U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Co-Optimization of Fuels & Engines

ASSERT FY16 Analysis of Feedstock Companion Markets

Co-Optima ASSERT Team

About the Co-Optimization of Fuels & Engines Project

This is one of a series of reports produced as a result of the Co-Optimization of Fuels & Engines (Co-Optima) project, a Department of Energy (DOE)-sponsored multi-agency project initiated to accelerate the introduction of affordable, scalable, and sustainable biofuels and high-efficiency, low-emission vehicle engines. The simultaneous fuels and vehicles research and development is designed to deliver maximum energy savings, emissions reduction, and on-road performance.

Co-Optima brings together two DOE Office of Energy Efficiency & Renewable Energy (EERE) research offices, nine national laboratories, and numerous industry and academic partners to make improvements to the types of fuels and engines found in most vehicles currently on the road, as well as to develop revolutionary engine technologies for a longer-term, higher-impact series of solutions. This first-of-its-kind project will provide industry with the scientific underpinnings required to move new biofuels and advanced engine systems to market faster while identifying and addressing barriers to commercialization.

In addition to the EERE Vehicle Technologies and Bioenergy Technologies Offices, the Co-Optima project team included representatives from the National Renewable Energy Laboratory and Argonne, Idaho, Lawrence Berkeley, Lawrence Livermore, Los Alamos, Oak Ridge, Pacific Northwest, and Sandia National Laboratories. More detail on the project, as well as the full series of reports, can be found at www.energy.gov/fuel-engine-co-optimization.

Availability

This report is available electronically at no cost from http://www.osti.gov/bridge.

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Abbreviations and Acronyms

AEO	Annual Energy Outlook
AFEX	Ammonia Fiber Expansion
BBL	Barrel
BETO	(U.S. DOE) Bioenergy Technologies Office
CMM	Companion Market Mode
DDGS	Dried Distillers Grain and Solubles
DML	Dry Matter Loss
DOE	U.S. Department of Energy
EIA	Energy Information Administration
GDP	Gross Domestic Product
GHG	Greenhouse Gas
Mton	Million (10^6) tons
$	U.S. Dollar at $\$_{2015}$
SI	Spark-Ignition
VTO	Vehicle Technologies Office
WTP	Willingness-To-Pay
yr	Year

Executive Summary

Purpose

Meeting Co-Optima biofuel production targets will require large quantities of *mobilized* biomass feedstock. Mobilization is critical as there is an abundance of projected biomass resources, yet little is affordable and available for purchase, let alone at desired quantity and quality levels needed for a continuous operation, e.g., a biorefinery. Therefore, Co-Optima research includes outlining a path towards feedstock production at scale by understanding routes to mobilizing large quantities of future supplies of biomass feedstock.

Continuing along the vertically-integrated path that pioneer cellulosic biorefineries have taken will constrain the bioenergy industry to high biomass yield areas, limiting its ability to reach biofuel production at scale. To advance the cellulosic biofuels industry, a separation between feedstock supply and conversion is necessary. Thus, in contrast to the vertically integrated supply chain typical of nascent biorefineries, two industries are required: a feedstock industry and a conversion industry. The split is beneficial for biomass growers and feedstock processers as they are able to sell into multiple markets. That is, depots that produce value-add feedstock intermediates that are fully fungible in both the biofuels refining and other, so-called companion markets. As the biofuel industry is currently too small to leverage significant investment in up-stream infrastructure, it requires an established (companion) market to secure demand, which reduces the risk of potential investments and makes a build-up of processing and other logistics infrastructure more likely. A common concern to this theory, however, is that more demand by other markets could present a disadvantage for biofuels production as resource competition may increase prices leading to reduced availability of low-cost feedstock for biorefineries.

To analyze the dynamics across multiple markets vying for the same resources, particularly the potential effects on resource price and distribution, the Companion Market Model (CMM) has been developed in this task by experts in feedstock supply chain analysis, market economics, and System Dynamics from the Idaho National Laboratory and MindsEye Computing.

Results Highlights

The CMM is a tool to investigate the dynamic link between raw and processed biomass markets given different demand patterns across the biofuel, animal feed, and other markets competing for processed herbaceous biomass (corn stover pellets). While the CMM is not a predictive model aimed at deriving exact quantities and prices traded in the future, it simulates a series of market dynamics and actor behavior under different paradigms including Gross Domestic Product (GDP), biofuel and companion market growth, as well as oil price developments. The main mechanism of the model is to allocate resources (i.e., raw and processed biomass) to the various markets based on their willingness-to-pay (WTP). This allows predicting actor behavior and identifying leverage points and hurdles for increased biomass mobilization.

In the biomass market, growers supply the raw biomass that is distributed across the various demand sectors including processers (pellet producers) and an aggregation of other markets that would purchase raw biomass, e.g., animal feed, or biorefineries that are using raw biomass as feedstock. In the pellet market, processers (depots) are the suppliers of pellets. The demand side includes biorefineries using pellets as feedstock, the companion market, which, in the herbaceous case is the animal feed industry, plus an aggregation of other participants (e.g., absorbents). Processers function as the bridge between the two markets.

The CMM is run from year 2016 through 2040, creating annual equilibria across both biomass and pellet markets. The initial condition (year 2016) reflects current industry levels of very limited herbaceous biomass processing (and respective low demand by the biofuels industry). The model behaves well in terms of expected market economics. For example, a drop in biomass supply increases biomass prices, which reduces the economic viability of processing and causes a respective drop in online pelleting capacity. The reduction in output then increases pellet prices, which again increases the viability of pelleting and increases demand for biomass, etc.

Key Conclusions

All runs show a cyclical market pattern reflecting delays in the system, including additional resource mobilization by growers in the biomass market and pelleting capacity changes by processers over time. The reference scenario represents a market growth of both biofuel and companion markets in-line with GDP developments. While biomass processing capacity increases over time, it does not quite reach a doubling until 2040. Simulated prices, across both biomass and pellet markets, seem to oscillate heavily around long-term equilibria (~$60 per ton for biomass and ~$95 per ton for pellets).

Comparing an individual growth of either biofuels or animal feed market (at 2.5% to 5% additional percentage points to overall GDP growth while the other one grows in-line with GDP only) indicates that the companion market mobilizes resources faster, yet prices stay lower overall. A simultaneous growth of both biofuel and companion markets increases biomass mobilization and pellet production beyond levels of any run, yet long-term pellet prices remain around $110 per ton despite large fluctuations in the short-term. This suggests that the markets do not out-compete each other for resources until much larger feedstock deployment levels are reached. The sensitivity scenarios indicate that neither oil price nor GDP developments drastically influence overall outcomes despite a modeled cross-elasticity between biofuel and oil prices.

Across all scenarios, both biomass and pellet markets grew with relatively stable prices over the long-term, buffered through pelleting capacity changes. Hence, we can initially conclude, based on these results, that the animal feed market does not threaten a development of a second generation biofuels industry reliant on corn stover in terms of resource competition or price hikes. Rather, as our model runs show, larger deployment/mobilization levels are achieved when we assume a steady growth in the companion market (animal feed in this case). The only situation in which this would not hold true is if the market is short of biomass; a situation that may arise in the future when biofuel production levels are significantly higher than today. At this point however such a situation is unlikely in the herbaceous biomass market as ample resources are still available and yet need to be mobilized, and the companion market of animal feed is expected to be limited in overall growth until 2040.

In FY17, an extension of the CMM is planned to incorporate woody biomass and respective companion markets for wood pellets such as co-firing (domestic and international), heating, absorbents, and animal bedding.

1 CONTEXT

1.1 Co-Optimization of Fuels and Engines

Co-Optimization of Fuels & Engines (Co-Optima) is a research and development program with collaboration among seven national laboratories supported by the Bioenergy Technologies and Vehicle Technologies Offices (BETO, VTO) of the U.S. Department of Energy (DOE). The objective of the program is to co-optimize fuels and engines with the aim of exploiting unique properties of biomass-derived fuels that can boost engine performance. The overarching hypothesis of Co-Optima is that it is possible to determine the critical fuel properties that enable advanced engine designs and, as a result of this understanding, co-develop engines and biomass-derived fuels that will offer improved performance and efficiency.

Through the process in Figure 1-1, Co-Optima will provide industry stakeholders the scientific underpinnings required to move new fuels and advanced engine systems to market faster. In summary, after desirable fuel properties are catalogued and measured for various fuel candidates, research will reveal how fuel properties influence engine design and performance. At the same time, Co-Optima will develop computational tools that will reduce the need for experiments to test new fuels' engine performance and will examine market factors that may influence the market penetration potential of new fuels. Finally, an objective of Co-Optima is to quantify reductions in greenhouse gas (GHG) emissions, fossil energy consumption, and transportation costs to consumers as a result of this effort.

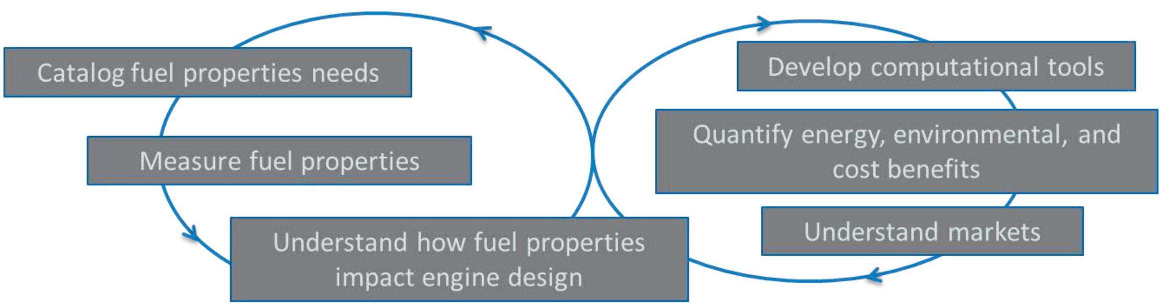

Figure 1-1. Research activities in Co-Optima

Co-Optima is divided into two thrusts. The first seeks to develop a biomass-derived fuel that would be used in spark ignition (SI) engines and use techniques such as downsizing and boosting engines to take advantage of unique properties of biomass-derived fuels, such as higher octane. Ethanol is already used in the capacity of adding octane to gasoline and it may be that high ethanol blends come to the forefront as the Thrust I fuel that can best improve SI performance once SI engines are modified to work with high-level ethanol blends. Thrust I is considering many potential fuel candidates in addition to ethanol; after eighteen months, the Co-Optima effort will assess the strongest high-octane blendstock candidates that could be the Thrust I fuel. If a different candidate comes to the forefront, more research and development will be necessary. Thrust II of Co-optima aims to identify fuels best suited for advanced compression ignition engines. Very little is known at this point about what the Thrust II fuel might look like.

1.2 Feedstock analysis within Co-Optima

The results of Co-Optima are expected to bring about reduced transportation sector GHG emissions and fossil energy consumption, through a combination of low carbon fuels and higher efficiency engines. However, the production of high volumes of biofuels to support meeting Co-Optima targets will require high volumes of biomass feedstock, and therefore Co-Optima research includes outlining a path towards feedstock production at scale by understanding routes to mobilizing large quantities of biomass feedstock. Co-Optima research provides an analysis of the tradability of feedstock intermediates, examining the influences of co-products and competing feedstock markets on the mobilization of resources and the scale-up of the feedstock supply industry. Traditional feedstock supply system analysis (i.e., resource assessments plus logistics engineering for cost/quality of scalable resources) was expanded to characterize the merchantability of feedstock intermediates, which is preprocessed biomass that could be sold into multiple markets. This addition is a risk and opportunity analysis, which identifies co-product feedstock markets and assesses whether and to what extent these markets and different types of feedstock intermediates could spurt the deployment of U.S. biomass resources and scale-up associated infrastructure to meet Co-Optima impact targets. Note that resource assessments (USDOE 2011, USDOE 2016a) underlying DOE biofuels production targets (USDOE 2016b) assume the existence of feedstock market drivers which generate the biomass demand, but a business case around generating those drivers prior to Co-Optima. This analysis is the first attempt to test some scenarios that would create the necessary market drivers to mobilize the feedstock resources needed to meet DOE biofuels production targets.

