Primary research Article

Biomass market dynamics supporting the large-scale deployment of high-octane fuel production in the United States

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Abstract
US Department of Energy research aimed at co-optimizing fuels and engine performance identified several bioblendstocks that can improve fuel economy including an aromatic-rich hydrocarbon derived from woody biomass. This work supports an analysis of its large-scale deployment implying a production target of approximately 15 billion liters of bioblendstock for the supply of 57 billion liters of high-octane fuel by 2050. It simulates potential transition pathways to lignocellulosic feedstock market structures capable of supplying a mature biorefining industry at this scale. In the present absence of biorefineries, transitions are modeled via nonbiofuel feedstock markets, so-called companion markets. The resource distribution across several demand industries is simulated to determine biomass availability and price dynamics over time. Results indicate that the wood supply base is mainly influenced by traditional markets including housing and pulp and paper. The selected companion market of wood pellet combustion for heat and electricity generation is found to positively stimulate biomass mobilization, especially in the initial absence of biorefineries. Eventually, biorefineries are found to be able to out-compete the companion market. As such, they directly benefit from the processing (i.e., pelleting) capacity established to produce commodity-type intermediates for the companion market. We conclude that the amount of bioblendstock produced is directly related to the size of the companion market (and its pelleting capacity). An initially larger companion market generates up to 20 million dry tonnes of additional feedstock, equivalent to 27 commercial-scale biorefineries, or an additional production of 5 billion liters by 2050. Distinguishing between industry-specific feedstock preferences based on average biomass quality characteristics, this analysis goes beyond past research efforts that assume automatic fungibility across different feedstocks. Improving engine performance is a key driver for the promotion of low-carbon fuels derived from bioblendstocks. This analysis portrays feedstock market transition pathways for their large-scale deployment.

Keywords: bioblendstock, biorefinery, commoditization, Co-Optima, forest biomass, high-octane fuel, market development, mobilization, system dynamics

Introduction
Fuel properties influence engine efficiency. A collaborative effort between nine US Department of Energy (DOE) National Laboratories is identifying the fuel properties that will enable enhanced fuel economy, blended fuels with these properties, and engines that will work with these fuels toward increased efficiency and fuel economy. The initiative has identified several blendstocks with fuel properties that can improve fuel economy; a subset of which was further assessed regarding their near-term economic and environmental viability (Dunn et al., 2018). From this list, two biomass-derived blendstocks (bioblendstocks) with Research Octane Number (RON) exceeding 98 and the potential to increase fuel economy were chosen for an analysis of large-scale deployment: isobutanol and an aromatic-rich hydrocarbon (ARHC). Isobutanol can be derived from herbaceous biomass. ARHC can be derived thermochemically from woody biomass. The two candidates were chosen for an analysis of large-scale deployment, defined as 10% of the 150,000 fueling stations in the US offering high-octane fuel (HOF) with a 25% blend level of bioblendstock (Dunn et al., 2016). This would result in approximately 15 billion liters of bioblendstock.
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, that is, a constant supply within quality specifications can guarantee the stable and high conversion yields necessary for an economically viable cellulosic biorefinery relying on these supply streams. At present, pilot scale cellulosic biorefineries rely on vertically integrated feedstock supply systems designed to support traditional agricultural and forestry industries, where feedstock is procured through contracts with local growers, harvested, locally stored, and delivered in low-density format to the nearby conversion facility. While these systems have been demonstrated to achieve high-volume, low-cost feedstock supply, they have not yet been able to consistently demonstrate narrow quality specifications and guarantee a reliable conversion in-feed process (Hess et al., 2009; Argo et al., 2013; Muth et al., 2014). Advanced feedstock supply systems (Searcy et al., 2015) based on a network of distributed biomass preprocessing centers (depots) and centralized terminals would help alleviate quantity, quality, and price uncertainties through the production of fungible, storable, and flowable commodity-type intermediates. At present however, the slow biorefining capacity build-out and the potential dependency on a single, regional client (biorefinery), have dampened the expansion of the depot concept. As such, future biorefineries will continue to be limited in expanding their operational capacity unless depot operations can be established through other, non-biofuel markets.

A common paradigm for developing feedstock supply systems is that it requires a demand pull from new biorefineries to mobilize the resources; an assumption that is, for example, consistent across current US DOE resource assessments (USDOE 2011, 2016). Under the present absence of increasing biorefining capacity, however, the mobilization of resources into the marketplace needs to be initiated via nonbiofuel, companion markets. Mobilization is creating the economic drivers required to catalyze the infrastructure investment and biomass resource development investment necessary to transition biomass from available resource, that is, what is on the field, to a marketable resource, that is, what is available for sale and accepted by buyers. With companion markets, depots would produce value-added feedstock intermediates that are fully fungible into both the companion and the biofuel market. At first, the established companion market mobilizes the biomass resource and helps establish logistics and supply structures upon which the biofuel industry can rely. In the long-term, an independent feedstock supply industry producing commodity-type feedstock intermediates, fungible across multiple markets, may (to some degree) create a supply push that could help de-risk and accelerate the deployment of bioenergy technologies.

