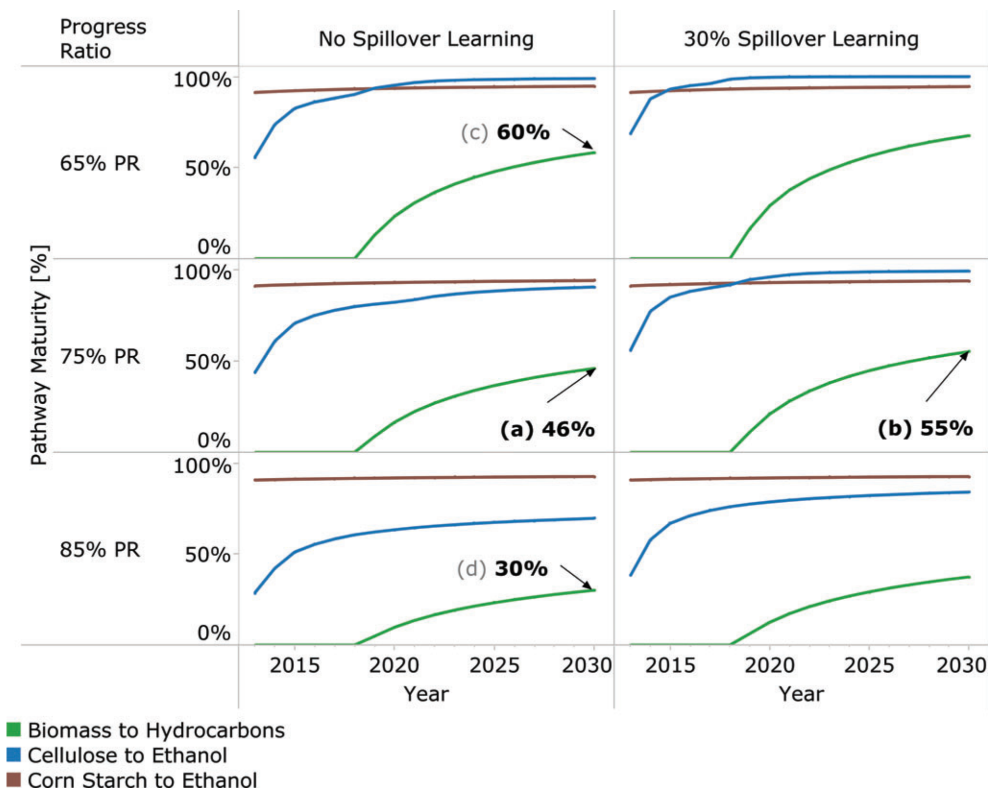


Figure 7. Commercial maturity is accelerated with more rapid learning from spillover or progress ratio assumptions.


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shows that learning increases with greater shared learning among pathways with the same product; that is, learning is shared across ethanol pathways and across hydrocarbon pathways, but not between ethanol and hydrocarbon pathways. Maturity increases with 30% spillover learning (right column) relative to 0% (left column), and increases with the more rapid learning that occurs at a 65% progress ratio (top row) relative to the slower learning at 85% progress ratio (bottom row). For example, at a 75% progress ratio, without spillover learning, maturity of biomass-to-hydrocarbons pathways rises from 0% in 2014 to only 46% in 2030 (a), versus 55% in 2030 with 30% spillover learning across all these pathways (b). Considering the effect of progress ratio without spillover learning, maturity for these pathways in 2028 was 60% under rapid learning assumptions with a 65% progress ratio (c) versus 30% under slower learning assumptions with an 85% progress ratio (d).

The ease of learning has implications for incentive cost effectiveness. For example, in the Point of Production Incentive scenario results of these simulations, a $500-million cumulative incentive investment in the cellulose-to-ethanol pathway brings production to a 2-billion liter per year (600-million gallon per year) production level by 2030 if learning-by-doing is more effective (65% progress ratio), but the same $500-million level of investment would bring production to only 0.9 billion liters per year (250 million gallons per year) by 2030 with less effective learning-by-doing (75% progress ratio). The figure also shows that spillover learning and progress ratio exhibit little synergy.