2 PROBLEM DESCRIPTION

2.1 Feedstock Supply System Types and Their Limitations

Feedstock variability with respect to quantities and resulting changes in supply costs (i.e., prices) are largely associated with irregular harvest volumes, linked to inclement weather (e.g., droughts) and other conditions affecting harvest timing (Kenney *et al.* 2013). Variations in quality, particularly for agricultural residues, are linked to natural, compositional and introduced variability. Empirical data for corn stover, for example, suggests that the harvest year has the strongest effect on compositional variation (e.g., physiological ash or carbohydrate content), followed by location and plant variety (Templeton *et al.* 2009). Harvest practices add an additional layer of complexity. For instance, single-pass harvest where combine and baling operation are done at once and the residue does not touch the ground, ash contamination (i.e., introduction of soil) is significantly reduced in comparison to conventional, multi-pass harvest where a separate combine and baling operation takes place (Hess *et al.* 2009).

To supply a national or global bioeconomy, logistics and market structures will need to address and cope with the spatial, temporal, and compositional variability of biomass. Only a reduction of this variability, i.e., a constant, large quantity supply within quality specifications, can guarantee stable and high conversion yields necessary for a viable business operation such as a cellulosic biorefinery relying on these supply streams.

At present however, pilot scale cellulosic biofuel production facilities rely on a vertically integrated feedstock supply systems designed to support traditional agricultural and forestry industries, hereafter referred to as conventional systems, where feedstock (predominantly agricultural residues such as wheat straw and corn stover) is procured through contracts with local growers, harvested, locally stored, and delivered in low-density format to the nearby conversion facility. These conventional systems were designed to support traditional agricultural and forestry industries. The conventional system has been demonstrated to work in a local supply context within concentrated supply regions (e.g., the U.S. Corn Belt).

Different analyses (Hess *et al.* 2009, Argo *et al.* 2013, Jacobson *et al.* 2014a, Muth *et al.* 2014) suggest that the conventional system may not be able to achieve high-volume, low-cost feedstock supply outside of high biomass yield regions and could even encounter issues in highly productive areas in some years due to inclement weather (e.g., drought, flood, heavy moisture during harvest, etc.). High volume, low-cost feedstock supply, however, is a prerequisite for the advanced biofuel industry to scale-up and become (more) competitive with fossil fuel derived alternatives. Furthermore, feedstock supply uncertainties tend to increase the risk, which – to some extent – has limited the cellulosic biorefinery concept from being broadly implemented (Gustafson 2008, Kenkel and Holcomb 2009, Babcock *et al.* 2011). Advanced feedstock design systems (Searcy *et al.* 2015) introduce methods to reduce feedstock volume, price, and quality supply uncertainties. Advanced systems are based on a network of distributed biomass preprocessing centers (depots) and centralized terminals/elevators. In this system, depots are located close to the biomass resource while shipping and blending terminals are located in strategic logistical hubs with easy access to high bulk transportation systems (e.g., rail or barge shipping).

A fundamental difference between the two logistics systems is that the conventional system relies on existing technologies and agri-business systems to supply biomass feedstocks to pioneer biorefineries and requires biorefineries to adapt to the diversity of the feedstock (e.g., square or round bales, silage, etc.). The advanced system on the other hand emulates the current grain commodity supply system, which manages crop diversity at the point of harvest and at the storage elevator, allowing subsequent supply system infrastructure to be similar for all resources (Searcy and Hess 2010, Searcy *et al.* 2015). Via preprocessing (at the depot) and blending (at the terminal), the variability within the system is reduced significantly in terms of quality and quantity, thus also stabilizing cost/price projections.

2.2 Potential Role of Processing Depots in Future Supply Systems

Pelleting (i.e., densification and stabilization) has enabled the forest industry to trade woody biomass in large volumes internationally. This is a transition from the previously dominating trade of wood chips, having moisture contents of up to 50%, which could only be traded locally or cross-border for low-value markets such as energy, or needed to be of high quality to access distant, higher value markets such as pulp and paper.

Due to the low-density format of agricultural residues, traditional thinking suggests cellulosic biorefineries are best suited to be located near the field and in high biomass yielding areas, and should be designed to handle single feedstock of similar format such as wheat straw bales or corn stover (Hess *et al.* 2009). Regional preprocessing near the point of production however, through a network of depots, would allow biorefineries to be built almost anywhere, including lower yield areas (Argo *et al.* 2013). This would not only allow biorefinery siting based on other, often very relevant criteria, including tax incentives, infrastructure, trained labor, etc., but may also prevent potential resource competition among biorefineries.

Individual depots could not only increase energy and bulk density, but also include quality management to achieve compositional homogeneity and specific cost targets by blending multiple feedstock. A network of depots could supply biorefineries with sufficient feedstock (volume), possibly from different biomass in a variety of forms (e.g., square and/or round bales, chipped, bundled, raw, etc.). Depots would have a continuum of functionality, from a "standard depot" that would, at a minimum, include particle size reduction, moisture mitigation, and densification, to "quality depots" which may include additional preprocessing steps such as leaching, chemical treatment, or washing (Lamers *et al.* 2015a).

The first depots to emerge would likely focus on improving feedstock stability (for storage), increase bulk density (for transport), improve flowability (for stable in-feed rates), and reduce dry matter loss (DML). Influencing feedstock quality is a result of these activities rather than a primary target of the operation. Passive quality management is optionally possible via feedstock blending.

Indirect quality impacts include, for example, drying, which is done to prevent DML. Consistent moisture levels however also benefit conversion efficiency and improve in-feed. Pelleting is done to increase bulk density and transportability, a key aspect in de-risking the feedstock supply system. At the same time, using pelleted feedstock also reduces contamination as it sterilizes (through compression and drying). Small diameter components, including impurities such as soil are drained in the liquor stream of the conversion pretreatment steps (e.g., deacetylation).

To address feedstock stability, bulk density, and flowability issues, depot process flow would likely include particle size reduction, moisture mitigation and densification. An example of an early-stage depot is a common pelleting process involving two stage size reduction (grinding), drying, and pelleting. Additional modifications could be made to make the process more efficient. An example of such modifications could include a high moisture pelleting process; which varies in process sequence, dryer type and size compared to the common pelleting process.

As more depots enter the marketplace, they would evolve from focusing on addressing format and creating a uniform product, to actively addressing feedstock quality aspects specific to the end-use market it targets, e.g., cellulosic biorefineries, animal feed, or the heat and power sector. It produces enhanced feedstock (with lower contamination levels) or even process intermediates and thus reduces the pretreatment requirements at the client facility (Jacobson *et al.* 2014b, Lamers *et al.* 2015b). To match its final markets, various kinds of pretreatment steps are possible within these "quality" depots. Thermal pretreatment technologies (e.g., torrefaction) create feedstock with structural homogeneity and superior handling, milling, and co-firing properties. Chemical pretreatment changes the composition and structure of the biomass. This reduces the energy required to grind or densify the feedstock, improves flowability and storage stability, and removes contaminants detrimental to downstream biorefinery processes.

An example of addressing quality at the depot is the ammonia fiber expansion (AFEX) process. AFEX is a promising pretreatment that involves an ammonia-based process resulting in physical and chemical alterations to lignocellulosic biomass that improves their susceptibility to enzymatic attack (Bals et al. 2011). As part of a depot concept, AFEX pretreatment of corn stover and switchgrass have shown to generate a higher return on investment compared to other depot configurations, e.g., wood-based pyrolysis facilities (Bals and Dale 2012). Furthermore, AFEX pellets can be sold to animal feed operations.

2.3 Merchandisable Feedstock Intermediates and Companion Markets

Feedstock supply systems are currently in a gridlock, where growers will likely not invest in a depot due to a slow market growth of biorefineries and the current, limited demand from a single, regional client (biorefinery). On the other hand, biorefineries continue to be limited in expanding their operations in size and number due to high feedstock supply variability in quantity, quality, and price. Thus, a market for feedstock intermediates generated by decentralized depots will not emerge by itself. Rather, a transition strategy is required to break the current development gridlock.

The advanced system is seen as a mature logistical and market structure in which multiple depot types and transloading terminals operate in a high volume (i.e., liquid) and competitive feedstock market to serve multiple industries in the bioeconomy. A stepwise introduction of the depot concept is seen as an organic transition towards this vision; yet depots alone do not represent the advanced supply system

A fundamental part of initiating (pilot-) depot operations is to establish the value proposition to the biomass grower, as the biomass becomes available to the market place only through mobilization. Mobilization is creating the economic drivers required to catalyze the infrastructure investment and biomass resource development investment necessary to transition biomass from available resource, i.e., what is on the field, to a merchandisable resource, i.e., what is available for sale.

The current paradigm for developing feedstock supply systems is that it requires a market pull (i.e., new biorefineries) to mobilize the resources; an assumption that is consistent across current DOE resource assessments (USDOE 2011, USDOE 2016a). A feedstock supply industry that would independently mobilize biomass by producing commodity-type feedstock intermediates that are fungible across multiple markets creates a market push that will de-risk and accelerate deployment of bioenergy technologies. Accomplishing this would still require a market pull, but the initiation comes via existing (non-biofuel) markets. Thus, the need for multiple markets (Figure 2-1). In other terms, the mobilization of biomass into the marketplace (where they become available to any demand party) will happen first via **companion markets**. Hence, depots produce value-add feedstock intermediates that are fully fungible into both the companion and the biofuels market. The stronger, established companion market mobilizes the biomass resource and helps establish logistics and supply structures upon which the second generation biofuels market can rely. Examples of such markets are biopower or animal feed operations (Figure 2-1). However, a common concern and pushback to this theory is that more demand by other markets will be a disadvantage for biofuels production as resource competition may increase prices leading to reduced quantities of available low-cost feedstock.

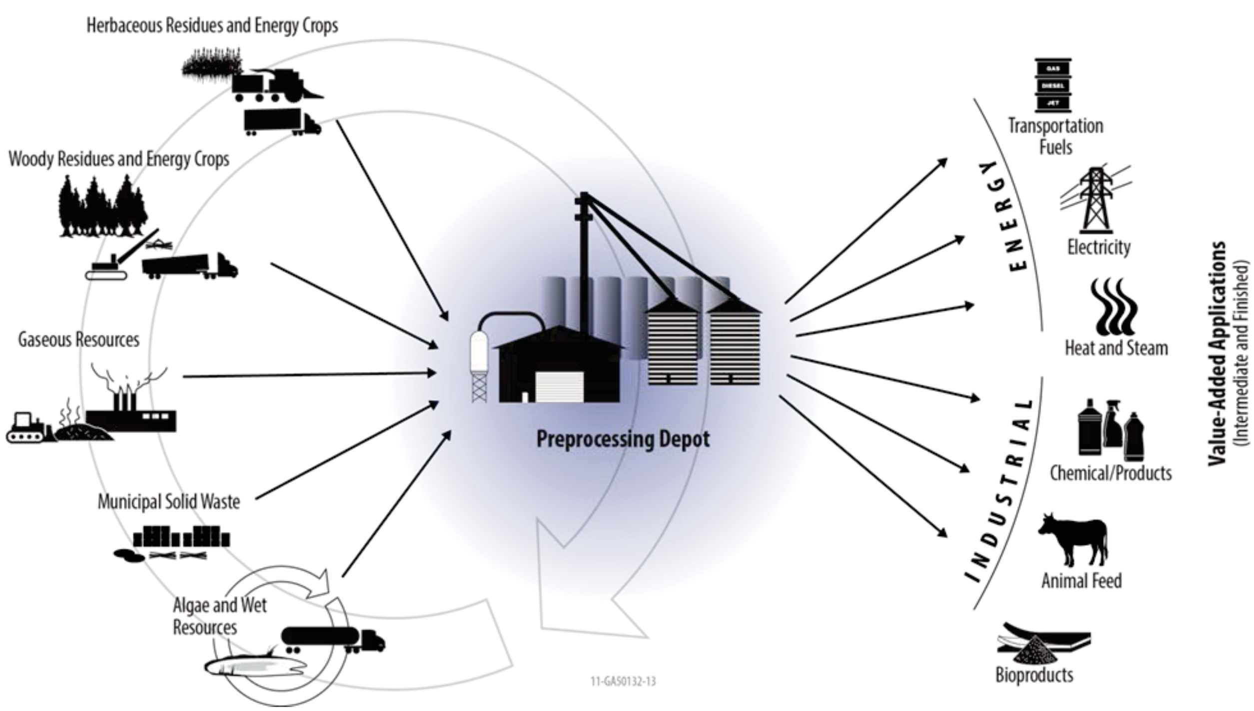

Figure 2-1. Modular depot concept illustrated for multiple biomass input streams and market options for merchandisable feedstock intermediates

3 OBJECTIVE AND SCOPE

3.1 Objective and Research Questions

Commodity-type feedstock intermediates have the potential to enable the biofuel industry to become a sustainable and viable economic industry independent from the biofuels industry by supplying a reliable, stable feedstock which would reduce risk, improve performance and reduce production costs. However, there is currently insufficient demand from the biofuels industry to mobilize significant amounts of densified lignocellulosic biomass. While more mature markets such as animal feed (herbaceous biomass) or biopower (woody biomass) have the potential to drive capacity expansions across the densification industry, it remains uncertain whether there will be enough low-cost densified biomass available to support a growing biofuel industry.

