Chapter

Insights from over 10 Years of Cellulosic Biofuel Modeling

Daniel Inman, Emily Newes, Brian Bush, Laura Vimmerstedt and Steve Peterson

Abstract

We present insights gained from over 10 years of system dynamic modeling of the cellulose to biofuel industry in the United States. We use a publicly-available Biomass Scenario Model to explore the impact of logistics system, economies of scale, and shared industrial learning on the developing cellulose-to-biofuels industry in the United States. One theme from this study as well as from the work performed over the last decade is the importance of the movement of the system toward maturation, both in terms of the supply system and the conversion processes. Mature processes imply lower investment risk, better yields, and better process economics.

Keywords: system dynamics, biofuels, biomass, modeling, renewable energy, cellulosic biofuel

1. Introduction

The Biomass Scenario Model (BSM), developed by the U.S. Department of Energy (DOE), is used to explore the emerging biofuels industry in the United States. Over the course of the last decade, the model has evolved along with the biofuels industry. This evolution includes numerous upgrades to the model and associated software, updates to the underlying data, and public release of the model (https://github.com/NREL/bsm-public).

The BSM has supported multiple analysis studies focused on various components of the feedstocks-to-biofuels supply chain; links to publications and reports associated with these studies can be found on NREL's OpenEI BSM wiki pages (https://openei.org/wiki/Biomass_Scenario_Model). Two important themes, which serve as focal points for this chapter, have emerged from our analyses: (a) the importance of feedstock logistics and (b) the impact of shared industrial learning. We present illustrative results from the publicly-available version[1] of the BSM that explore both themes.

1.1 Biofuels in the United States

Biofuels—specifically soy-based biodiesel and corn-starch-based ethanol (**Figure 1**)—have benefited from government support within the United States. Both the ethanol and biodiesel markets have grown following the Energy Tax Act [1], a law passed by the federal government in 1978 to promote fuel efficiency with

[1] https://github.com/NREL/bsm-public; git commit # e62598a.

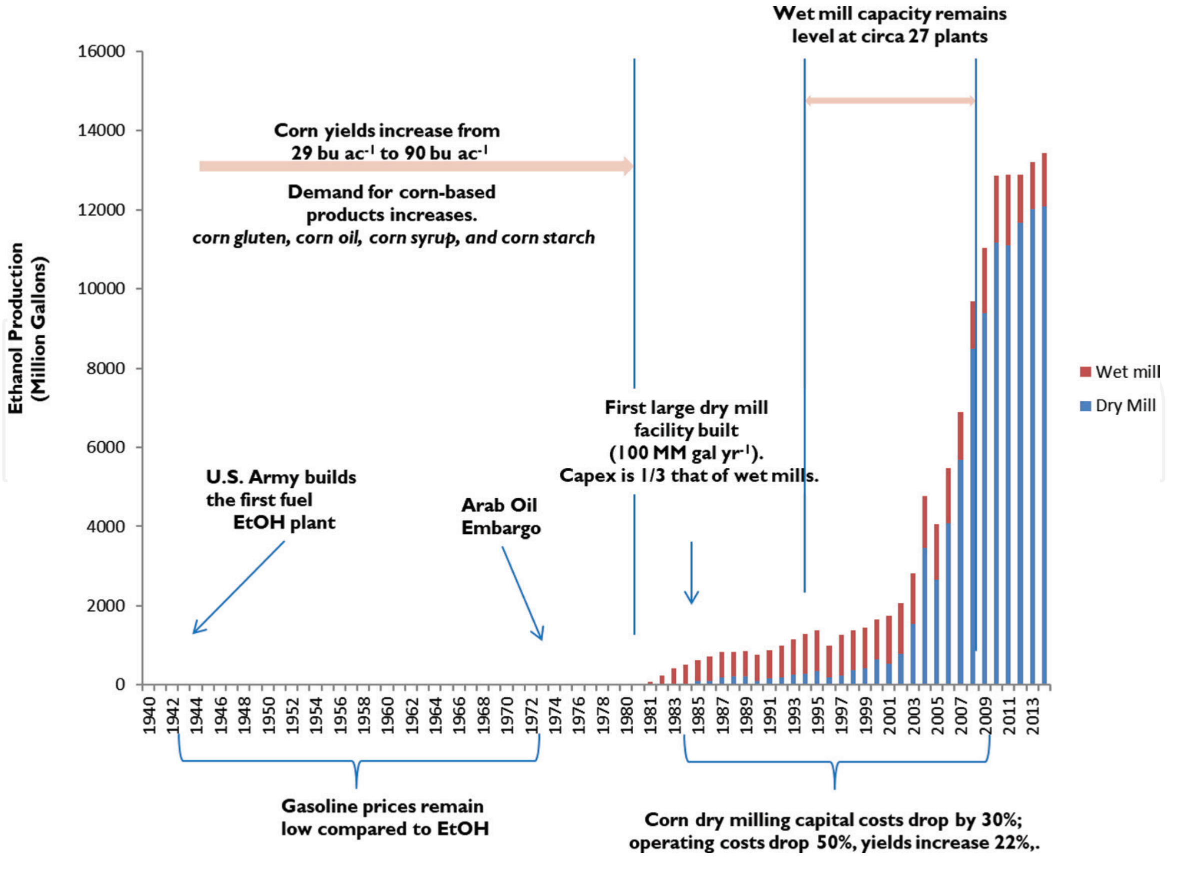


Figure 1.
Growth of the ethanol industry and a timeline of major biofuel legislation.

favorable tax incentives. Other government measures, such as guaranteed loans and research funds, helped de-risk the markets further [2].