The BSM results characterize design trade-offs between pathway diversity and direct incentive cost and characterizing implications of technology learning. They illustrate the application of the BSM to explore specific issues related to technology investment (the third need from the literature review) and to understand the impacts of incentives (the fourth need). Regarding technology investment, the BSM explicitly represents conversion technology selection, and can compare the relative market penetration of various biomass-to-biofuels conversion technology pathways under a wide range of resource, technological, incentive, regulatory, and other assumptions. Regarding the impact of incentives, the BSM can estimate the effects of various types of incentives along the biomass-to-biofuels supply chain, on market development, market share by technology, resource, and fuel, and financial performance. This article applies BSM capabilities on technology investment and on incentives to compare scenarios with and without incentives for conversion technology diversity.

## Dynamics of rapid growth

Conditions could favor rapid industry growth with – or even without – incentives. If the industry grows rapidly, resources for constructing new biorefineries may become scarce, and resource allocation then becomes a powerful force shaping the overall growth trajectory and relative shares of conversion pathways; at more moderate growth levels these constraints are less influential. During rapid growth, competition between conversion pathways for investment, feedstocks, and markets intensifies and may slow overall growth, especially that of less-competitive pathways. If demand for ethanol increases, ethanol production – an established commercial process – can respond rapidly.

### During rapid growth, scarcity of resources for constructing new biorefineries shapes the biofuel industry's growth trajectory and influences pathway shares

Construction of new biorefineries involves specialized resources, such as skilled labor, machinery, materials, and financial expertise. The BSM estimates the allocation of these resources among conversion pathways, scales, regions, and other uses. The BSM represents an overall constraint on these resources by setting an annual limit on the number of commercial facilities that can start being constructed in the biorefining industry and in industries that directly compete with biorefining for construction resources. Figure 8 shows the importance of this limit on capacity for construction of commercial-scale biorefineries when industry growth accelerates. The three panels represent numbers of biorefineries of different types when the annual limit on facility construction starts is 12, 25, or 75.[‡‡] This limit affects both overall biofuels industry growth and the share of biorefineries of a given type. The low end of this range of 12 facilities per year approximates typical historical construction rates in the corn-starch-to-ethanol industry, and 25 facilities per year is close to the maximum number of corn-starch-to-ethanol conversion facility starts seen in that industry.[4] The upper end of this range is close to the historical maximum number of ethanol conversion facilities under construction in any given year.[36] Facility construction starts in the 25–75 range would be consistent with strongly favorable and sustained

‡‡ This constraint on annual plant starts implies a constraint on additional new production capacity in terms of production volume that varies by time (due to learning) and by technology. Annual production volume for a mature commercial plant may be calculated from data in Table 3, where Annual Production Volume = Feedstock Throughput (Mg day$^{-1}$) × Fuel Yield (L Mg$^{-1}$) × Operating Days (Days yr$^{-1}$).