The objective of this work is to provide insight into the dynamics of resource competition across multiple industries, feedstocks, and regions, and help identify strategies that may enable biofuel production at scale. It focuses on developing a dynamic simulation model identifying business opportunities to help explore the impacts of multiple markets for densified, stable, flowable, commodity-type feedstock intermediates. The research employs a holistic or systems view of the biofuel market in competition for biomass with other industries such as animal feed.

The main research questions are:

1. With competing industries vying for the same biomass commodity, would biofuels be able to economically compete for the commodity feedstock, or will the other industries consume all of the material?
2. Will mature markets such as animal feed, soil amendments, or foreign demand and the development of a densified material aid the biofuel industry or strand the biorefineries without any feedstock?
3. What are the policies that would enable the biofuel industry to succeed in the face of uncertainty with respect to feedstock supply?

3.2 Processing Technology Assumption

The selected processing technology is pelleting, which is one of the least-cost technologies to achieve commodity-type characteristics required for market expansion and feedstock deployment at scale including feedstock stability (for storage), bulk density (for transport), flowability (for stable in-feed rates), and DML reduction. Influencing feedstock quality is a result of these activities rather than a primary target of pelleting. Passive quality management is optionally possible via feedstock blending. We acknowledge that pelleted feedstock may not be the most desirable form of input material for all conversion pathways, including biochemical routes which typically prefer wet material.

4 METHODOLOGY

4.1 Market Economics: Dynamic Demand-Supply Relationships

Figure 4-1 portrays the main market economics that make up the dynamic demand and supply relationships between the biomass and the pellet market. It is critical to note that there are two basic types of **demand**. Price change induced demand changes reflect movement up and down the *current* demand curve. Changes in non-price factors, e.g., new entries to the market or introduced substitutions result in shifts of the *entire* demand curve. A **supply** curve captures the marginal cost of production for each additional unit produced. As with demand, supply has two distinct forms and terms. *Quantity supplied* changes with price variation whereas *Supply* is influenced by external factors, e.g., changes in technology, shifts in input prices. There are two reasons why quantity supplied increases with higher prices: Due to higher prices, higher-cost producers will start production/ supply, and current producers are willing to produce more product. A market equilibrium is established when supply matches demand.

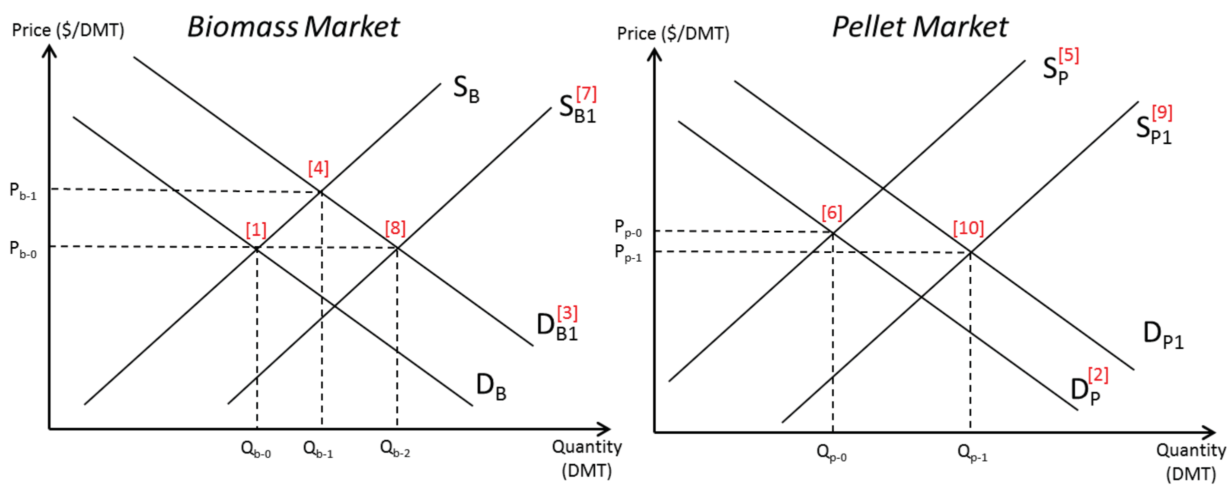

Figure 4-1. Demand-supply curve dynamics

These following steps outline how the biomass market gives rise to the pellet market. Numbers in square brackets refer to specifics in Figure 4-1. The system begins with the biomass market in equilibrium where Q_{b-0} units of biomass are sold at price P_{b-0} [1]. Assuming a competitive market, P_{b-0} is (close to) the unit cost of producing a unit of biomass. An emerging biorefinery industry or a companion market thereof would create a new demand D_p for herbaceous pellets [2]. At first, as there is no herbaceous pellet supply yet, pellet demand goes unmet (note that this situation would be different in the wood pellet market, where a demand and supply already exist). Assuming perfect information distribution, entrepreneurs see this as a business opportunity for pelletizing biomass, creating an additional demand for biomass, which shifts the biomass demand curve to D_{B1} [3]. This shifts the equilibrium in the biomass market as the current pool of growers supplies more biomass to meet the new demand D_{B1}. As a result, the equilibrium adjusts and biomass prices have risen to P_{b-1} and the quantity of biomass traded in the market increased to Q_{b-1} [4]. Now that processors have biomass feedstock for pelleting, a pellet supply curve is established S_P [5]. This generates a first pellet market equilibrium with an initial pellet price P_{p-0} and quantity traded Q_{p-0} [6].

How the markets evolve going forward is a dynamic question. The following steps suggest one possible way the evolution could take place. Responding to the profit motive (i.e., the current market price is higher than unit production cost: $P_{b-1} > P_{b-0}$), new growers (i.e., external to the current pool establishing S_B) enter the biomass market by offering additional material for sale. Biomass supply increases to S_{B1} [7]. Growers will continue to enter the market until the market price returns to the level of unit cost. Different biomass feedstocks will have different unit cost, so for prices less than P_{b-0}, additional supplies may come online but these must be feedstocks with lower unit cost. As pellet processers (suppliers) see that the biomass supply increase drives prices down, they buy the additional quantity ($Q_{b-2} – Q_{b-0}$) and create a new equilibrium in the biomass market [8]. With excess biomass at hand, processers can increase production capacity (or load factors), increasing the total supply of pellets to S_{P1} [9] (input prices decrease so the supply increases). As such, the pellet market reaches a new equilibrium with lower prices (P_{p-1}) and more quantity traded (Q_{p-1}) [10]. Lower pellet prices should lead to additional demand for pellets, creating additional biomass demand, etc.

4.2 Implementation into System Dynamics

System Dynamics models are built from a combination of stocks (reservoirs), flows (change the amount in the reservoirs) and auxiliary calculations (operational rules) (see Appendix for screenshots of the model). In this model, the Companion Market Model (CMM), there are basically two nearly identical structures, one for modeling the biomass market and the other for modeling the pellet market. Each market on their own exhibit complex dynamics over time but the interaction of the two markets is where the System Dynamics framework is of added value.

The purpose of the model is to allocate resources (biomass and pellets) to the various markets based on each market's willingness-to-pay (WTP). We are using system dynamics rather than the traditional microeconomic approach because the markets are rarely in perfect equilibrium and there is much to be learned in the dynamic behavior of markets. Figure 4-2 provides a schematic model overview. It shows feedstock mobilization from field to market going through two markets: the biomass and the pellet market.

The model is based on the roles of the various players in the feedstock and pellet industries. In the **biomass market**, growers provide the raw biomass that can be distributed across the various industries based on their respective WTP. When processers decide to go into business or increase their production they will need to order more raw biomass from the growers. Other raw biomass users are an aggregation of all other markets that would purchase raw biomass (e.g., animal feed or biorefineries that are using raw biomass as feedstock). In the **pellet market**, processers (depots) are the suppliers of pellets. Users include biorefineries that are using pellets as their feedstock as well as the main companion markets. Finally, other pellet users are reflected in an aggregation of other participants. Processers function as the bridge between the two markets.

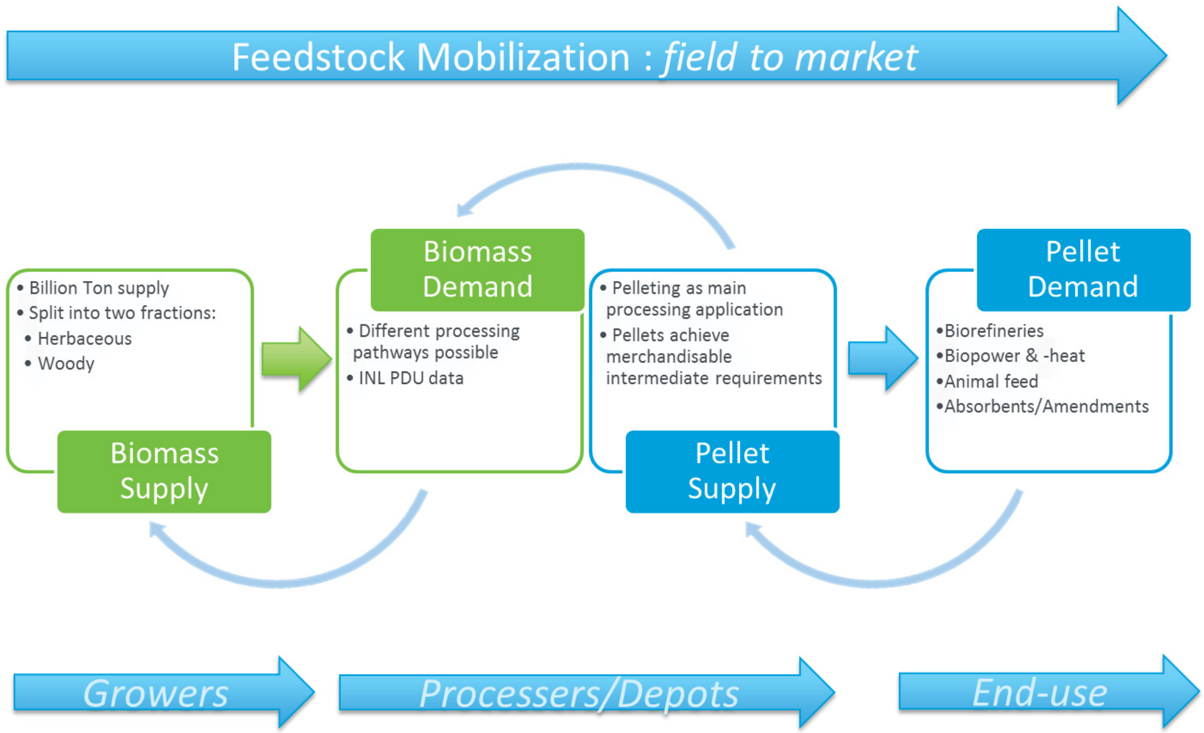

Figure 3-2. Schematic Model Overview

4.3 Companion Market Model (CMM): Parameters, Mechanisms, and Calibration

It is important to note the difference between theoretically available biomass and actually mobilized feedstock available for purchase to a market/industry. Our supply curves of theoretically available biomass follow those of the Billion Ton 2016 Update (USDOE 2016a). The CMM then determines the actual quantity of physically mobilized (supplied) feedstock available for purchase by the processing (pellet) industry.