Ethanol received another boost when methyl tertiary butyl ether (MTBE) was banned [3], which opened new markets for ethanol as an oxygenate in gasoline. Ethanol use in gasoline was reinforced a year later with the 2015 passing of the Energy Policy Act [4], which removed oxygenation requirements and mandated that refiners blend up to 10% ethanol by volume [5], adhering to the new Renewable Fuels Standard.

From 1978 to 2005, energy policies continued to favor the domestic ethanol industry through production tax credits and capitol grants, among other industry incentives. The passing of the Energy Independence and Security Act of 2007 slanted in favor of lignocellulosic ethanol—increasing biofuel volume requirements while incentivizing lignocellulosic feedstocks over corn starch through Renewable Identification Numbers (RINs) [5].

Ethanol continues to be the primary biofuel in the US. However, because of limits on blending, incompatible distribution and dispensing equipment, and limited market penetration of vehicles capable of using high ethanol blends (~ E-85), the overall biofuel market has been limited and less than anticipated volumetric goals reported in early legislation [6]. Additionally, much of the ethanol blended in the US is derived from corn-starch, which is classified as a "renewable fuel" by the EPA, meaning the fuel achieves a 20% reduction in CO_2 as compared to conventional gasoline. To develop a more environmentally sustainable biofuels industry in the US, corn -starch-based ethanol is limited to 15 billion gallons annually, whereas lignocellulosic biofuels are incentive through their eligibility for D5 and D3 RINs. Despite legislation that provides incentives for advanced and cellulosic biofuels, the market for such fuels has been slow to take off.

One factor that has limited the market for advanced and cellulosic biofuels is the development of integrated biorefineries. The technologies for converting lignocellulosic feedstocks into ethanol and hydrocarbons are underdeveloped. Technologies for feedstock processing and handling have, at best, recently become commercial, and the markets for biomass feedstocks may not exist altogether.

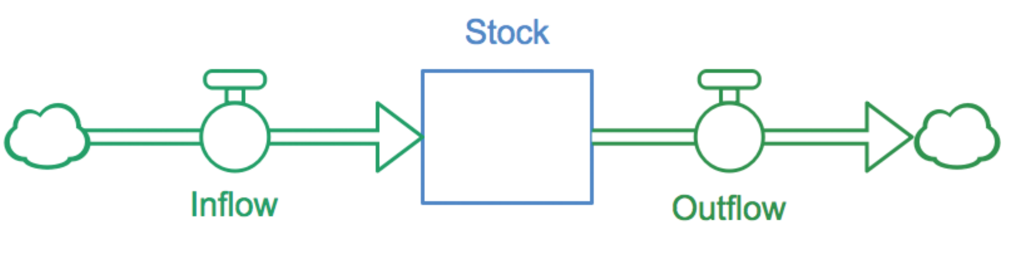
These biorefineries are gaining support from both public and private channels [7]. Among the former, both the DOE and the U.S. Department of Agriculture (USDA) have helped commercialize renewable, non-starch biofuels and development of feedstock supplies. Their R&D leadership in the sector has helped develop lignocellulosic feedstocks and has gone beyond biofuels to include growth in bioproducts and biopower [8]. The USDA is also empowering the sector through its Biorefinery Assistance Program, which guarantees loans for biorefineries [9], and through research into alternative feedstock species, and programs that incentivize producers [10].

1.2 The Biomass Scenario Model

Many of the physical processes, decision processes, feedbacks and constraints found in the biomass-to-biofuels supply chain are represented in the BSM [11]. The BSM is a system dynamics model developed under the auspices of the DOE as part of a multi-year project at the National Renewable Energy Laboratory. It is a tool designed to better understand biofuels policy as it impacts the development of the supply chain for biofuels in the United States and the economic agents influencing development through their decisions. The model is intended to generate and explore plausible scenarios for the evolution of a biofuel transportation fuel industry in the United States, representing multiple pathways leading to the production of fuel ethanol as well as advanced biofuels such as biomass-based hydrocarbons such as biomass-based gasoline, diesel, jet fuel, and butanol. The BSM, which is implemented using the STELLA [12] system dynamics simulation platform, integrates representations of resource availability, physical/technological/economic constraints, behavior, and policy to model dynamic interactions across the supply chain. It simulates the deployment of biofuels given technological development and the reaction of the investment community to those technologies in the context of land availability, the competing oil market, consumer demand for biofuels, and government policies over time. It has a strong emphasis on the behavior and decision making of various agents along the supply chain.