A common concern and pushback to the companion market theory are that nonbiofuel markets may disadvantage biofuel production as resource competition may increase prices and reduce low-cost supply quantities. The objective of this work was to analyze the dynamics of biomass resource distribution across multiple industries under different conditions. To this end, a simulation model is developed that projects the volume and price dynamics between the biomass resource base (supply) and different demand industries including intermediate processing (i.e., mobilization) and end-use markets (traditional, companion, and biofuels). This allows us to model resource mobilization and price developments over time given varying levels of companion and biofuel market growth. The following research questions (RQ) guide the undertaking:

RQ1: What impact do different market demand signals have on the development of the woody biomass supply base over time given that it underlies a multi-annual time lag (between plantation and harvest)?
RQ2: Does the mobilization of woody biomass via combustion (companion) markets aid the future biorefining industry or limit low-cost biomass supply over time?
RQ3: What main influencing factors determine future mobilization levels of commodity-type intermediates (pellets) and how do these relate to the availability of feedstock for biorefineries?

The paper is organized into three sections portraying the model structure and data applied, the modeling results and sensitivity analysis, and a discussion of the results.

Materials and methods

A simulation model was built in Powersim Studio 10 Premium©, a system dynamics software, to explore the volume and price dynamics between the biomass resource base (supply) and different industrial demands, including intermediate processing (pelleting) and end-use markets (traditional, companion, and bioblendstock). The model is split into four separate modules covering the forest sector (resource base), the wood products sector, the pellet sector, and the biofuel (bioblendstock production) sector. All modules are interconnected and operated from a single user interface. The selected biomass 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 stability (for storage), bulk density (for...
Forest sector module and assumptions

The forest sector module tracks loblolly timberland, number of trees, and weight of trees. Land use information data are extracted from the US Forest Service (USFS) Forest Inventory Analysis (FIA) for private loblolly forest land (USFS 2017). In the southern forest region, loblolly pine represents the major forest type, with a total of more than 21.5 million hectares in 2015.

Harvest and management practices are related to land ownership. We distinguish between five different ownership groups. For each group, there is a 1-year delay between making a harvest decision and actual harvest.

1 Industry: Forest stands are thinned at 15 and 25 years and harvested at 35 years.
2 Corporate (including timber investment management organizations and real estate investment trusts): Forest stands are thinned at 15 and 25 years harvested at 35 years if profitable or thinned if not, then harvested at 45 years if profitable or thinned if not. Stands are harvested at 55 years regardless of profit.
3 Family/individual timber: This group thins their stands at 25 years. The percent of stands to be thinned and the percent of this group to thin their stands depend on the ratio of pulpwood and sawtimber prices. When the ratio is low, only 20% thin one-third of their stand. When the ratio is high, 100% will thin half of their stand. This group harvests timber from 35 years onwards depending on the market price.
4 Family/individual nontimber: This group also thins their stands at 25 years. When the pulpwood-sawtimber price ratio is low, only 10% thin one-third of their stands. When the ratio is high, 100% will thin half of their stand. Irregular harvests start from year 46 depending on price.
5 Conservation: 5% of this group practice regular thinning at 15, 25, and 35 years. Irregular harvests start after 55 years depending on market prices.

Tree weight is calculated (based on equations from Baldwin, 1987) using tree age, survival rate, height of dominant and codominant, and quadratic mean diameter as inputs. Total dry weight includes dry bole weight inside bark and crown dry weight of wood. Tree survival and mean diameter are calculated based on Baldwin & Feduccia (1987). We distinguish between three harvest fractions: sawtimber, pulpwood, and logging residues. The share of each fraction depends on the stand age and the type of management activity (Table S2).

The distribution of harvest fractions to different wood products industries overlaps, for example, sawmills buy raw material as whole trees and also procure pulpwood indirectly. In reverse, pulp mills may also procure sawtimber quality lumber. We assume that when pulpwood price is high, sawmills try to sell as much pulpwood to pulp mills as possible. When sawtimber price is high, pulp mills will try to sell as much of their sawtimber to sawmills as possible. If under either scenario the seller is unable to sell all biomass to a buyer at the desired price, they will use the remaining material for their own production. For logging residues, we assume that 70% of all harvest residues arrive at landing and 30% are left in the forest for sustainability reasons (USDOE 2016).