Table 4-1 presents the main modeling parameters. This report deals with the herbaceous biomass case in which the animal feed industry is the main companion market. FY17 expansions of the model will also deal with woody biomass and companion markets for wood pellets.

In the **biomass market**, growers decide how much land (or capacity) to dedicate to biomass production based on the expected profit margin of biomass. Expected profit margin is calculated from long-term expected biomass price and production cost. Once the capacity is established, growers have to adjust the capacity utilization by looking at the expected markup ratio. This ratio is computed based on short-term biomass price and expected variable cost.

Biomass sales are a function of biomass demand and maximum biomass shipment rate. While biomass demand is constantly changing due to fluctuated short-term price, maximum shipment rate depends on biomass inventory and minimum order processing time. The inventory level also has an effect on short-term price. When inventory is higher than the desired level (calculated from demand), price goes down; otherwise price goes up.

Biomass demand is not only a function of biomass price, but also a function of economic growth, represented by the GDP annual growth rate.

A similar mechanism is set up for the **pellet market**. The pellet industry builds their capacity based on expected profit margin and decides capacity utilization based on expected markup. Raw biomass is processed as the pellet capacity is utilized. The remaining biomass is kept track as raw biomass storage.

Pellet sales depend on demand and maximum pellet shipment rate. Pellet inventory has an effect on short-term pellet price as it is compared with desired inventory level calculated from demand. In addition to be driven by short-term price, pellet demand is influenced by oil price (via cross price elasticity) and GDP growth.

Table 4-1. Overview of the main modeling features

	FY16 Model Version **Herbaceous biomass**	**FY17 Model Addition** **Woody biomass**
Biomass	Corn stover	Pulpwood, forest residues
Biofuel/Conversion pathway	Feedstock agnostic	Feedstock agnostic
Main companion market	US animal feed industry	Biopower & -heat (domestic & abroad)
Other (aggregated) companion markets	Absorbents, soil amendments, mushroom cultivation, etc.	Absorbents, soil amendments, etc.
Geographic focus	US Central Region	US Coastal Region
Current pellet industry size	Mostly small-scale (250,000 tons capacity online)	Large-scale (14.6 Million tons capacity online)
Sensitivity parameters	Economic growth (GDP) Oil price development	Economic growth (GDP) Oil price development International demand

Despite the fact that many other industries (to biofuel producers) also desire input material to be easy to handle, quality controlled/on-spec, etc. (i.e., commodity-type like), there is very little herbaceous pellet production across the US at this point. By September 2016, around 250,000 tons of agricultural residue pellet production capacity was online (Biomass-Magazine 2016).

However, a promising companion market of herbaceous pelleted biomass is emerging as a new feed material with desirable attributes for animal health (Clark *et al.* 2013, Peterson *et al.* 2014a, Peterson *et al.* 2014b). Researchers at universities in Iowa and Nebraska have conducted experimental trials where corn stover pellets are mixed into feed rations at beef cattle finishing lots (Clark *et al.* 2013, Peterson *et al.* 2014a, Peterson *et al.* 2014b). These studies measure factors such as weight gain and animal morbidity in animals fed a control ration and an experimental ration. Although slightly varied in their approach, the experiments use some combination of alfalfa, dried distillers grain and solubles (DDGS), and shelled corn as the control ration with the experimental ration containing some mix of corn stover pellets and blended materials. For proprietary reasons the blended materials are not disclosed in the studies.

In order to model how demand for herbaceous pellets may play out over time, while keeping an eye to the development of corn stover pellets as an animal feed product, the CMM needs a demand function that values corn stover pellets for animal feed. As there is not an existing industry supplying corn stover pellets to the animal feed market yet (with the accompanying data), an approximation is warranted. To that end, this analysis imputes a demand for corn stover pellets in the animal feed market based on the experimental studies noted above, an elasticity estimate from the economics literature, and previous research funded by BETO.

A demand function is a mathematical equation that relates the collective WTP of buyers in a market with the quantities buyers would like to purchase. Equation (1) is the demand function, modeled as a constant elasticity of demand, used in the CMM to represent the demand for corn stover in the animal feed market.

(1) $$Q = A\, r(\gamma) P^{-\alpha}$$

In (1) Q represents millions of tons of corn stover pellets, P is price per ton, with A and α as parameters in the equation. The function $r(\gamma)$ increases demand over time consistent with the economic growth parameter listed in Table 8-1. While the growth function is applied in the CMM, it is not carried through the following derivations for ease of exposition. An alternative approach to model demand is as a linear relationship however the constant elasticity approach adopted here reduces complexity in estimating the parameters.

Equation (1) can be rearranged into an expression for A,

(2) $$A = \frac{Q}{P^{-\alpha}}$$

and estimated with the following assumptions.

- Mathews and McCollell (2012) estimate the price elasticity of demand for feed grains in the animal feed industry to be -0.139. This is α in (2).
- Lamers and Hartley (2016) estimate 63 million tons as the total quantity of corn stover in raw format that could be potentially available for the animal feed market. This is Q in (2).
- Iowa Agricultural Bio Fibers is one of the firms referenced in the experimental studies noted previously. Based on a request for a price list, the price for a feed ration approximately equal to the ration used in the experimental studies is $165 per ton (Chute, A., & Cordes, D., 2016, personal communication.). This is P in (2).

Based on these data and assumptions, the stylized demand function used in the CMM to approximate industry value for corn stover in the animal feed market follows.

(3) $$Q = 128.11 P^{-0.139}$$

The following is the equation used to model demand for pellets:

(4) $$P = \left(\frac{Q_D}{A}\right)^{-\frac{1}{\alpha}}$$

Equation (4) relates the price of pellets (in units of $/ton) to the quantity demanded (millions of tons) of pellets in the pellet market. The parameters *A* and α are demand function parameters.

The supply function for pellets is given by equation (5).

(5) $$P = B + 10^{\beta * Qs}$$

Similar to the demand function, the parameters *B* and β are supply function parameters the analyst sets to run the simulation.

In (4) and (5), the parameters determine the initial size of the market.

5 RESULTS

The CMM is not a predictive model. Individual results such as annual equilibria should be interpreted in the context of market behavior rather than as a prediction of exact future quantities or market prices.

5.1 Reference Scenario

The CMM is run from year 2016 through 2040, creating annual equilibria across biomass and pellet markets. The initial condition in 2016 is shown in Table 5-1. Our reference GDP growth (2.4%) and oil price scenarios are aligned with the most recent Annual Energy Outlook data (EIA 2016). The CMM represents the impact of oil on the demand for biofuel through a cross price elasticity between oil and biofuels substitutes. It is set at 2.75 (based on Anderson 2012 for ethanol as a substitute for gasoline) for all runs. In the reference scenario, the companion market and the biofuel market growth are set to 0% per year, which assumes these markets do not grow faster than economy-wide growth.

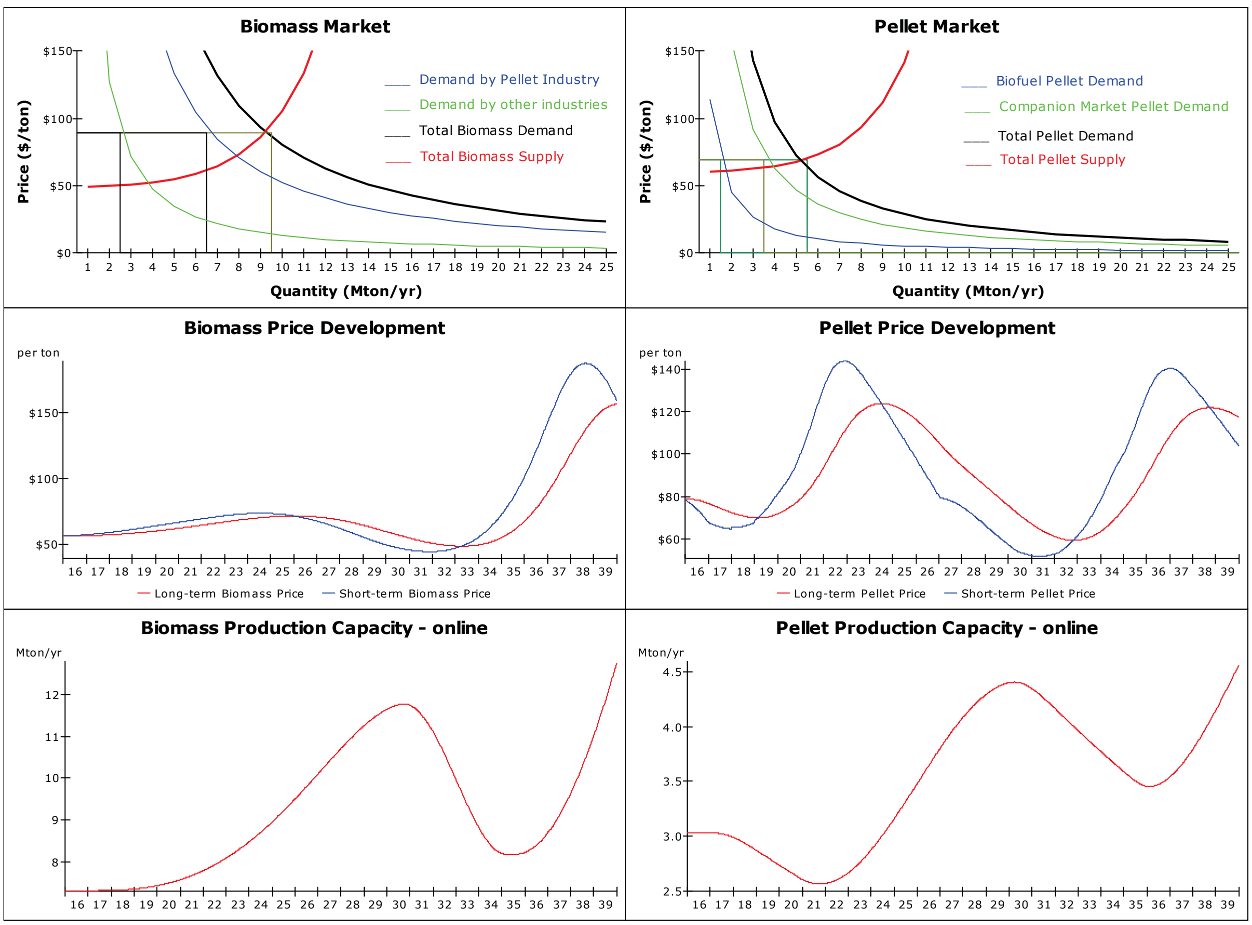

Figure 4-1. Reference Scenario

Figure 5-1 (top row) contains the equilibria in year 2040 across both markets, as well as the markets' price developments per ton of biomass or pellets respectively (middle row), and the capacity per market that is "in production", i.e., online (bottom row). The two price lines across the middle row indicate short-term (time-step basis) and long-term prices (smoothing of short term variations). These short- and long-term price expectations influence behavior and respective changes over time in the individual markets, e.g., growers providing more biomass to the market, which increases pellet production volumes, etc. (see Section 4.1 for details).