1.3 System dynamics modeling

System dynamics is used in a wide range of modeling applications to represent and simulate complex non-linear systems driven by multiple interacting physical and social components. As a modeling philosophy, system dynamics relies on three key concepts: stocks, flows, and system feedback [13]. **Figure 2** shows a basic stock-flow structure and corresponding mathematical representation. Below is a brief explanation of these concepts.



$$Stock\ (t) = \int_{t_0}^{t} [Inflow - Outflow]dt + Stock\ (t_0)$$

Figure 2.
A basic stock-flow structure and corresponding mathematical representation.

1.3.1 Stocks and flows

Accumulations, and the activities that cause accumulations to rise and fall over time, are fundamental to the generation of dynamics. System dynamics models are built up from stock and flow primitives. In the BSM, we use stocks to represent concepts such as prices, inventories, conversion facilities, and station owners who are contemplating investment in E85 tankage and dispensing equipment. Corresponding flows would include price changes; production, consumption, and shrinkage of inventories; investment or obsolescence of facilities; and deciding not to invest in tankage and equipment.

1.3.2 Feedback

Dynamic social systems can contain rich webs of feedback processes. Positive feedbacks tend to drive reinforcing growth in key quantities, while negative feedbacks support self-correcting behavior. In the BSM, we have sought to capture key feedbacks within and across each stage of the supply chain.

The BSM is built and designed using a top-down, modular approach representing the flow of feedstocks to flow down the supply chain to be converted into biofuels, with feedback mechanisms among and between the various modules. Our modeling approach respects the need for transparency, modularity, and extensibility. This enables standalone analysis of individual modules as well as testing of different module combinations. As shown in **Figure 3**, the model is framed as a set of interconnected sectors and modules. Each supply-chain element is modeled as a standalone module but is linked to the others to receive and provide feedback. The feedstock production module simulates the production of biomass as well as five major commodity crops (corn, wheat, soybeans, cotton, and other grains) through farmer decision logic, land allocation dynamics, new agricultural practices, markets, and prices. The feedstock logistics module models the harvesting, collection,

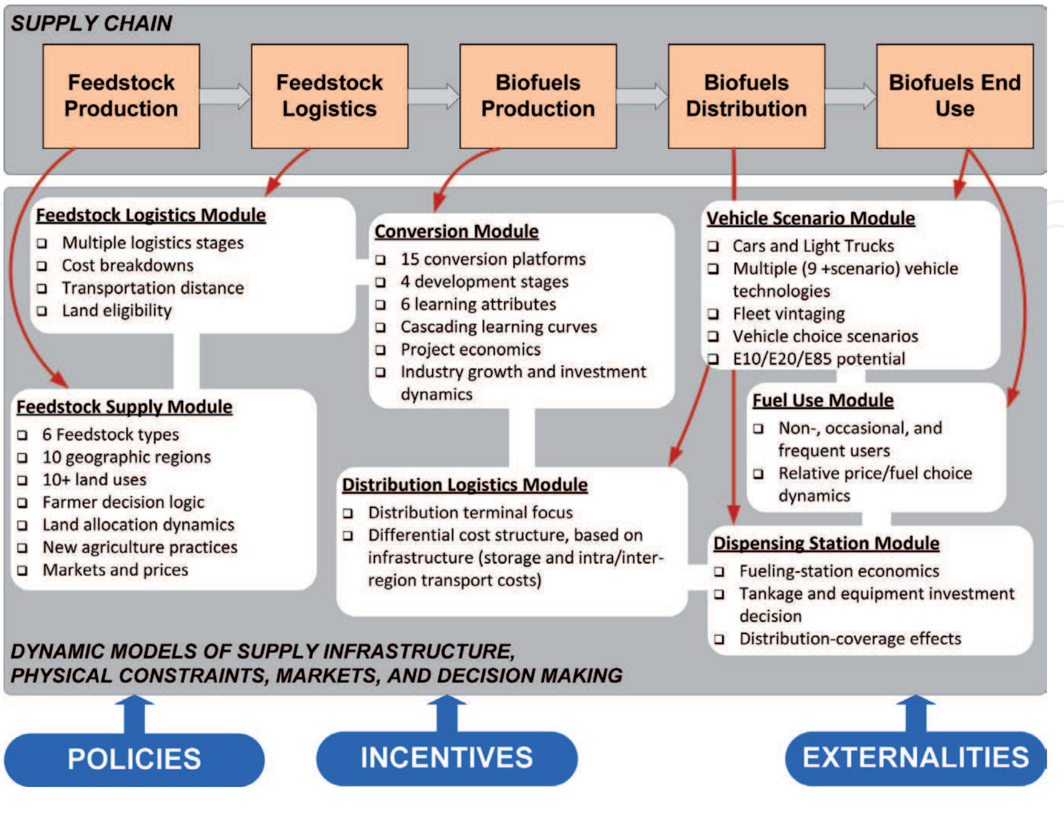


Figure 3.
The modules in the BSM represent elements of the biomass-to-biofuels supply chain.

storage, preprocessing, and transportation of biomass feedstocks from the field (or forest) to the biorefinery. The conversion module represents more than a dozen biofuel conversion technologies at pre-commercial and commercial scales. In the model, the biofuel produced in the conversion stage is then distributed to dispensing locations and end users. The model is solved numerically at a sub-monthly level and typically reports annual output for the 30–40-year timeframe. Modules receive and react to information in a response to, among other factors, industrial learning, project economics, installed infrastructure, consumer choices, and investment dynamics. The model is geographically stratified using the 10 USDA farm production regions [14] as a basis, which facilitates analysis of regional differences in key variables.