Wood products sector module and scenarios

The wood products sector module tracks sawtimber, pulpwood, mill, and logging residue markets. Sawtimber and pulpwood markets are calibrated with historical demands from 2000 to 2014 suggesting a linear growth pattern (Fig. S4). A linear extrapolation from 2015 to 2050 suggests an annual growth of +1.4% and +3.0% for pulpwood and sawtimber, respectively. As historic data also include demand from new markets, for example, wood pellet production for energy, we adjust the pulpwood demand projection to a +1% p.a. increase in the reference case. The +1% per year pulpwood and +3% per year sawtimber demand scenarios match the maximum average annual increase for each market and scenario combination made for the US south in USDOE (2016; Fig. S5).

The pulpwood demand for the US southeast is projected to increase by +1% per year in the reference case, derived from a linear extrapolation of historic data. A one percent increase can be regarded as optimistic, as industry projections for the region are slightly increasing at best, but more likely to remain stable or decline over time as no new pulp mills are expected to come online in the region given present and expected global pulp and paper market trends (Latta et al., 2016). Sawtimber demand in the reference case follows the High Housing scenario from USDOE (2016; Fig. S5), which best matches the present housing market trend (Forisk 2017).

In our model, sawmills and pulp mills are price setters. From the projected demand, they take into account a 1-month inventory coverage and a 6-month inventory adjustment time to estimate a desired delivery rate for a certain period. Depending on whether the supply rate falls below or rises above their desired rate, they will increase or decrease prices accordingly. Linear demand curves are used for both sawtimber and pulpwood. Demand elasticities are −3 for sawtimber and −4 for pulpwood.

Delivered pulpwood and sawtimber prices are calculated from stumpage prices plus adding handling and transportation costs (Tables S3 and S4). The initial stumpage prices are set at $18.40 per dry tonne for pulpwood and $76.09 per dry tonne for sawtimber in the year 2000 (Bardon, 2016). Keeping transportation and handling costs constant out to 2050 is a...
simplication as costs are subject to industry learning effects and oil price changes. A possible future model extension could detail these effects.

Pulpwood use in the material sector does not create residue (or loss) fractions while 24% of sawtimmer becomes mill residue in integrated operations (Platzer, 2016). USFS data suggest that around 5% of all US softwood sawmill residues are unused or unaccounted for (Spelter et al., 2007). The model initiates runs in the early 2000s, with usage rates between 70% and 90% for mill residues. Non degraded unused mill residue is the main input material for pellet production. Non degraded implies a maximum of 1-year storage time between generation and use.

Increased demand for energy could cause disruptions in existing supplies to traditional wood product industries. To avoid a complete displacement via price competition, we limit the possible penetration of the energy market demand (companion and bioblendstock) to 60% of the total mill residue supply. Demand for mill residue from energy markets first taps into stacked mill residue. Once this stock is emptied, fresh mill residue is utilized. Energy markets are the main drivers for mill residue price, which is competitively determined based on a linear demand curve, with an elasticity of \(-4\). The initial mill residue price is set at $35.27 per dry tonne, converted from $24.80 per green tonne with 30% moisture content wet basis (Forest2Market 2015).

In the US southeast, 70% of logging residues end up at the landing (USDOE 2016). However, they have different characteristics (e.g., ash contents) than pulpwood, mill residue, or sawtimmer. As such they are not fully fungible with these feedstocks unless processed. Potential logging residue suppliers thus observe annual logging residue demand and once this demand reaches a threshold level (initially set to 1 million short tons p.a. in our model), they will decide to clean logging residues with a cleaning loss of 15% (Jacobson et al., 2014). The decision time delay is set at 3 months. Similar to the mill residue market, the logging residue market is competitive, and the price is determined by a linear demand curve with an elasticity of \(-5\) as the demand is less elastic than mill residue. The initial price for logging residues is set at $44.09 per dry tonne. Both mill and logging residue prices are converted to delivered prices by adding transportation and handling cost of $20.35 per dry tonne, which resemble an average between clean pine and forest residue values from the most recent Idaho National Laboratory (INL) Woody Feedstock State of Technology report (Hartley et al., 2016).

**Pellet sector module and scenarios**

The US wood pellet production and recent capacity expansion are primarily driven by demand from export markets. The modeled states across the US southeast cover 100% of this volume in terms of capacity and production (Fig. S6). US domestic demand presently only includes residential heating, of which very little supply originates in the modeled states. It is thus neglected as part of the decision dynamics to increase pelleting capacity. Potential future domestic demand from biopower and/or bioblendstock production, however, is included.