Table 5-1. Reference scenario

Time	Jan 01, 2016	Jan 01, 2022	Jan 01, 2028	Jan 01, 2034	Jan 01, 2040
Total Biomass Supplied (Mton/yr)	7.24	7.76	8.25	8.86	9.28
Total Pellets Supplied (Mton/yr)	3.00	3.28	3.62	4.71	5.13
Biomass Capacity (Mton/yr)	7.30	7.78	10.70	8.81	12.75
Pellet Production Capacity (Mton/yr)	3.03	2.57	4.09	3.77	4.56
Short Term Biomas Price ($/ton)	56.84	69.71	62.44	55.65	159.66
Long Term Biomass Price ($/ton)	56.84	64.89	68.82	49.89	156.73
Short Term Pellet Price ($/ton)	78.84	105.82	84.56	69.58	116.19
Long Term Pellet Price ($/ton)	78.84	93.70	94.34	63.39	117.24

5.2 Scenarios A-C and Observed Dynamics

First, to better understand individual market behavior, we grow the biofuels and the companion (animal feed) market independently from each other at 2.5% (leaving the other at 0%) in addition to reference economy wide growth (GDP). The results are shown in Table 5-2 and Table 5-3.

Table 5-2. Scenario A: 2.5% biofuel market growth, 0% companion market growth

Time	Jan 01, 2016	Jan 01, 2022	Jan 01, 2028	Jan 01, 2034	Jan 01, 2040
Total Biomass Supplied (Mton/yr)	7.24	7.76	8.25	8.86	9.28
Total Pellets Supplied (Mton/yr)	3.00	3.35	3.88	5.01	5.67
Biomass Capacity (Mton/yr)	7.30	7.78	10.70	8.81	12.75
Pellet Production Capacity (Mton/yr)	3.03	2.69	4.44	4.15	5.68
Short Term Biomas Price ($/ton)	56.84	69.71	62.44	55.65	159.66
Long Term Biomass Price ($/ton)	56.84	64.89	68.82	49.89	156.73
Short Term Pellet Price ($/ton)	78.84	116.94	85.23	77.25	113.51
Long Term Pellet Price ($/ton)	78.84	102.57	94.38	71.50	118.67

Table 5-3. Scenario B: 2.5% companion market growth, 0% biofuel market growth

Time	Jan 01, 2016	Jan 01, 2022	Jan 01, 2028	Jan 01, 2034	Jan 01, 2040
Total Biomass Supplied (Mton/yr)	7.24	7.76	8.25	8.86	9.28
Total Pellets Supplied (Mton/yr)	3.00	3.47	4.23	5.38	6.45
Biomass Capacity (Mton/yr)	7.30	7.78	10.70	8.81	12.75
Pellet Production Capacity (Mton/yr)	3.03	2.85	4.87	4.97	7.20
Short Term Biomas Price ($/ton)	56.84	69.71	62.44	55.65	159.66
Long Term Biomass Price ($/ton)	56.84	64.89	68.82	49.89	156.73
Short Term Pellet Price ($/ton)	78.84	127.78	87.22	83.63	111.38
Long Term Pellet Price ($/ton)	78.84	111.75	95.85	79.08	115.68

Secondly, we accelerate both markets simultaneously at 2.5% and 5% (Table 5-4 and Table 5-5) in addition to reference economy wide growth (GDP).

Table 5-4. Scenario C: companion market and biofuel market grow at 2.5% each

Time	Jan 01, 2016	Jan 01, 2022	Jan 01, 2028	Jan 01, 2034	Jan 01, 2040
Total Biomass Supplied (Mton/yr)	7.24	7.76	8.25	8.86	9.28
Total Pellets Supplied (Mton/yr)	3.00	3.57	4.51	5.69	6.97
Biomass Capacity (Mton/yr)	7.30	7.78	10.70	8.81	12.75
Pellet Production Capacity (Mton/yr)	3.03	3.01	5.20	6.08	8.24
Short Term Biomas Price ($/ton)	56.84	69.71	62.44	55.65	159.66
Long Term Biomass Price ($/ton)	56.84	64.89	68.82	49.89	156.73
Short Term Pellet Price ($/ton)	78.84	132.62	89.79	84.02	110.68
Long Term Pellet Price ($/ton)	78.84	116.65	97.40	82.67	110.60

Table 5-5. Scenario D: companion market and biofuel market grow at 5% each

Time	Jan 01, 2016	Jan 01, 2022	Jan 01, 2028	Jan 01, 2034	Jan 01, 2040
Total Biomass Supplied (Mton/yr)	7.24	7.76	8.25	8.86	9.28
Total Pellets Supplied (Mton/yr)	3.00	4.05	5.65	7.58	9.41
Biomass Capacity (Mton/yr)	7.30	7.78	10.70	8.81	12.75
Pellet Production Capacity (Mton/yr)	3.03	3.40	6.40	9.67	14.66
Short Term Biomas Price ($/ton)	56.84	69.71	62.44	55.65	159.66
Long Term Biomass Price ($/ton)	56.84	64.89	68.82	49.89	156.73
Short Term Pellet Price ($/ton)	78.84	149.61	104.86	103.26	114.24
Long Term Pellet Price ($/ton)	78.84	132.95	110.81	102.88	111.07

The Reference Scenario shows the dynamic connection between pellet equilibrium prices and *online* (i.e., operating) pelleting capacity (Figure 5-1). We see a drop in capacity as the markets evolve. This reduces pellet output which in turn increases pellet prices. Higher prices make more pelleting capacity economically viable which again increases online capacity, available pellet quantity, and leads to a reduction in pellet prices over time. The oscillation continues with respective delays in adjusting supply (changing capacities) and pellet market prices. Simulated prices across both biomass and pellet markets oscillate heavily, but seemingly around long-term equilibria (~$60 for biomass and ~$95 for pellets). Pellet production grows only slowly, in-line with GDP growth (Table 5-1).

Comparing an individual growth of either biofuels or animal feed demand indicates that the companion market mobilizes resources faster, yet prices stay lower overall (Table 5-2 and Table 5-3). A simultaneous growth of both biofuel and companion markets increases biomass mobilization and pellet production beyond previous levels, yet long-term pellet prices remain low despite large fluctuations in the short-term (Table 5-4 and Table 5-5). This suggests that the markets enable rather than out-compete each other.

The sensitivity scenarios (see Appendix 8.2) indicate that neither oil market nor GDP growth drastically influence overall outcomes.

6 INITIAL CONCLUSIONS AND PATH FORWARD

Meeting Co-Optima biofuel production targets will require large quantities of mobilized biomass feedstock available for purchase by biorefineries. Therefore Co-Optima research includes outlining a path towards feedstock production at scale by understanding routes to mobilizing large quantities of biomass feedstock. Continuing along the vertically-integrated path that pioneer cellulosic biorefineries have taken will constrain the bioenergy industry to high biomass yield areas, limiting its ability to reach biofuel production at scale. To advance the cellulosic biofuels industry, a separation between feedstock supply and conversion is necessary. Thus, in contrast to the vertically integrated supply chain, two industries are required: a feedstock industry and a conversion industry. The split is beneficial for growers and feedstock processers as they are able to sell into multiple markets. That is, depots that produce value-add feedstock intermediates that are fully fungible in both the biofuels refining and other, so-called companion markets. As the biofuel industry is currently too small to leverage significant investment in up-stream infrastructure build-up, it requires an established (companion) market to secure demand, which de-risks potential investments and makes a build-up of processing and other logistics infrastructure more likely. A common concern to this theory however is that more demand by other markets could present a disadvantage for biofuels production as resource competition may increase prices leading to reduced availability of low-cost feedstock for biorefineries. To analyze the dynamics across multiple markets vying for the same resources, particularly the potential effects on resource price and distribution, a System Dynamics model, the Companion Market Model (CMM), has been developed in this task.

The CMM is a tool to investigate the dynamic link between biomass and pellet markets given different demand patterns across the biofuel, animal feed, and other markets competing for processed herbaceous biomass (corn stover). The main mechanism of the model is to allocate resources (biomass and pellets) to the various markets based on each market's willingness-to-pay (WTP). The model is based on the roles of the various players (actors) in the biomass and pellet industries. In the biomass market, growers provide the raw biomass that can be distributed across the various industries based on their respective WTP. When processers decide to go into business or increase their production they will need to order more raw biomass from the growers. Other raw biomass users are an aggregation of all other markets that would purchase raw biomass (e.g., animal feed or biorefineries that are using raw biomass as feedstock). In the pellet market, processers (depots) are the suppliers of pellets. Users include biorefineries that are using pellets as their feedstock as well as the main companion market of animal feed industries (herbaceous pellets) and an aggregation of other participants. Processers function as the bridge between the two markets.

It is important to note that the CMM is not a predictive model aimed at deriving exact quantities and prices traded in the future. Rather, it is a simulation of market dynamics and actor behavior under different paradigms including GDP, biofuel and companion market growth, as well as oil price developments.

The CMM is run from year 2016 through 2040, creating annual equilibria across both biomass and pellet markets. The initial condition (year 2016) reflects current industry levels of very limited herbaceous biomass processing (and respective low demand by the biofuels industry). The model behaves well in terms of expected market economics. For example, a drop in biomass supply increases biomass prices, which reduces the economic viability of processing and causes a respective drop in online pelleting capacity. The reduction in output then increases pellet prices, which again increases the viability of pelleting and increases demand for biomass, etc.

All runs show a cyclical market pattern reflecting delays in the system, including additional resource mobilization by growers in the biomass market and pelleting capacity changes by processers over time. The reference scenario represents a market growth of both biofuel and companion markets in-line with GDP developments. While processing capacity increases over time, it does not quite reach a doubling until 2040. Simulated prices, across both biomass and pellet markets, seem to oscillate heavily, around long-term equilibria.

Comparing an individual growth of either biofuels or animal feed market (at an additional 2.5% to GDP growth while the other one grows in-line with GDP only) indicates that the companion market mobilizes resources faster, yet prices stay lower overall. A simultaneous growth of biofuel and companion markets increases biomass mobilization and pellet production beyond levels of any run, yet long-term pellet prices increase only by 10-15% per ton despite large fluctuations in the short-term. This suggests that the markets do not out-compete each other for resources until much larger feedstock deployment levels are reached. The sensitivity scenarios indicate that neither oil price nor GDP developments drastically influence overall outcomes despite a modeled cross-elasticity between biofuel and oil prices.

Across all scenarios, both biomass and pellet markets grew with relatively stable prices over the long-term, buffered through pelleting capacity increases. Hence, we can initially conclude, based on these results, that the animal feed market does not threaten a development of a second generation biofuels industry reliant on herbaceous biomass in terms of resource competition or price hikes. Rather, as our model runs show, larger deployment/mobilization levels are achieved when we assume a steady growth in the companion market. The only situation in which this would not hold true is if the market is short of biomass; a situation that may arise in the future when biofuel production levels are significantly higher than today. At this point however such a situation is unlikely in the herbaceous biomass market as ample resources are still available and yet need to be mobilized.

In FY17, an extension of the CMM is planned to incorporate woody biomass and respective companion markets for wood pellets such as co-firing (domestic and international), heating, absorbents, and animal bedding (see Table 4-1).