2. Modeling approach

We used the BSM to examine the impacts of (1) feedstock format and logistics, (2) biorefinery economies of scale, and (3) the impacts of shared industrial learning between fuel production technologies. In order to understand potential synergies between logistics, scale, and shared learning we modeled 10 combinations of feedstock logistics and economies of scale (**Table 1**). The feedstock formats and logistics considered include bale-based and advanced densified formats. At present, in the United States, the advanced densified logistics system is under development and we do not yet know the mechanism(s) for how these innovations may infuse into the broader market. Because of this, we model the transition from the current bale-based system to the advanced densified system based on the extent to which a commercial-scale industry has taken hold within a given region. In other words, the market demand has to be sufficiently large before large-scale investment in advanced logistics systems is warranted. Therefore, the transition to an advanced densified feedstock system is based on the number of commercial-scale biorefineries that are constructed within a given region during a model simulation. It should be noted that this study is not intended to assess the mechanism by which the biofuels industry transitions to more advanced feedstock logistics systems, but instead is focused on the system-level impact of the different feedstock logistics systems. The feedstock logistics systems modeled in this study are: Bale—feedstock is delivered to the biorefinery from within a 50-mile radius and is harvested using conventional

Combination	Format	Economies of scale	Shared learning
1	Bale	1	0
2	Densified A	1	0
3	Densified B	1	0
4	Densified A	≤2.5	0
5	Densified B	≤2.5	0
6	Bale	1	1
7	Densified A	1	1
8	Densified B	1	1
9	Densified A	≤2.5	1
10	Densified B	≤2.5	1

Table 1.
Feedstock format and economies of scale combinations explored in this study.

agricultural equipment and transported via truck in large round bales; Densified *A*—feedstock is harvested and collected using advanced equipment and is densified and delivered to a centralized depot from which the refinery receives feedstock, transition to an advanced system in which feedstock is harvested and collected using advanced equipment begins once the of one commercial-scale biorefinery (i.e. capable of processing 2,000 dry Mg per day) is constructed in the region; and Densified *B*—transition to an advanced system in which feedstock is harvested and collected using advanced equipment begins once five commercial-scale biorefineries (i.e. capable of processing 2,000 dry Mg per day) are constructed within a given region. We explored the impact of economies of scale by (1) holding the biorefinery scale constant at 2,000 dry Mg per day and (2) allowing the biorefineries to be constructed up to 2.5 times the base design case throughput of 2,000 dry Mg per day.

Shared learning (also known as spillover learning) is the process by which proximate industries have mutually beneficial conditions from accrued industrial learning (learning by doing). The process of industrial learning and shared learning has been documented in the literature [15, 16]. Examples of shared learning include knowledgeable employees working for different companies or different processes that use a technology purchased from a third party, movement of employees between firms, government-sponsored research being published in the open literature, informal sharing and/or trading of information through professional societies/conferences, and patents. In this study we explore two scenarios—(1) no shared learning between similar processes, (2) shared learning between similar processes (e.g., thermochemical processes learn from one another, biochemical processes learn from each other).

For this study, background model conditions include modeling incentives that are currently in-place and allowing them to end according to their legislative schedules. Specifically, we include the Low Carbon Fuel Standard of California, RIN credits, and the Biomass Crop Assistance Program [6, 17, 18]. For each of these we use historical data and allow them each to expire according to their respective schedules. The results and implications presented in this study should be viewed in the context of this minimal incentive environment.

3. Insights

3.1 Feedstock logistics and economies of scale

Insights reported herein should be considered in the context of the US Energy Information Administration's Reference oil price scenario. Overall, the impact of economies of scale is modest (**Figure 4**). However, the impact of feedstock format and logistics system is salient. The impact of feedstock format and logistics, without spillover learning, are shown in **Figures 5** and **6**. Moving from the status quo bale-based feedstock system to a densified advanced logistics system (Densified A and B) can facilitate higher volumes of feedstock production in response to higher demand for biofuels. Densified feedstock formats can be transported over longer distances, at lower costs, than bale-based systems, thus opening up larger areas of collection, enabling higher-throughput refineries, helping to insulate the system against risks associated with feedstock procurement (e.g., regional supply shocks such as those caused by drought, flooding, pests, etc.). Comparing simulations from the Densified A to those from Densified B, there is a clear advantage to moving to a densified feedstock supply system earlier in the simulation (Densified A transitions after construction of one commercial-scale facility whereas Densified B transitions after five commercial-scale facilities are constructed). Comparing feedstock and biofuel production levels, the system under the Densified A scenario begins growth earlier and reaches a sustained