The contracted wood pellet quantity is tracked in a backlog. As current export combustion markets are subsidy-driven, US export volumes are supplied via long-term contracts (reflecting the underlying policy period and remuneration levels) rather than via the spot market. As a result the export market is not (yet) very sensitive to price changes, an increase in backlog will increase delivery delay, which in turn reduces future contracts. An increase in delivery delay also increases pellet prices. When the export market dominates (over, e.g., demand from domestic biopower or bioblendstock demand), the model automatically caps pellet supply prices.

Capacity expansion depends on two main factors: net present value (NPV) and capacity utilization. From the backlog, demand for the next 3 years is calculated, compared with current capacity, and incorporated into an expected utilization, which determines potential additional future capacity. Once an investment decision is made, the additional capacity comes online, and investment costs are tracked. When NPV equals zero at an internal rate of return (IRR) of 10%, the model remembers that year. Adding 3 years of capacity expansion delay to the tracked year indicates a potential year for the next investment. However, if the capacity is not utilized up to the minimum expected level (65%), no new investment is made.

Variable costs of pelleting include raw material cost, operating expenses (OPEX), and transportation cost. Raw material cost is calculated as the weighted average cost per dry tonne percent share of each feedstock used. This cost is converted to 9% moisture content wet basis. Transportation cost is fixed at $8.82 per tonne (wet basis). OPEX are calculated from a function of operating capacity \(x\) (Eqn 1). From this variable cost and pellet price, a markup ratio is calculated to define capacity utilization.

\[
-0.495 \times \ln(x) + 50.493
\]  

(1)

The level of capacity utilization determines how much raw material is procured for pellet production given a minimum inventory coverage of 8 weeks and safety coverage of 4 weeks, for a total coverage of 12 weeks. As the wood product sector module is constructed for loblolly based on the resource base, which accounts for 77.5% total pine supply, the desired woody material usage rate for pellet production is scaled down to calculate loblolly demand. Once the loblolly supply is calculated, this number is scaled up to reflect total pine supply. The pelleting process has a raw material loss of 25% on a dry weight basis (Pantaleo et al., 2014) or 17.5% conversion from dry materials to pellets with 9% moisture content wet basis.

The preferred feedstock for pellet production is mill residue (sawdust). The decision to substitute mill residue with other feedstock (i.e., logging residue, pulpwood, or sawtimmer) depends on the delivered price ratios between mill residue and the substitute(s). Logging residue is the closest substitute to mill residue in terms of price. However, we assume logging residues can only make up a maximum of 50% of the total feedstock supply due to their higher ash content and ash limitations in pellet quality standards. Pulpwood can theoretically make up all pelleting feedstock, but historical industry data from the US southeast have shown it to be at a maximum of...
85% (EC-DG-ENV 2015), which is also applied in our model. Sawtimber is generally eligible as feedstock for pellet and bioblendstock production. Its use is determined via price and the respective industry’s willingness to pay.

We distinguish between two main companion market demand schemes (Fig. S7):

1. **Business As Usual (BAU):** This reference case follows industry projections for US wood pellet export volumes which are expected to peak by 2024 and drop in following years due to the phase-out of subsidies in main demand states within the European Union.

2. **High:** The high scenario assumes that the excess production following the drop in export demand will be utilized in US biopower markets. Furthermore, it predicts a logarithmic increase in production until 2050 with an even split of additional capacity and production going to export and domestic biopower markets.

**Biofuel sector module and scenarios**

The demand for woody feedstock for the production of ARHC is taken from exogenous runs which combined the National Renewable Energy Laboratory’s (NREL) Automotive Deployment Options Projection Tool (ADOPT), projecting the future vehicle fleet, with NREL’s Biomass Scenario Model (BSM), projecting biorefinery capacity build-out (Dunn et al., 2017). BSM determines feedstock demand in willingness-to-pay (WTP) brackets between $22 and $220 per tonne in $22 increments (Fig. S8). Table S5 lists the main parameters used for the base-case simulation of the large-scale deployment of ARHC as the high-octane bioblendstock.

The achievement of a 15 billion liters bioblendstock production target for ARHC would require roughly 61 million dry tonnes of woody feedstock, depending on the conversion process. BSM simulation indicates that a maximum 11 billion liter production level for ARHC can be reached by 2050, largely impacted by an annual biorefinery capacity build-out limit of 25 mature plants (Dunn et al., 2017). This production level translates to roughly 45 million dry tonnes of woody feedstock by 2050. To reflect this level of feedstock demand, we implement the following bioblendstock scenarios:

1. **Business As Usual (BAU):** No policy incentives with a resulting maximum feedstock demand of 82 000 dry tonnes by 2050 at up to $22 per dry tonne.