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8 APPENDIX

8.1 Initial Market Equilibria

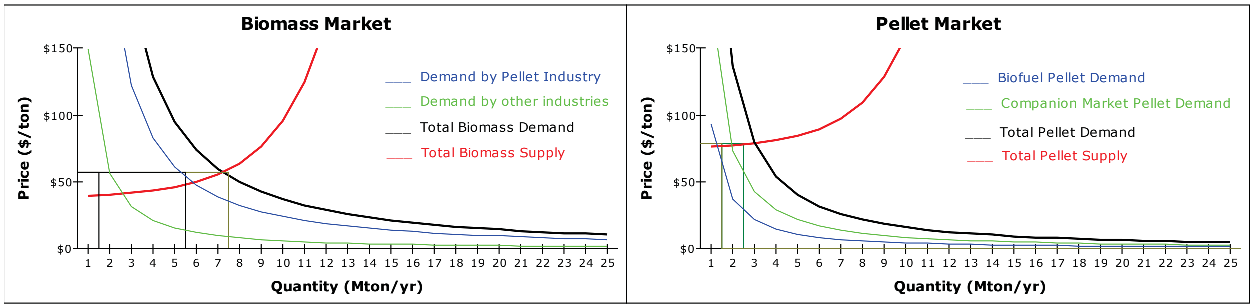


Figure 8-1. Initial condition in the Reference Scenario in 2016

8.2 Sensitivity to Oil Price and GDP Development

Table 8-1. GDP and oil price development indicators

	Economic growth (GDP)	Oil price development
Reference scenario	2.4%	1.57%
Sensitivity scenario 1 (low)	1.8%	-1.3%
Sensitivity scenario 1 (high)	2.9%	6.38%

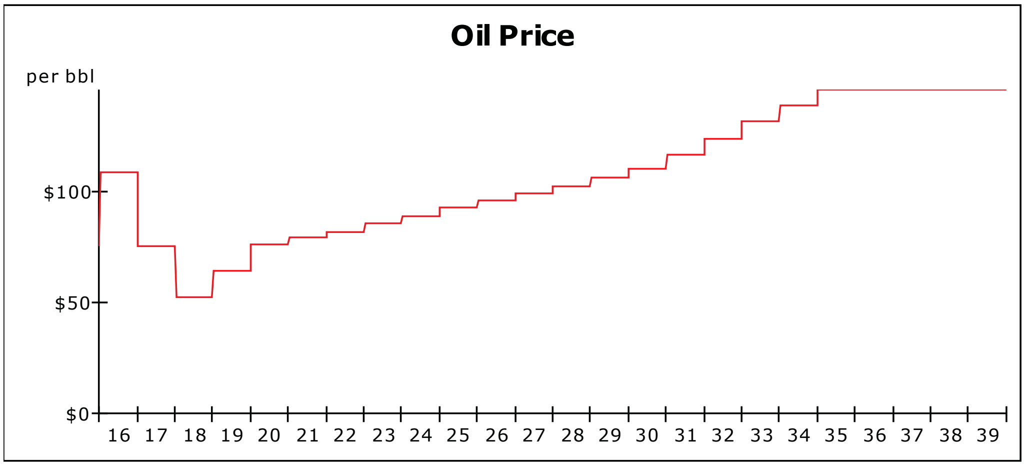


Figure 8-2. Reference oil price development

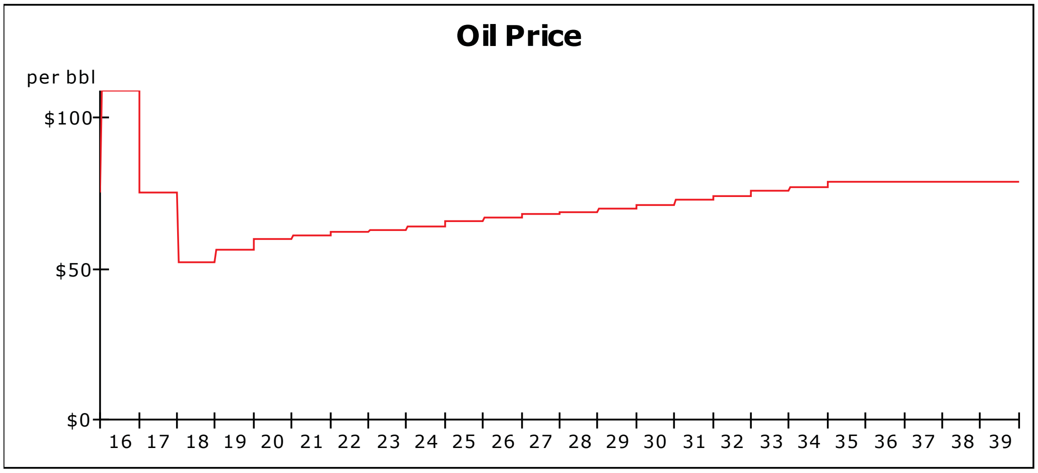


Figure 5-3. Low oil price development

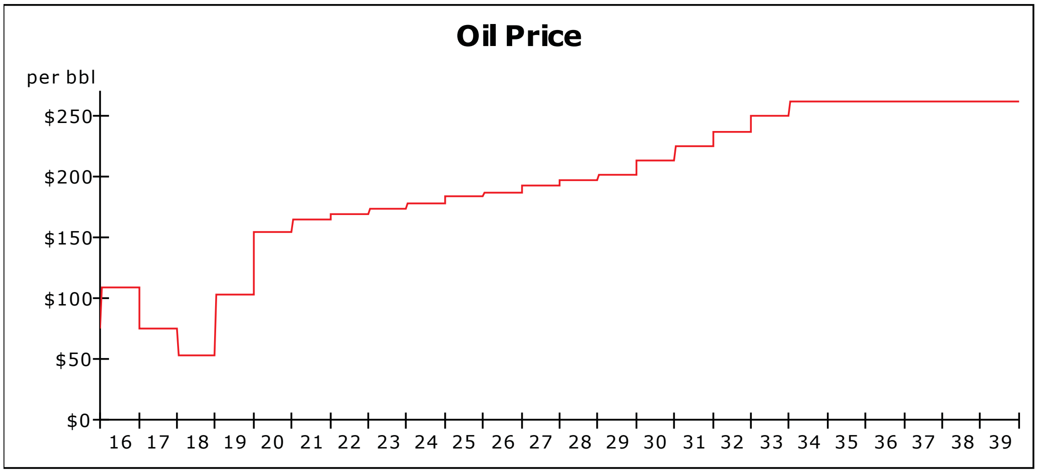


Figure 8-4. High oil price development

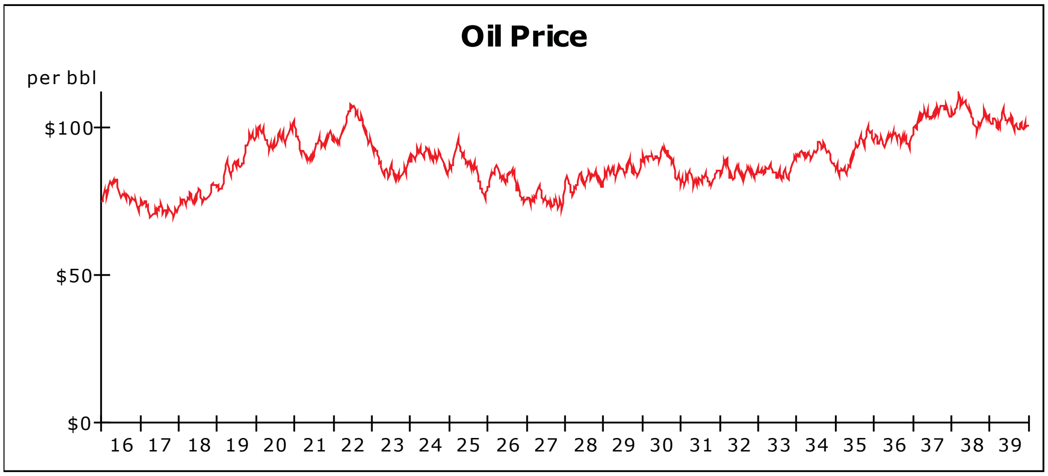


Figure 8-5. Randomized oil price development

The first sensitivity scenario assumes a lower than reference GDP (1.8%) and oil price growth over time. Lower oil prices make it harder for biofuels to compete and reduces the demand for pelleted feedstock. This decreases the online pelleting capacity (Figure 8-6).

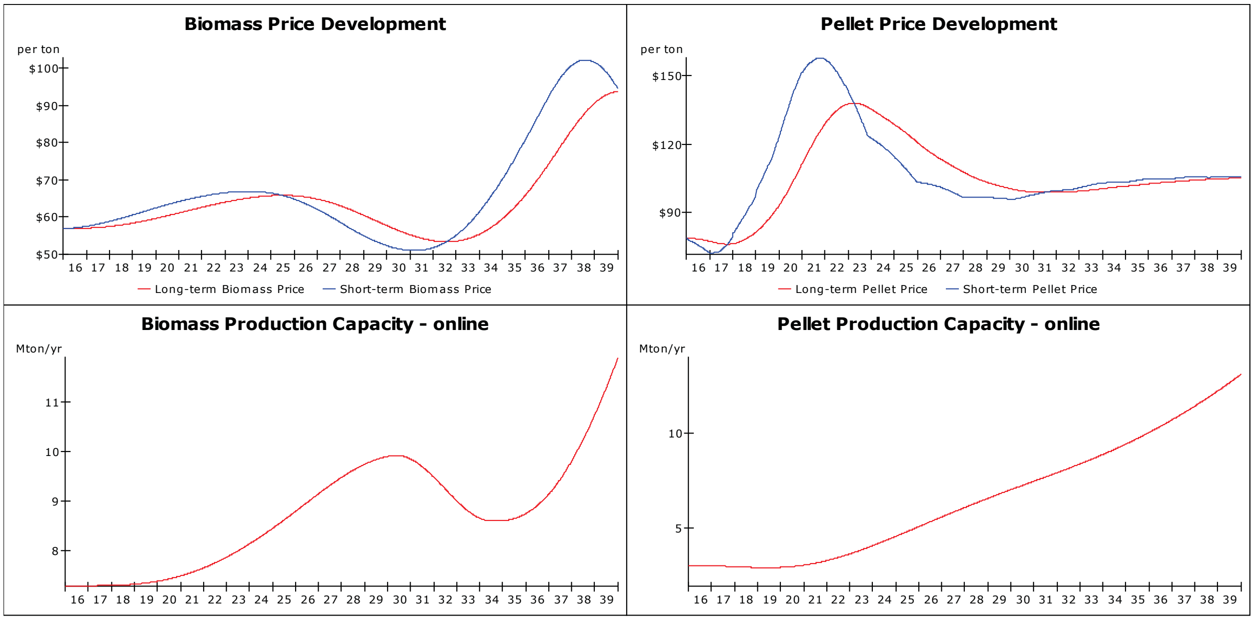


Figure 8-6. Sensitivity scenario 1

The second sensitivity scenario assumes a higher than reference GDP (2.9%) and oil price growth over time. As oil prices continue to rise, pellet capacity will correspond as biofuels become more competitive (Figure 8-7).

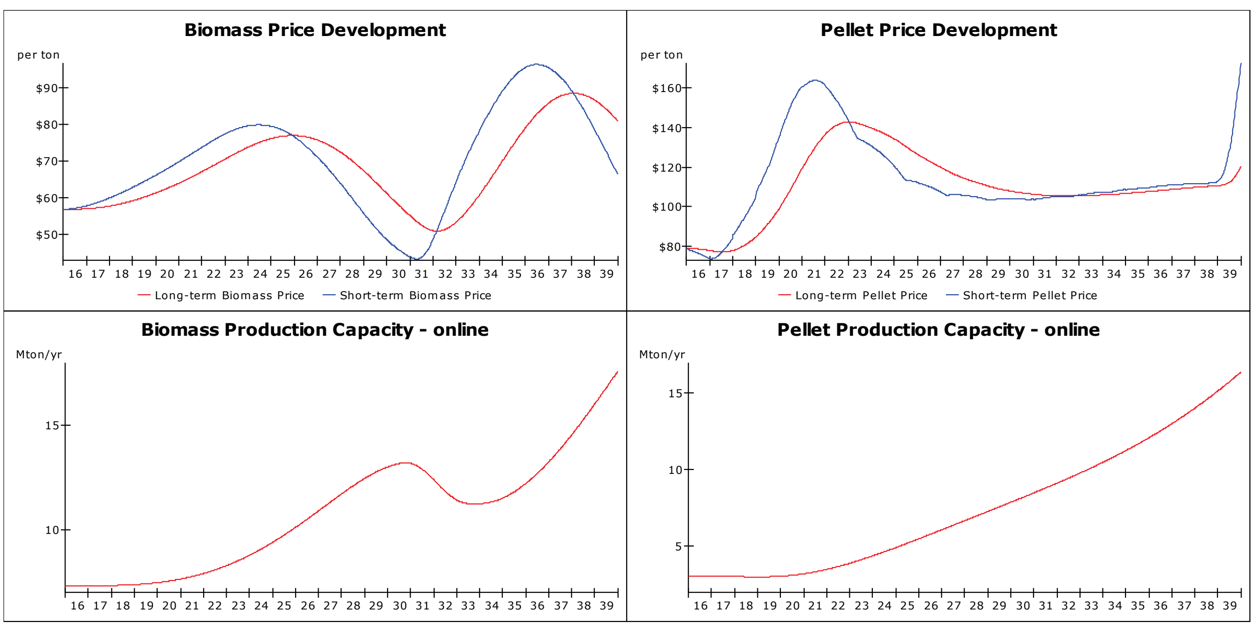


Figure 8-7. Sensitivity scenario 2

The third sensitivity scenario assumes a reference GDP (2.4%) but a random oil price growth over time (Figure 8-8).