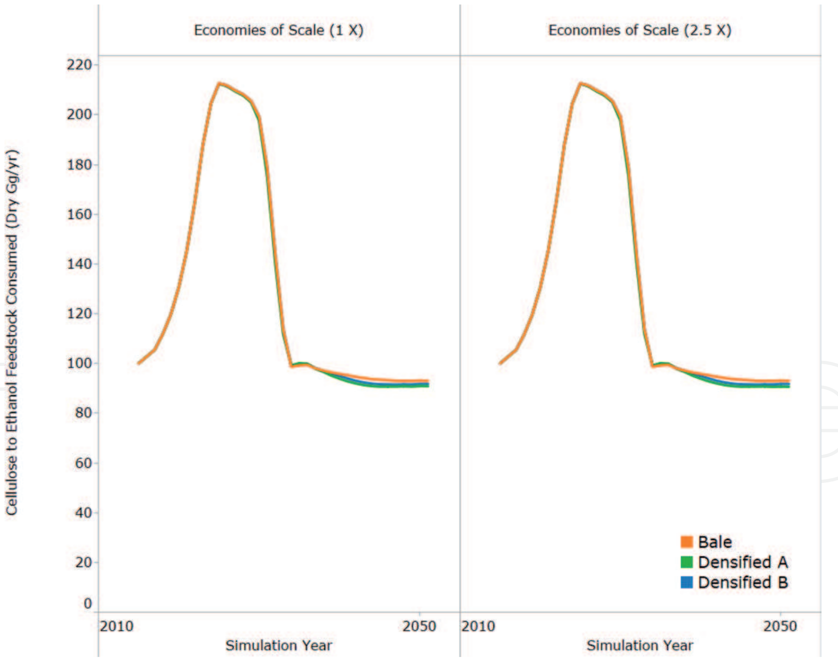


Figure 4.
Simulated cellulosic feedstock production for a 35-year period, in the United States, with and without economies of scale. Feedstock production volumes for three feedstock format and logistics systems. Bale—feedstock is delivered to the biorefinery from within a 50-mile radius and is harvested using conventional agricultural equipment and transported via truck in large round bales; Densified A—feedstock is harvested and collected using advanced equipment and is densified and delivered to a centralized depot from which the refinery receives feedstock, transition to an advanced system in which feedstock is harvested and collected using advanced equipment begins once the of one commercial-scale biorefinery (i.e., capable of processing 2000 dry mg per day) is constructed in the model; and Densified B—transition to an advanced system in which feedstock is harvested and collected using advanced equipment begins once the construction of five commercial-scale biorefineries (i.e., capable of processing 2000 dry mg per day) is constructed in the model.

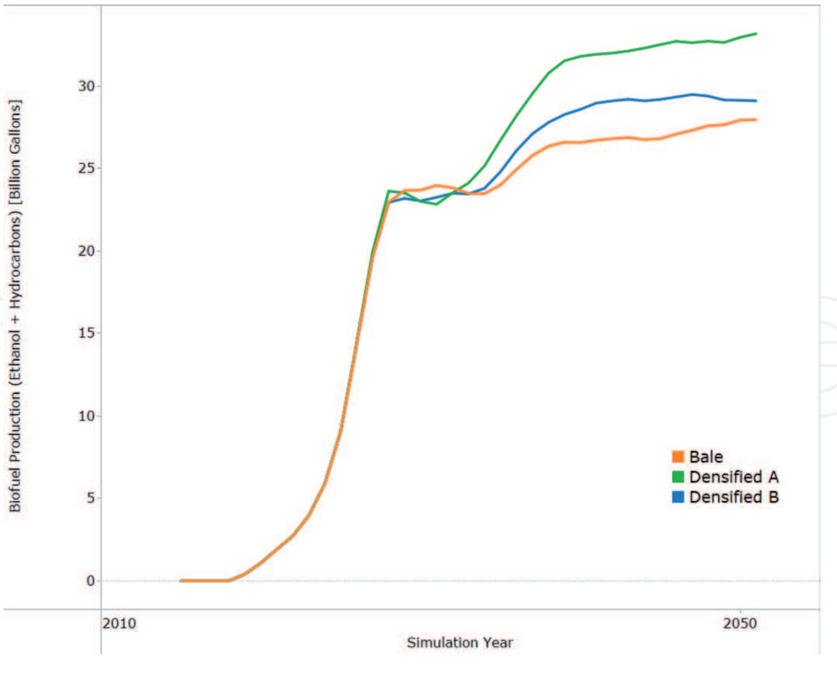


Figure 5.
Simulated cellulosic biofuel (ethanol and hydrocarbons) production for a 35-year period, in the United States. Fuel production volumes are shown for three feedstock format and logistics systems. Bale—feedstock is delivered to the biorefinery from within a 50-mile radius and is harvested using conventional agricultural equipment and transported via truck in large round bales; Densified A—feedstock is harvested and collected using advanced equipment and is densified and delivered to a refinery, transition to an advanced system in which feedstock is harvested and collected using advanced equipment begins once the of one commercial-scale biorefinery (i.e., capable of processing 2000 dry mg per day) is constructed in the model; and Densified B—transition to an advanced system in which feedstock is harvested and collected using advanced equipment begins once the construction of five commercial-scale biorefineries (i.e., capable of processing 2000 dry mg per day) is constructed in the model.