2. **Steady:** Early and steady biorefinery deployment toward a total feedstock demand of 41.1 to 44.0 million dry tonnes by 2040 at up to $220 and $22 per dry tonne, respectively, equaling a production of 10–11 billion liters of ARHC.

3. **Exponential:** Late but exponential biorefinery deployment toward a total feedstock demand of 47.6–51.2 million dry tonnes by 2050 at up to $220 and $22 per dry tonne, respectively, equaling a production of 11.7–12.9 billion liters of ARHC.

Given feedstock quality requirements for thermochemical ARHC production routes (Biddy & Jones, 2013; Jones et al., 2013; Tan et al., 2015), pulpwood and wood pellets are considered preferred feedstock options over mill and logging residues. As a result, the model first compares pulpwood and pellet prices to determine the procurement amount. Following, demand for the next type of material is computed based on supply gaps. This iteration continues until the last type of material (i.e., logging residue) is considered.

The biofuel sector determines its pellet demand based on pellet supply prices. Combustion markets (export and US biopower) adjust their projected demand based on the pellet delivery delay. This creates the total pellet demand. Once the pellet sector procured biomass to meet the demand, it will supply to each sector based on their demand share. This is an approximation due to the lack of specific demand curves for each market.

Initial INL analysis on biorefinery reliability confirms that raw biomass handles very differently from pelleted material. First estimates show handling and conversion losses twice as much raw biomass has to be procured compared with pelleted biomass. To account for this benefit, we introduce a pellet factor, which can be adjusted by the user. The factor functions as a divisor of the delivered pellet price (i.e., halves the price at a factor of 2). Given the influence that this factor has on delivered feedstock prices and resulting feedstock competition, it is subject to sensitivity analysis.

**Scenario portfolio**

The scenario portfolio includes a reference case plus two segments covering traditional and new markets (Table 1). The Traditional Markets Scenarios (TMS) cover variations between the demand for pulp and paper and sawtimber. The New Markets Scenarios (NMS) cover variations in bioblendstocks and pellet market demands (i.e., domestic and export combustion markets).

**Results**

**Traditional market demand–supply dynamics (RQ1)**

In the reference case, feedstock prices increase moderately over the projection period (Fig. S9). Sawtimber and pulpwood see exponential price spikes post-2045 due to increasing supply shortages in both markets. The (endogenously modeled) pellet price spikes post-2045 due to increasing supply shortages in both markets. The (endogenously modeled) pellet capacity build-out and combustion market pellet sales closely match industry forecasts (Fig. S12). The pellet feedstock portfolio is initially dominated by mill residues with an increasing share of pulpwood and logging residues over time (Fig. S10), which matches historic and projected industry practice. When pulpwood prices continue to increase post-2040 the pellet feedstock portfolio shifts toward higher mill residue fractions. Biorefinery feedstock demand is fulfilled by pellets and pulpwood (Fig. S11). The overall low-bioblendstock feedstock demand in the reference case is not sufficient to create steady, long-term price signals to drive additional pelleting capacity buildout. All pellet supplies to bioblendstocks are redistributed to companion (combustion) market supply.
Demand from traditional markets is the foremost driver of forest resource base developments. Pulpwood is partially grown on purpose, but mostly a coproduct from sawtimber production. Pulpwood supply includes biomass from thinnings and a portion of timber harvest. If pulpwood demand outgrows timber demand, more thinnings could be conducted, but the biomass contribution of young trees is insignificant compared with pulpwood fraction in mature timber. As a result, sawtimber demand is the main determinant of pulpwood supply over time. In the TMS1 scenario, keeping traditional market demands for pulpwood and sawtimber stable influences feedstock supply negatively over time, especially for pulpwood. Switching to a pulpwood demand increase of 1% per year in the TMS2 amplifies the effects of pulpwood supply shortage and results in price increases. In both scenarios, pulpwood sees the strongest delivered price increase over any other feedstock (Fig. S13). The TMS3 keeps pulpwood demand stable while increasing sawtimber demand by 3% per year. This reduces the pulpwood shortages as additional pulpwood becomes available due to more timber harvest. The additional material closes the supply gap in the traditional markets and causes an overall moderate price increase across the feedstock markets in TMS3. Given these feedstock prices, pellet production again reaches industry projections, and US bioblendstock production is partially fulfilled by pellets originally aimed for sale in the companion market. The model is able to include or exclude sawtimber for energy use (in pellets or bioblendstocks). This reflects past discussions, for example, within pellet export markets in the European Union, to possibly ban sawtimber quality roundwood from use as energy feedstock. However, under a 1% traditional pulpwood demand increase as in the reference scenario, pulpwood supply shortages widen over time, which would most likely cause a resource utilization shift from sawtimber ending up in pulp mills and possibly also a relabeling of the resources in the field to be eligible for energy. Hence, our runs generally allow sawtimber to be utilized in energy markets. Results indicate that <20% of the feedstock would be sawtimber across all TMS for both pellet and bioblendstock production (Figs 1 and 2).