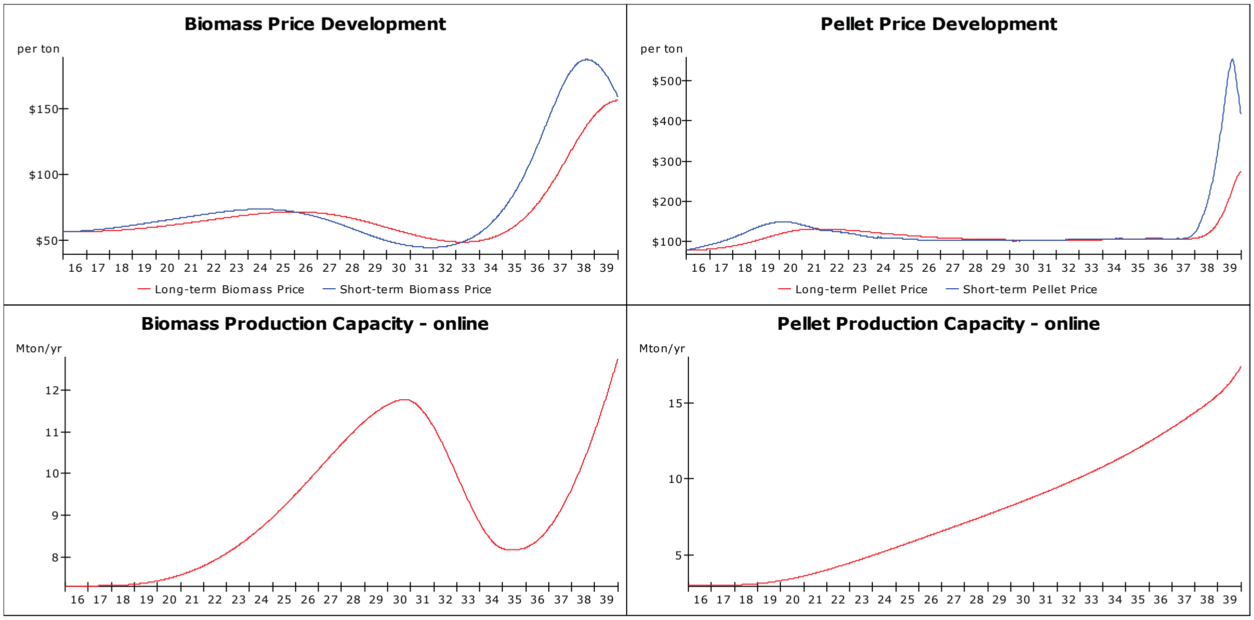


Figure 8-8. Sensitivity scenario 3

8.3 Model Interface

There is a model interface that allows users to adjust parameters, run simulations and visualize results. The model can be run without the use of an interface but for those not familiar with the model this can be very difficult. The interface opens up the model usage to all audiences. Figure 8-9 below shows the "Home" page of the interface.

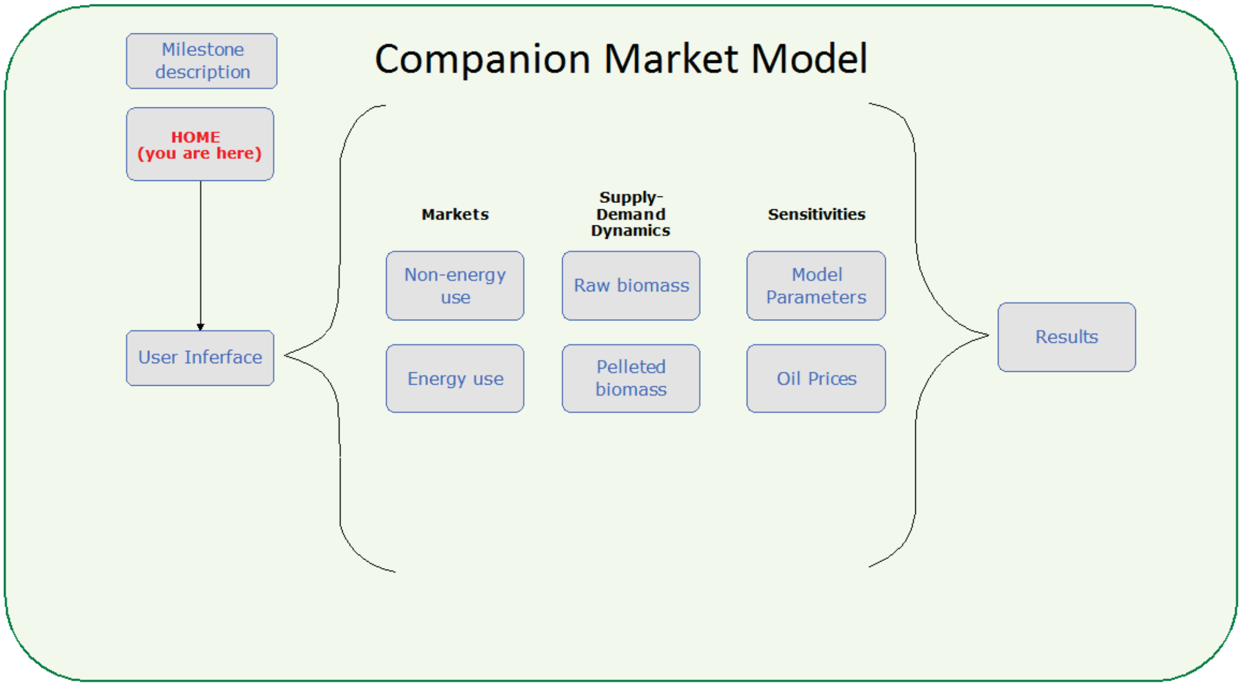


Figure 8-9. Home page for the User Interface for the Companion Market Model. Each of the icons is clickable links to model sections or information screens. This is the screen that allows the user to navigate around the model and run simulations.

The next screen is the User Interface (Figure 8-10). This is the place where the user can set various scenario options, such as petroleum market behavior, GDP growth, cross price elasticities of the various markets with petroleum prices, and animal feed market growth rate. This is only a small selection of options available to adjust but for the current model test these are the most important. Other options can be added in the future.

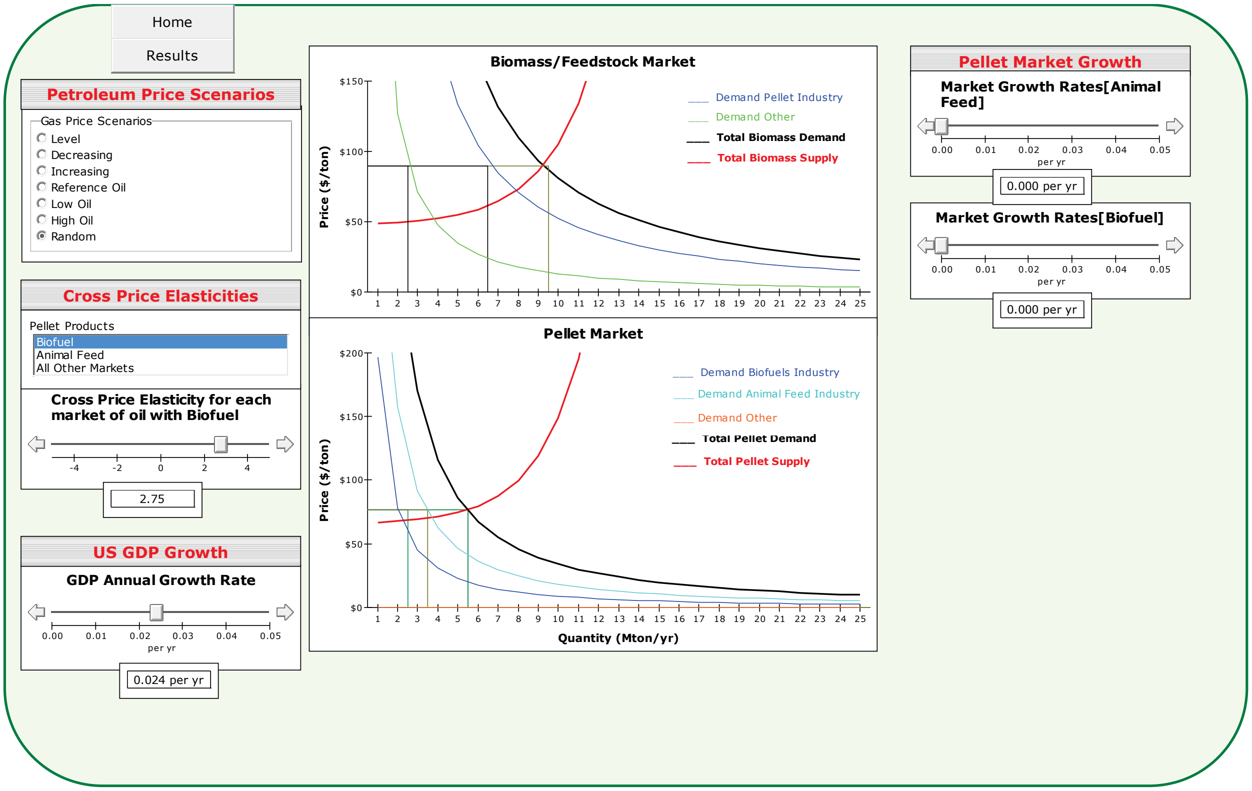
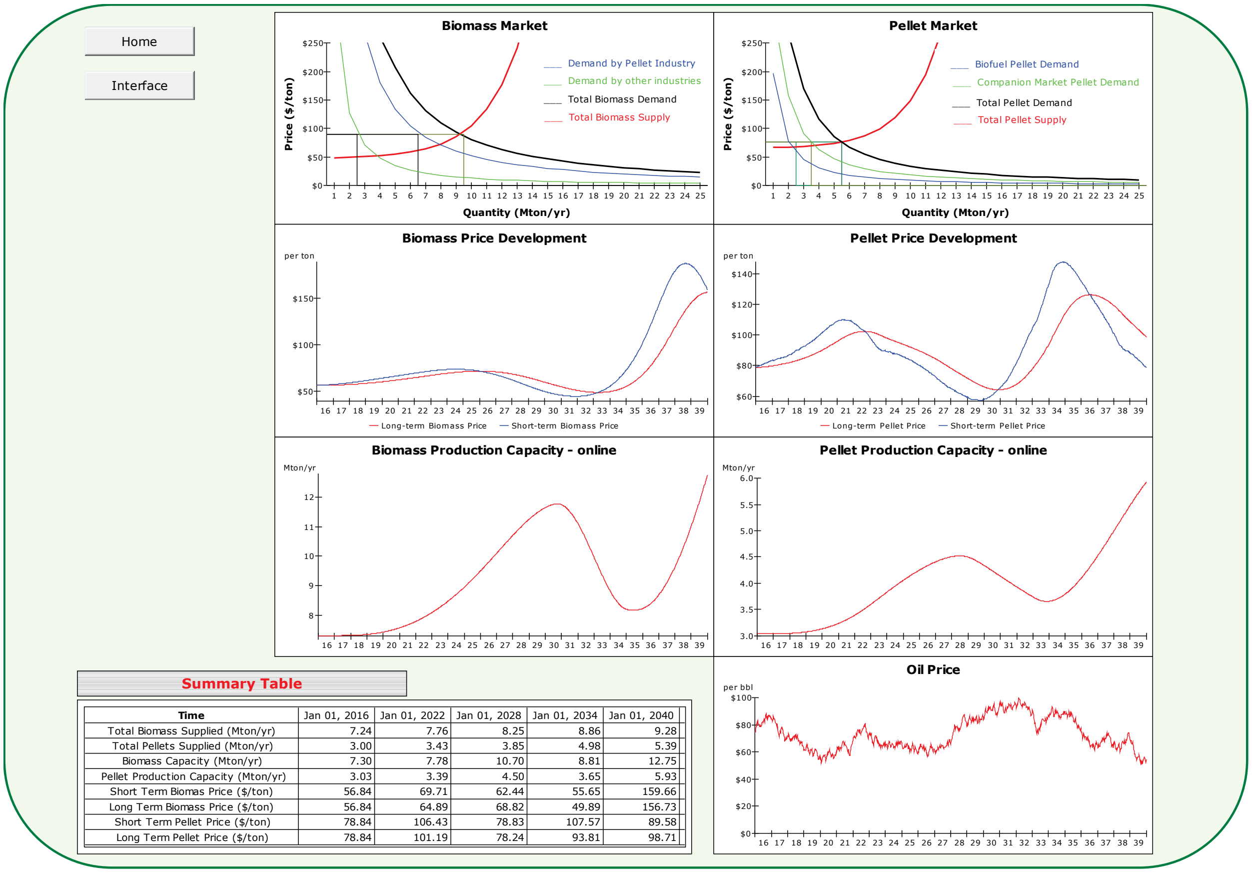