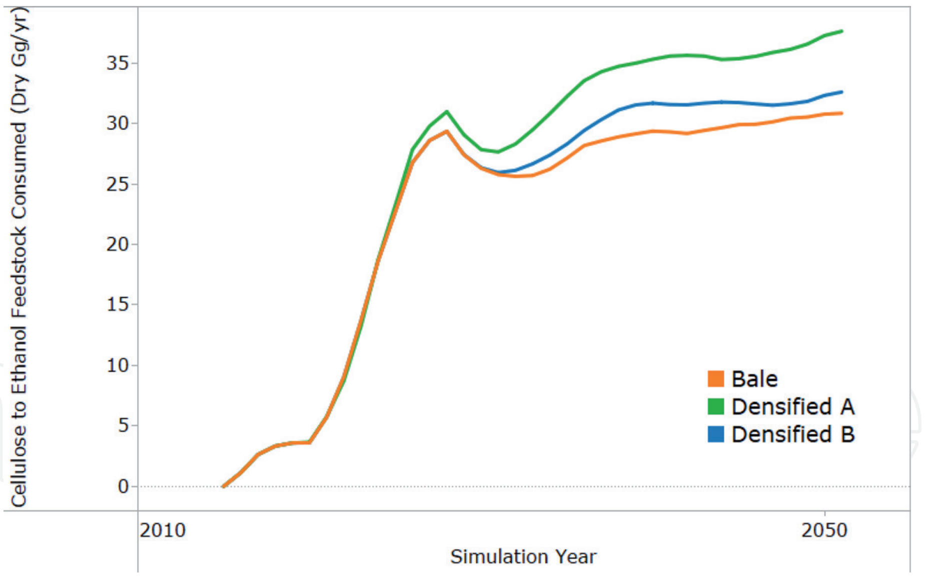


Figure 6.
Simulated cellulosic feedstock production for a 35-year period, in the United States. Feedstock production volumes for three feedstock format and logistics systems. Bale—feedstock is delivered to the biorefinery from within a 50-mile radius and is harvested using conventional agricultural equipment and transported via truck in large round bales; Densified A—feedstock is harvested and collected using advanced equipment and is densified and delivered to a refinery, transition to an advanced system in which feedstock is harvested and collected using advanced equipment begins once the of one commercial-scale biorefinery (i.e., capable of processing 2000 dry mg per day) is constructed in the model; and Densified B—transition to an advanced system in which feedstock is harvested and collected using advanced equipment begins once the construction of five commercial-scale biorefineries (i.e., capable of processing 2000 dry mg per day) is constructed in the model.