**Companion market demand-supply dynamics (RQ2)**

The NMS keep the traditional market settings at the reference case level, that is, an annual demand increase of 3% for sawtimber and 1% for pulpwood, respectively (Table 1). NMS1 and NMS2 both implement *Exponential* bioblendstock deployment scenarios with a *BAU* pellet demand in NMS1 and a *High* pellet demand in NMS2. NMS3 and NMS4 model a *Steady* bioblendstock demand scenario with a *BAU* pellet demand in NMS3 and a *High* pellet demand in NMS4.

Across all scenarios, pellet supply shifts from the companion to the bioblendstock market over time (Fig. 3). As the US biorefining industry (according to

### Table 1 The scenario portfolio includes a reference case and permutations of demand from traditional wood markets (Traditional Market Scenarios: TMS) as well as new markets (New Market Scenarios: NMS) including the demand by companion markets and bioblendstock (biofuel) production

| Scenario     | Reference | TMS1 | TMS2 | TMS3 | NMS1 | NMS2 | NMS3 | NMS4 |
|--------------|-----------|------|------|------|------|------|------|------|
| Sawtimber demand | +3% p.a. | Stable | Stable | +3% p.a. | +3% p.a. | +3% p.a. | +3% p.a. | +3% p.a. |
| Pulpwood demand | +1% p.a. | Stable | +1% p.a. | Stable | +1% p.a. | +1% p.a. | +1% p.a. | +1% p.a. |
| Pellet demand | BAU | BAU | BAU | BAU | BAU | High | BAU | High |
| Bioblendstock demand | BAU | BAU | BAU | BAU | Exponential | Exponential | Steady | Steady |

The gray highlights indicate reference case settings within the permutations.
BSM runs) has a higher WTP than export markets, pellet producers can increase pellet prices in correlation with feedstock price increases. This effect helps them maintain existing capacity utilization and open up opportunities for capacity expansion. All feedstock options are used in the NMS5. Allowing sawtimber to be used in pellet production relieves the supply stress and actually causes a growth in pellet production in the long-term for High companion market demand in both the Exponential (NMS2) and Steady scenarios (NMS4) (Fig. 3b, d). An ineligibility of sawtimber for energy use, combined with a growing supply gap in the pulpwood sector, restricts the resource base for pellets to the extent that production drops over time in NMS4 (Fig. S15).

The bioblendstock feedstock portfolio across the scenarios is mainly made up of pulpwood and pellets. All scenarios observe a widening supply gap for sawtimber and pulpwood over time. This supply gap is largest in NMS1 and NMS2 due to the higher bioblendstock demand volumes. Supply from logging and mill residues as well as sawtimber fractions remains low across all scenarios and only become competitive feedstock options when pulpwood prices are high in the out years (Figs 4a,b, S16 and S17). While outside the scope of this model, the supply gap could be reduced via, for example, short-rotation woody crops on nonforest land, which are expected to supply a growing share of US woody biomass (USDOE 2016).

Projected mobilization levels of commodity-type intermediates (RQ3)

In NMS1, it is questionable whether the prior excess pelleting capacity, following a drop in companion market demand around 2028, can be kept at a (very) low utilization level over the demand time lag of roughly 12 years until bioblendstock demand starts to increase (Fig. 5).

NMS2 accounts for domestic biopower expansion, which fills the void in export demand after 2028. This translates to higher pellet sales and related bioblendstock feedstock portfolio changes compared with the NMS1 (Fig. S15). NMS2 also expands pelleting capacity to account for US biopower demand. Nevertheless, pellet sales to bioblendstocks increase sharply after 2047 in NMS2 (Fig. 4). This is caused by additional pelleting capacity coming online (Fig. 5) due to consistent price signals over several years.