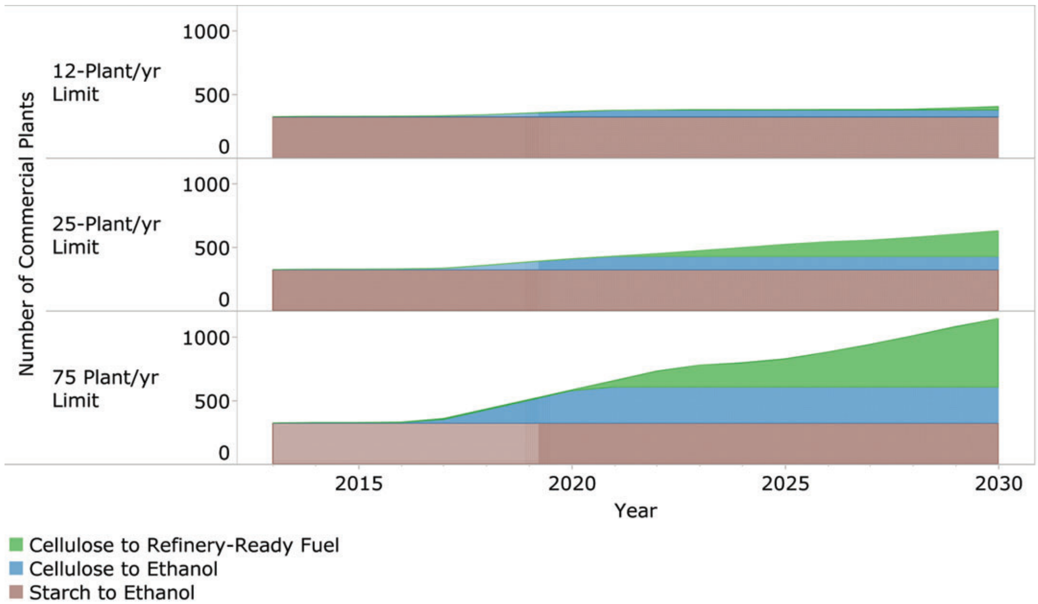


Figure 8. Growth in number of commercial biorefineries depends on the annual limit on the number of facility starts.

market conditions if market pressures spur development of greater construction capacity for biorefineries during a period of rapid expansion. During this rapid expansion, biofuels conversion facilities would compete strongly for industry capacity expansion resources in the United States.

## When pathways experience robust growth, competition for feedstock and market share intensifies and limits growth

Three related renewable pathways – corn-starch-to-ethanol, cellulose-to-ethanol, and biomass-to-hydrocarbons – create the potential for competition between conversion pathways for feedstock supply and competition to meet demand in ethanol markets. BSM results show some indications of these interactions: the biomass-to-hydrocarbons pathway appears to compete with the cellulose-to-ethanol pathway for cellulosic feedstocks; the corn-starch-to-ethanol pathway competes with the cellulose-to-ethanol pathway for ethanol market share (in both low- and high-blend fuel markets). The following highlights from Fig. 9 illustrate this competition:

1. Point-of-production-focused incentives scenario (Point of Production Incentive): Under this scenario, growth in demand for biofuels is slight and ethanol remains the major biofuel sold. The corn-starch-to-ethanol industry does not face competition from the cellulose-to-ethanol industry and can meet all the ethanol demand.
2. Ethanol-focused incentives scenario (Ethanol Focused): When cellulosic ethanol incentives are high, the industry takes market share away from the corn-starch-to-ethanol industry [Label (a)]. This is likely due to more favorable techno-economics for mature cellulose-to-ethanol facilities than for corn-starch-to-ethanol ethanol facilities, and to the competition that corn-starch-to-ethanol industry faces from food and feed markets. The cellulose-to-ethanol industry can overcome its initial immaturity and take advantage of its better techno-economics and lower-cost feedstocks, but the corn-starch-to-ethanol ethanol industry can recover somewhat in the long term because of its maturity (b). Overall growth in the ethanol market is restricted and relies on downstream infrastructure incentives to prevent significant industrial bottlenecks and encourage market penetration.
3. Pathway diversity-focused incentives scenario (Pathway Diversity) and Output-focused incentives scenarios (Output Focused): With incentives, the biomass-to-hydrocarbons pathway can outbid the cellulose-to-ethanol pathway for cellulosic feedstocks (c). This drives up feedstock costs, which gives the corn-starch-to-ethanol industry an advantage over the cellulose-to-ethanol industry and slows industry growth because of the interaction between higher feedstock cost and the lower pathway maturity reached in the Pathway Diversity scenario. Additionally, unlike ethanol, biomass-to-hydrocarbons