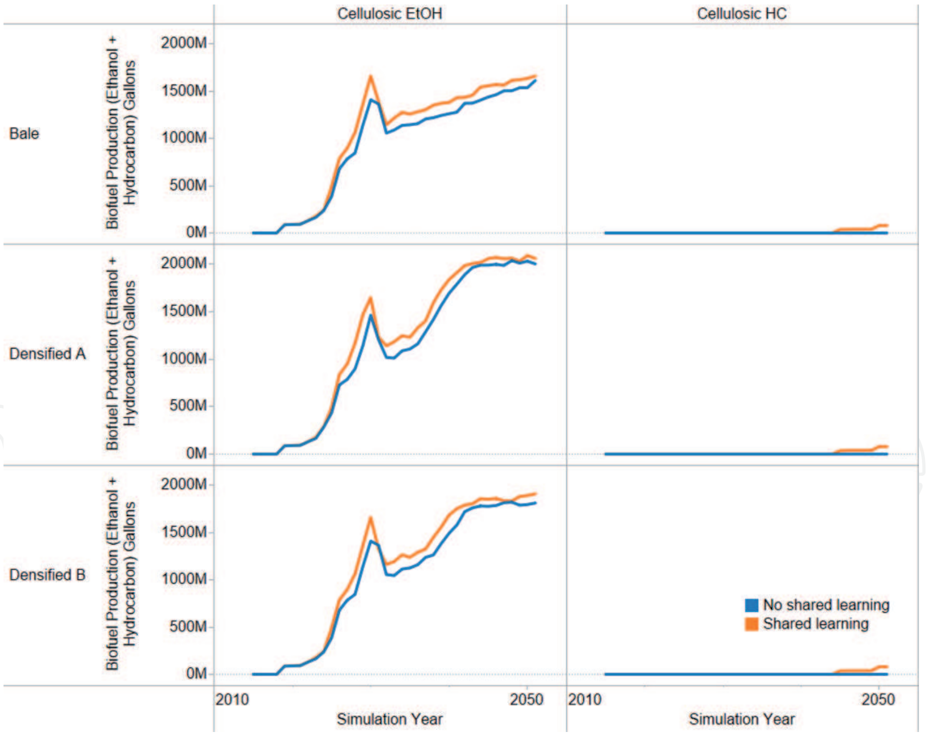


Figure 7.
Simulated cellulosic ethanol and hydrocarbon production for a 35-year period in the United States, showing impact of spillover (or shared) learning across technology pathways and for three feedstock format and logistics systems. Bale—feedstock is delivered to the biorefinery from within a 50-mile radius and is harvested using conventional agricultural equipment and transported via truck in large round bales; Densified A—feedstock is harvested and collected using advanced equipment and is densified and delivered to a centralized depot from which the refinery receives feedstock, transition to an advanced system in which feedstock is harvested and collected using advanced equipment begins once the of one commercial-scale biorefinery (i.e., capable of processing 2000 dry mg per day) is constructed in the model; and Densified B—transition to an advanced system in which feedstock is harvested and collected using advanced equipment begins once the construction of five commercial-scale biorefineries (i.e., capable of processing 2000 dry mg per day) is constructed in the model.

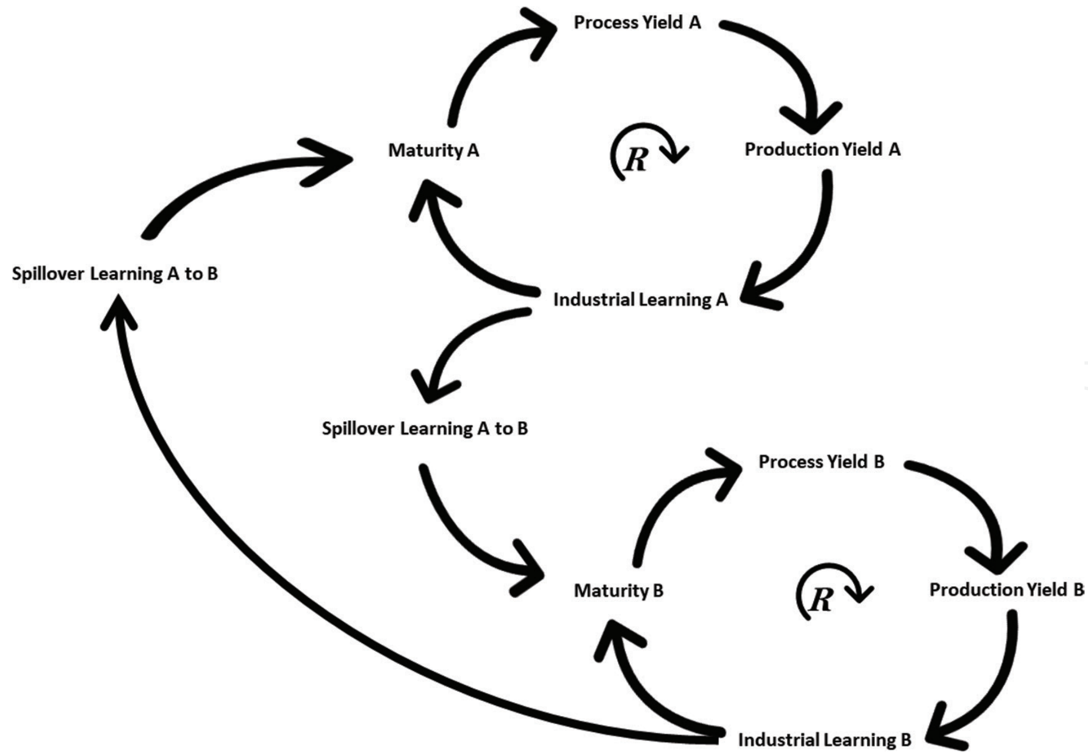


Figure 8.
Causal loop diagram illustrating the reinforcing (positive) feedback loop among learning, maturity, investment attractiveness, and production, for two generic fuel production pathways (A and B). Note: (+) sign at arrowheads means that input and output tend to vary in the same direction; (−) sign at arrowhead means that output varies in output varies in opposite direction from input.

higher level of output. Industrial learning is a high-leverage nonlinear system parameter in which small changes early on result in large differences later in the simulation.

3.2 Shared learning

Simulated lignocellulosic biofuel production with and without shared learning, in the United States, is shown in **Figure 7**. Shared learning has been shown to exert [15, 16]. Shared learning has a marked impact on both cellulosic ethanol and hydrocarbon production. In the latter case, without shared learning, cellulosic hydrocarbons do not experience any appreciable production. Industrial learning is a key system lever and acts on the system through a positive feedback loop, whereby higher learning rates result in stronger relationship between production and growth in maturity, which increases the investment attractiveness. A technology that attracts more initial investment will then have more fuel production, with associated learning advances. This increase in maturity, and the associated improvements in cost and performance, raises the attractiveness of future investment (**Figure 8**).