The earlier demand by bioblendstocks in NMS3 and NMS4 benefits the pellet capacity utilization (compare, e.g., NMS1 vs. NMS3 in Fig. 5) with higher pellet supply in the years following 2030. Additional demand from US biopower markets after 2028 expands pelleting

Fig. 1 The pellet feedstock production portfolio across the three Traditional Market Scenarios (TMS) is dominated by mill residues and pulpwood. Mill residue shortages are compensated by pulpwood and an increasing share of logging residues in later years. Simulation runs are performed with sawtimber as ineligible feedstock (a–c). Allowing sawtimber as pellet feedstock (d–f) does not change the portfolio drastically. Rather, sawtimber replaces some fraction of the pulpwood supply.
capacity and sales in the NMS4 to the highest observed level across all NMS runs (Fig. 5). This suggests that rather than a sudden high demand increase from bioblendstocks, a long-term consistent demand shows a stronger mobilization effect measured in total biomass processing capacity.
Sensitivity analysis

Initial INL analysis on biorefinery reliability confirms that raw biomass handles very differently from pelleted material. Preliminary estimates show that due to handling and conversion losses twice as much raw biomass has to be procured (plus additional processing lines) compared with pelleted biomass to achieve similar results.

Fig. 4  The biorefinery feedstock demand portfolio is dominated by pulpwood and pellets across all New Market Scenarios (NMS).

Fig. 5  The endogenous projections for pellet capacity build-out and pellet sales match the exogenous (historic and projected industry) data well across all New Market Scenarios (NMS). NMS1 (a) shows that when the expected drop in export pellet demand after 2027 is not compensated by domestic demand for biopower as in NMS2 (b) or bioblendstock as in NMS3 (c), overall pelleting capacity build-out stagnates, limiting pellet availability to US biorefineries in later years.

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annual production levels. To account for this benefit in a price driven model, we apply a pellet factor, which acts as a divisor of the delivered pellet price. Based on the aforementioned INL results, it is set at 2.0 in the reference, TMS and NMS runs. The results are sensitive to this factor, but we do not yet have a confirmed value for the thermochemical pathways underlying the ARHC production. Thus, we performed a Latin hypercube analysis with pellet factors of ±100%, that is, between 1.0 and 3.0, to determine the possible amount of wood pellets supplied to bioblendstock production (Fig. 6).

Figure 6 illustrates that despite a pellet factor of 1.0 (i.e., no handling, processing, or conversion yield benefit through utilizing pellets in bioblendstock production), pellets will still be demanded by bioblendstocks to a significant extent, out-competing combustion companion markets over time.

To determine the impact of different size companion markets on bioblendstock feedstock consumption over time, we compare the BAU vs. High companion market demands across the same scenarios for the other markets, that is, NMS2 vs. NMS1 and NMS4 vs. NMS3. A lower value (MIN) is calculated by subtracting annual individual percentiles:

$$\text{MIN}_i = \min(\{\text{NMS}_2^{\text{percentile}} - \text{NMS}_1^{\text{percentile}}; \text{NMS}_4^{\text{percentile}} - \text{NMS}_3^{\text{percentile}}\})$$

where: $i$: year; $j$: 10-percentile, 25-percentile, average, 75-percentile, 90-percentile.

An upper value (MAX) is calculated via the largest annual difference across the sensitivity runs:

$$\text{MAX}_i = \max(\max(\text{NMS}_2) - \min(\text{NMS}_1); \max(\text{NMS}_4) - \min(\text{NMS}_3))$$

where: $i$: year.

The difference between the scenarios shows that overall there is a positive impact on total pellet supplies to bioblendstocks given an initially larger companion market (demand). This is shown in the positive gap between a higher and lower companion market demand. The minimum difference across the NMS4 and NMS3 as well as NMS2 and NMS1 comparison reaches 4.3 million dry tonnes, equaling roughly six commercial-scale biorefineries or 1.1 billion liters of ARHC. The maximum impact of an initially larger companion market reaches 20 million dry tonnes, equivalent to 27 commercial-scale biorefineries or an additional amount of roughly 5 billion liters of ARHC (Fig. 7).

Discussion

The model results demonstrated that the supply base was mostly driven by traditional wood product demand. Sawtimber (mainly housing) markets were the foremost determinant of the long-term development of the resource base defining land management and harvest patterns. The potential impact of varying demand by the traditional forest products industry was critical to understand as it directly translated into pulpwood and residue availability over time.

Companion combustion markets were found to have a positive impact on the mobilization of biomass resources especially in the (initial) absence of biorefineries. We also found that biorefineries were able, in the long-term, to out-compete companion markets and directly benefit from the mobilized resources in intermediate/processed format (pellets). The results confirmed a direct relationship between an initially larger companion market and a long-term higher supply of processed biomass (pellets) to biorefineries. Through sensitivity analysis, it was determined that the impact of an initially larger companion market could be in the range of 20 million dry tonnes, equivalent to 27 commercial-scale biorefineries or an additional production of 5 billion liters of ARHC from a total production target of 15 billion liters of ARHC by 2050.