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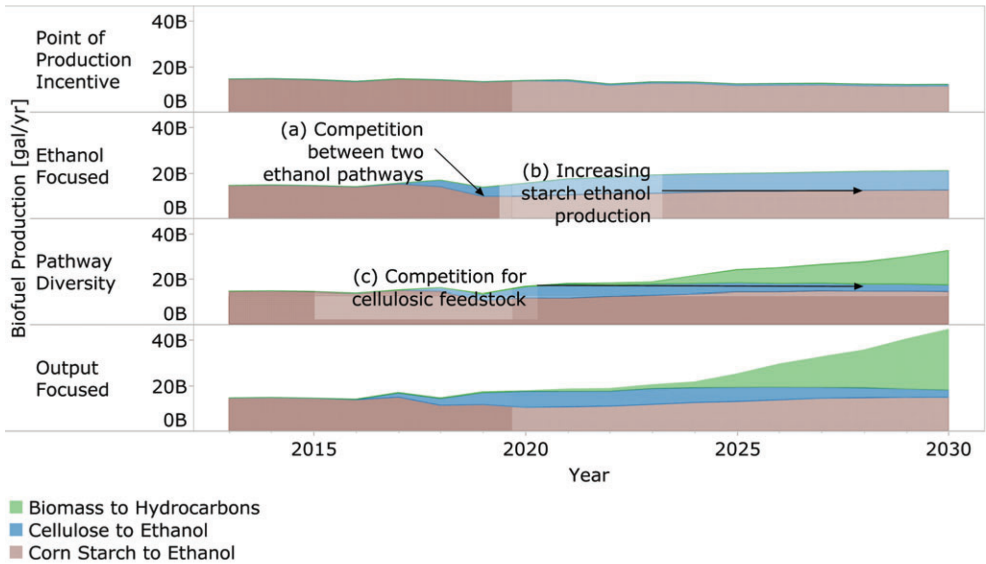


Figure 9. Competition between biomass-to-biofuel conversion technology pathways.

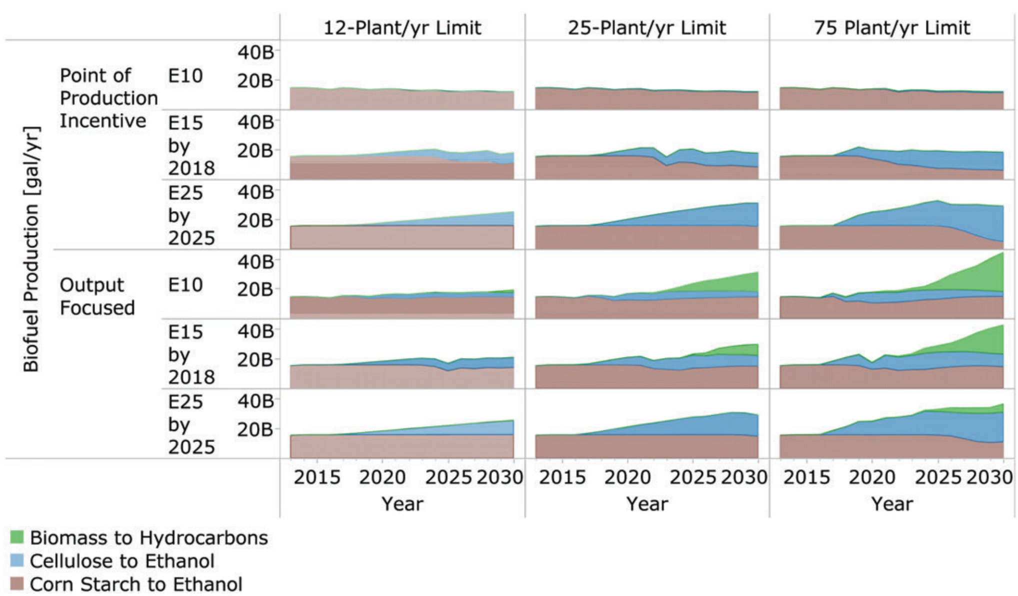


Figure 10. Production quantities and shares over time at three levels of ethanol blending.

fuels are infrastructure compatible and are modeled with unlimited demand and no interference (bottlenecks) from lack of downstream infrastructure.