Figure 8-10. This is a screen shot of the user interface. This screen allows the user to set various options prior to running the simulation.

Another user interface screen to discuss is the results screen (Figure 8-11). This screen displays a series of charts and summary table of vital statistics from the simulation. As the user runs a simulation these charts and tables are changing based on the current value. The users are allowed to pause a simulation at any time and review the current status of the model. More charts and tables can be added as additional information is identified that needs to be tracked.



Time	Jan 01, 2016	Jan 01, 2022	Jan 01, 2028	Jan 01, 2034	Jan 01, 2040
Total Biomass Supplied (Mton/yr)	7.24	7.76	8.25	8.86	9.28
Total Pellets Supplied (Mton/yr)	3.00	3.43	3.85	4.98	5.39
Biomass Capacity (Mton/yr)	7.30	7.78	10.70	8.81	12.75
Pellet Production Capacity (Mton/yr)	3.03	3.39	4.50	3.65	5.93
Short Term Biomas Price ($/ton)	56.84	69.71	62.44	55.65	159.66
Long Term Biomass Price ($/ton)	56.84	64.89	68.82	49.89	156.73
Short Term Pellet Price ($/ton)	78.84	106.43	78.83	107.57	89.58
Long Term Pellet Price ($/ton)	78.84	101.19	78.24	93.81	98.71

Figure 8-11. Results screen displays the outcome of the two markets. The first graphs show the supply and demand curves for both markets. The other charts show the short term and long term price for the markets.

The model also includes a Supply and Demand Curve interface (Figure 8-12). This screen allows the user to adjust the shape and location of both the supply and demand curves for either biomass and pellet markets. Note on the demand side the user needs to set the parameters for the individual markets not the aggregated demand curve.

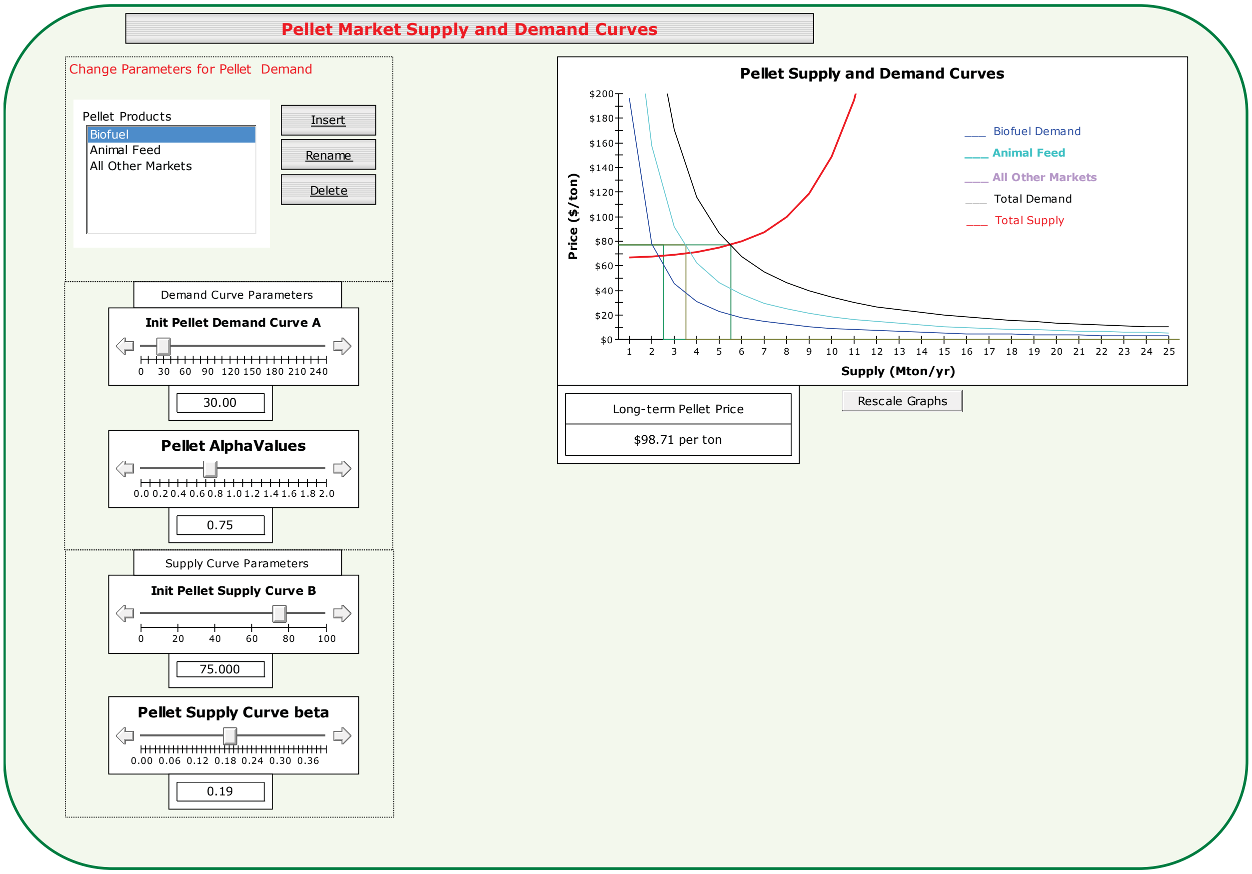


Figure 8-12. This figure shows the supply and demand interface screen for the pellet market. From here the user can modify the parameters for the individual demand curves or the supply curve.

8.4 System Dynamics

Figure 8-13 shows a representation of a typical system dynamics stock and flow model. The square boxes are stocks. Stocks collect material. The icons that look like a valve, i.e., "Short Term Biomass Price Change", are flows. Flows are the only mechanism for changing the value of a stock. The diamond shapes are constants. Their values do not change throughout the simulation. The round icons are auxiliary variables. Auxiliaries are where calculations and decisions are calculated.

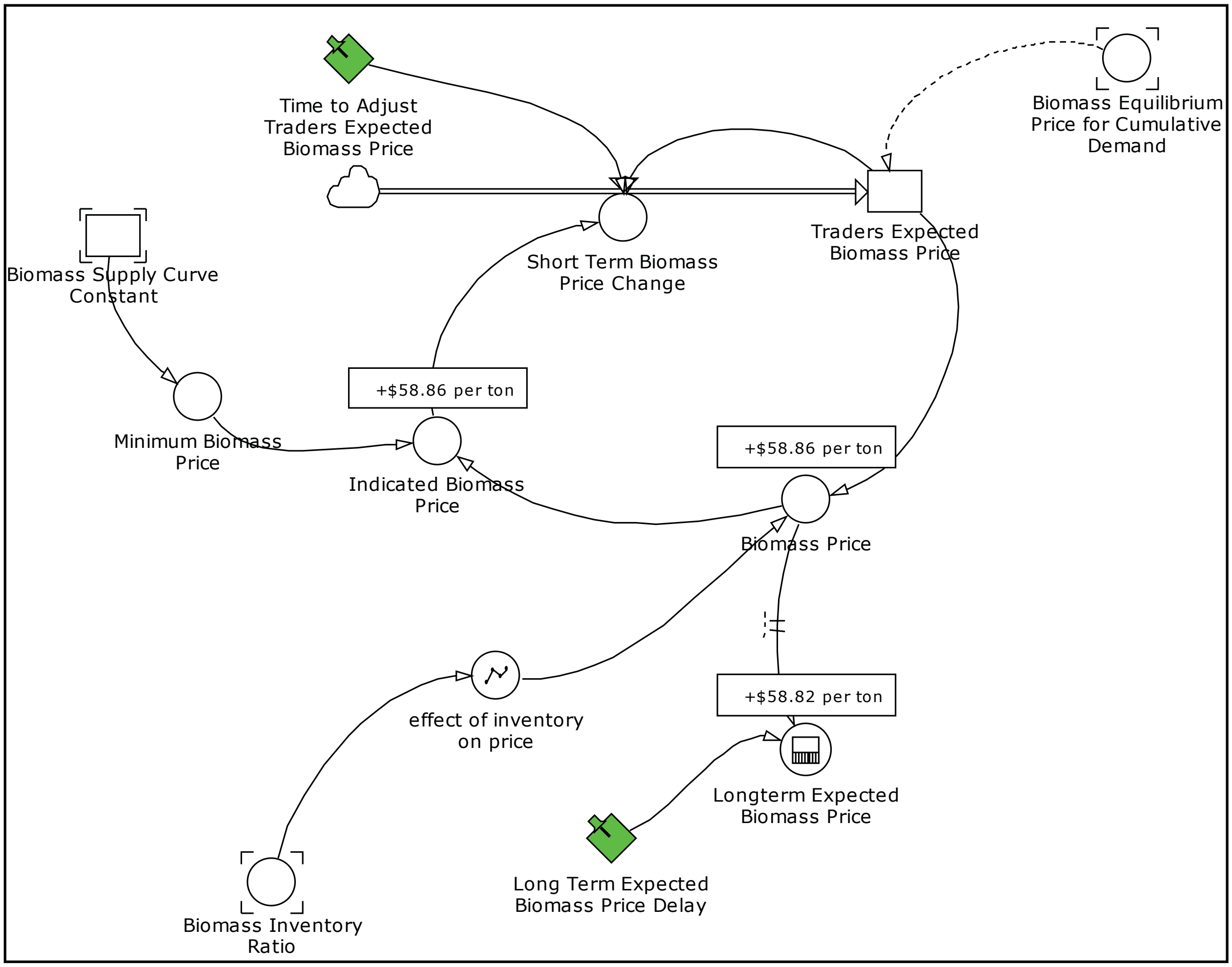


Figure 8-13. A typical system dynamics stock and flow model

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