This modeling effort did not assume automatic fungibility across different feedstocks; a typical assumption in other modeling efforts. Rather, based on average quality characteristics, preferred feedstock per industry was determined, which allowed for stacked demand (i.e., rankings of preferred feedstock options). Also, residue clean-up was accounted for, based on cost data from INL State of Technology Feedstock Analysis (Hartley et al., 2016), which considers for instance typical contamination levels such as introduced soil, affecting supply price, and quantities within our model.

The model’s regional scope covers the nation’s primary wood basket with previously established, high-yielding pine plantations of the US southeast. It excludes agricultural land, which could be utilized to grow woody perennials. This limitation may reduce overall supply in our model and could possibly amplify the effects of supply shortages. However, the dynamics of energy crop deployment on agricultural land differ from forest management and therefore were excluded in this model version. Also, anecdotal evidence suggests that actual grower participation in new practices involving energy crop production may be lower than for crop or forest residues. An analysis of these adoption dynamics appears necessary before they can be incorporated in future model versions.

This modeling effort does not include a greenhouse gas (GHG) analysis component. A combined technoeconomic (TEA) and lifecycle analysis (LCA) for HOFs including ARHC has, however, been performed in conjunction with this analysis and is presently under
In the past. Assessments of similar supply chains covering the same forest biomass fractions from US southeastern forests, processed into wood pellets and transported to and used for instance in European combustion units have generally shown to provide net GHG benefits (Dwivedi et al., 2014; Jonker et al., 2014; Wang et al., 2015; Hanssen et al., 2017). The individual results depend on methodology and metric choices as well as framework assumptions; with most variability being introduced through differences in assumptions about the counterfactual scenario, that is, the reference system without bioenergy (Lamers & Junginger, 2013).

In this model, the feedstock demand for bioblendstock production was created exogenously. In the future, a direct link between this model and the BSM, for instance, could create additional insights into demand–supply dynamics between bioblendstock production and biomass processing capacity build-out (modeled endogenously within our model).

Furthermore, the build-out of processing infrastructure will have short- and long-term direct and induced effects on rural jobs and economic development. An analysis, for example, in conjunction with NREL’s Jobs and Economic Development Impact (JEDI) model could...
quantify the additional job and economic impacts of biomass mobilization through companion markets. Also, this model did not yet dynamically account for oil price changes and their potential effects on bioblendstock demand and operational costs, for example, transportation, which would influence delivered feedstock prices, and eventually total mobilized biomass volumes.

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Appendix S1. Supporting Information.

Figure S1. Installed US wood pellet capacity, monthly production and sales as of April 2017 (EIA 2017).

Figure S2. USDA Farm Production Regions (Source: https://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/documentation/#Maps).

Figure S3. Companion Market Model – Forestry (version 1.40).

Figure S4. Historic pulppwood and sawtimber data (Forest2Market 2015) from 2010 to 2014 with linear extrapolation towards 2050.

Figure S5. Softwood sawlog and pulpwood harvest projections in USDOE (2016) compared to a linear annual increase.

Figure S6. US wood pellet production by region and product in 2016 (EIA 2017).

Figure S7. US wood pellet demand scenarios.

Figure S8. Feedstock demand scenarios for the production of aromatic-rich hydrocarbon bio-blendstock within the $\leq$100 and $\leq$200/ton price brackets.

Figure S9. Reference scenario: delivered feedstock prices.

Figure S10. Reference scenario: pellet feedstock supply (dry tons) and portfolio (%).

Figure S11. Reference scenario: bio-blendstock feedstock supply (dry tons) and portfolio (%).

Figure S12. Reference scenario: pellet industry capacity and annual sales (dry tons).

Figure S13. Feedstock price developments across the Traditional Market Scenarios (TMS).

Figure S14. Feedstock price developments across the New Market Scenarios (NMS).

Figure S15. New Market Scenario (NMS): pellet supply distribution across markets when sawtimber is not eligible as energy feedstock.

Figure S16. New Market Scenarios: Pellet feedstock portfolio.

Figure S17. New Market Scenarios: Biofuel feedstock portfolio.

Figure S18. Difference in supply quantities to bio-blendstocks under sensitivity runs performed for NMS1 vs. NMS2 (Exponential bio-blendstock demand) and NMS3 vs. NMS4 (Steady bio-blendstock demand).

Table S1. Quality parameters for PFI and ENplus pellets.

Table S2. Materials from thinned and harvested trees corresponding with age and initial density.

Table S3. Historic pulppwood and sawtimber demand used to initialize the model (Forest2Market 2015).

Table S4. Transportation and handling costs for pulppwood and sawtimber per dry ton.

Table S5. ARHC blend base case simulation parameters (Dunn et al., 2017).