## Ethanol production can increase rapidly enough to meet demand from higher blending proportions, even as demand approaches RFS levels

Most ethanol in the United States is sold as E10. The EPA granted a waiver to approve raising the maximum blend level of ethanol in most gasoline from 10% to 15%, but this fuel was approved for model year 2007 and newer light-duty gasoline-fueled vehicles only.[37] Specially purposed gas stations and flexible-fuel vehicles can use the higher ethanol blends known as E85 and blended as high as 85% ethanol by volume with gasoline. The market for ethanol is therefore limited by blending regulation. Because cellulose-to-ethanol production is mature relative to other advanced biofuels pathways, it can respond more rapidly than biomass-to-hydrocarbons pathways, increasing commercial development in response to increased demand from a change to a higher blending proportion, as shown in the BSM results in Fig. 10, under different conditions of incentives and annual construction limits.

Incentives could contribute significantly to rapid industry growth. The results in this article explore such scenarios, providing an example of the application of the BSM to the need identified in the modeling review to assess the impacts of incentives.[6,7] These results also illustrate the potential for competition between technologies and blending constraints on ethanol production, potentially informing technology investment decisions, the third need from the modeling review.

## Conclusions

This study illustrates the application of the BSM to four bioenergy modeling analytic needs that were identified in a recent literature review: the need for holistic models that can simulate bioenergy development over time, the need to understand the value of coordinated decisions for bioenergy development, the need to support technology investment decisions, and the need to assess the impacts of incentives.

Reaching RFS levels of biofuels production would require rapid growth in the biofuels industry, including overcoming the current immaturity of some biomass-to-biofuels conversion technology pathways. Rapid industrial growth and maturation of the industry relate through a reinforcing feedback relationship. BSM exploration of this dynamic demonstrated the critical importance of coordinating investments with respect to timing, pathway, and target sector in the biofuels industry. Metrics of incentive effectiveness include timing and magnitude of increased production, incentive cost and cost effectiveness, and avoidance of windfall profits, all of which improve if incentives catalyze learning-by-doing and associated maturation of the biofuels industry. The BSM analysis locates bottlenecks in the supply chain and identifies the magnitude of incentives required to overcome these bottlenecks as modeled.

Potential trade-offs exist between pathway diversity (risk mitigation) and direct incentive cost because of uncertainty in maturation and techno-economics. Characteristics of learning, such as its rate and sharing across pathways, can dramatically influence pathway competition timing and outcomes.

The maturation and techno-economics of conversion pathways are uncertain; thus, the magnitudes of public and private investments that would develop a self-sustaining industry are difficult to estimate. It is unknown how rapidly the industry will mature in response to a given investment, or how effective learning-by-doing will be. The ultimate possible techno-economic performance is also uncertain. In BSM simulation results, incentives influence the maturation of conversion pathways, and can be selected to simulate maturation of a single biomass-to-hydrocarbons pathway or of multiple biomass-to-hydrocarbons pathways. Further analysis would be needed to evaluate the relative risk-adjusted cost of investment in a single pathway versus multiple pathways.

If the biofuels industry grows rapidly, simulation results suggest that the scarcity of biorefinery construction resources and competition between pathways for feedstock and market share may shape – and sometimes limit – that growth. As modeled and considering current maturity levels, biomass-to-hydrocarbons pathways are less able to respond to rapidly increasing demand in the near-term than are the more-mature cellulose-to-ethanol pathways.

The BSM is a detailed system dynamics model of the biofuels industry; as such, its simulations document possible system behaviors and ranges of values of incentive cost and production under scenarios that target RFS levels of biofuel use. They also provide insights into system behaviors that could aid or challenge efforts to reach these levels of biofuel production.

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