4. Summary

A key theme from this study as well as from the work performed over the last decade is the importance of the movement of the system toward maturation, both in terms of the supply system and the conversion processes. On the feedstock supply side, advanced supply systems have advantages relative to bale in terms of transport, handling, storage, and losses. From the conversion process perspective, mature processes imply lower investment risk, better yields, and better process economics.

Our simulations suggest that it is beneficial for the feedstock supply system to transition away from short-distance (i.e., <50 miles) transport of bales and/or any other low-density formats, to a densified system modeled after the modern commodity grain system, using larger collection radii and centralized depots. Our simulations also suggest that the temporal component is substantial—earlier transition to a high density, commodity logistics system leads to the largest gains in cellulosic feedstock production and utilization—in our model, densified A scenario accelerates maturation of the feedstock supply 21. By the end of our simulation, the Densified A scenario results in ~15% greater feedstock production.

Industrial learning (learning by doing) is a key system lever in developing industries such as the biofuel/bioproducts industry. Because the industrial learning process follows a positive feedback loop, small perturbations have large system impacts. Shared learning amplifies the industrial learning process. Advances across similar industries are shared among the industries, resulting in a substantial positive impact on the industry. A potential extension would be to look at what percent of learning needs to be shared across similar technologies for a substantial increase in overall biofuel production.

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References

[1] Energy Tax Act of 1978 Public Law 95-618, 92 Stat. 3174. https://www.govinfo.gov/app/details/STATUTE-92/STATUTE-92-Pg3174

[2] U.S. Energy Information Administration. Fuel Ethanol Overview, 1981-2012. 2014. https://www.eia.gov/petroleum/data.php

[3] U.S. Environmental Protection Agency. State Actions Banning MTBE (Statewide) (No. EPA420-B-04-009). 2004. https://nepis.epa.gov/Exe/ZyNET.exe/P1004KHN.TXT?ZyActionD=ZyDocument&Client=EPA&Index=2000+Thru+2005&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5Czyfiles%5CIndex%20Data%5C00thru05%5CTxt%5C00000021%5CP1004KHN.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL

[4] Energy Policy Act of 2005. Public Law 109-58. https://www.govinfo.gov/app/details/PLAW-109publ58

[5] U.S. Environmental Protection Agency. Gasoline|Methyl Tertiary Butyl Ether (MTBE)|US EPA [WWW Document]. 2013. Available from: http://www.epa.gov/mtbe/gas.htm

[6] H.R. 6 (110th). Energy Independence and Security Act of 2007. Pub L No. 110-140, 121 Stat 1492. 2007. https://www.govinfo.gov/app/details/PLAW-110publ140

[7] Bacovsky D, Ludwiczek N, Ognissanto M, Worgetter M. Status of Advanced Biofuels Demonstration Facilities in 2012: A Report to IEA Bioenergy Task 39 (No. T39-P1b). International Energy Agency; 2013. http://task39.sites.olt.ubc.ca/files/2013/12/2013_Bacovsky_Status-of-Advanced-Biofuels-Demonstration-Facilities-in-2012.pdf

[8] U.S. Department of Energy. Bioenergy Technologies Office Multi-Year Program Plan. 2013. http://bioenergy.energy.gov/pdfs/mypp_may_2013.pdf

[9] U.S. Department of Agriculture. Biorefinery Assistance Program [WWW document]. 2015. Available from: http://www.rd.usda.gov/programs-services/biorefinery-assistance-program

[10] Agricultural Act of 2014. Pub L No. 113-79, 128 Stat 649. February 4, 2014. https://www.govinfo.gov/content/pkg/PLAW-113publ79/pdf/PLAW-113publ79.pdf

[11] Peterson S, Peck C, Stright D, Newes E, Inman D, Vimmerstedt L, et al. Overview of the Biomass Scenario Model. NREL/CP_6A20-60172. 2015. https://www.nrel.gov/docs/fy15osti/60172.pdf

[12] Isee Systems. Lebanon, NH. Available from: https://www.iseesystems.com

[13] Sterman J. Learning from evidence in a complex world. American Journal of Public Health. 2006;**96**(3):505-514

[14] U.S. Department of Agriculture, Economic Research Service. U.S. Farm Resource Regions. Retrieved from Agricultural Resource Management Survey (ARMS): Resource Regions. 2014. Availabe from: http://webarchives.cdlib.org/wayback.public/UERS_ag_1/20111128195215, http://

www.ers.usda.gov/Briefing/ARMS/resourceregions/resourceregions.htm#new

[15] McDowell R. Learning by doing and spillovers in renewable energy [Ph.D. thesis]. Massachusetts Institute of Technology, Department of Economics; 2016

[16] Irwin DA, Klenow PJ. Learning-by-doing spillovers in the semiconductor industry. Journal of Political Economy. 1994;**105**(6):1200-1227

[17] Executive Order S-01-07. State of California, Office of the Governor. 2007. Available from: https://www.arb.ca.gov/fuels/lcfs/eos0107.pdf

[18] Public Law 110-246-June 18, 2008. The Food, Conservation, and Energy Act of 2008. Available from: https://www.agriculture.senate.gov/imo/media/doc/pl110-246.pdf