Economic impact of combined torrefaction and pelletization processes on forestry biomass supply

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Abstract

The cost of supplying wood biomass from forestry operations in remote areas has been an obstacle to expansion of forest-based bioenergy in much of the western United States. Economies of scale in the production of liquid fuels from lignocellulosic biomass feedstocks favor large centralized biorefineries. Increasing transportation efficiency through torrefaction and pelletization at distributed satellite facilities may serve as a means to expand the utilization of forestry residuals in biofuel production. To investigate this potential, a mixed-integer linear program was developed to optimize the feedstock supply chain design with and without distributed pretreatment. The model uses techno-economic assessment of scale-dependent biomass pretreatment processes from existing literature and multimodal biomass transportation cost evaluations derived from a spatially explicit network analysis as input. In addition, the sensitivity of the optimal system configuration was determined for variations of key input parameters including the production scale of pretreatment facilities, road and rail transportation costs, and feedstock procurement costs. Torrefaction and densification were found to reduce transportation costs by $0.84 per GJ and overall delivered costs by $0.24 per GJ, representing 14.5% and 5.2% cost reductions compared to feedstock collection without pretreatment. Significant uncertainties remain in terms of the costs associated with deploying torrefaction equipment at the scales modeled, but the level of potential cost savings suggests further analysis and development of these alternatives.

Keywords: biomass, densification, economics, geographical information system, logistics, optimization, pelletization, pretreatment, supply chain, torrefaction

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Introduction

Biofuels have the potential to substantially reduce fossil fuel dependence and greenhouse gas emissions from transportation and electricity generation. Bioenergy development also can facilitate regional economic growth from associated feedstock production. The US federal renewable fuel standard (RFS) (Congressional Budget Office, 2014) and the low carbon fuel standard (LCFS) in California (California Air Resources Board, 2010) have set ambitious greenhouse gas reduction goals that necessitate expansion in the production of bioenergy. In California, the available biomass that might be supplied for industrial processing was estimated to be about 36 Tg per yr in 2010, with projections of 40 Tg per yr by 2020 not including dedicated energy crops both on bone dry basis (Williams et al., 2008). At present, <15% of the available resource is used for energy purposes, mostly for direct combustion electric power generation (Kaffka et al., 2011). California has strong policy measures enforcing a renewable portfolio standard (RPS) for electric utilities as well as mandates for reductions in greenhouse gas emissions from all economic sectors. Bioenergy has some distinct attributes when compared to other renewables including ancillary forest health and landfill diversion effects. In addition, biomass can be stored and used on demand in complement to variable solar and wind to improve the overall performance of renewable energy systems. Despite a number of favorable characteristics, reductions in the levelized cost of electricity (LCOE) from solar photovoltaics and wind energy systems have made bioenergy increasingly more costly relative to other renewables (Pogson et al., 2013). The high cost of bioenergy is partly a result of the relatively high cost of feedstock acquisition in addition to escalating capital costs including emissions control. The potential for biomass to support baseload or load following electricity generating options and liquid fuel production for high-value transportation and other sectors continues to motivate technical innovation for its sustainable use (Jones, 2014; Milbrandt et al., 2014).
Biomass feedstocks produced from forest management activities are distributed across forested landscapes in varying amounts depending upon growing conditions, management practices, and policy factors. As a result, biomass procurement and transportation costs can vary greatly and have a profound effect on the overall production cost of energy. Previous studies have extensively explored spatially explicit supply chain designs in an attempt to optimize facility siting and scale to minimize cost or maximize profit (Dunnett et al., 2008; Parker et al., 2010; Tittmann et al., 2010; Parker, 2011). In these studies, total bioenergy production costs were derived using component costs for feedstock procurement, transportation, site-specific conversion costs, and fuel delivery costs into final demand. Sensitivity analysis in these studies showed that transportation costs have significant impact on the optimal system configuration, highlighting the potential advantages of increasing the efficiency of biomass feedstock transport.

The combination of torrefaction and pelletization is what is referred to by the Energy Research Center of the Netherlands (ECN) as the TOP process converts heterogeneous wood feedstock from forest management practices into a densified intermediate with higher energy and mass density than the original wood, albeit with some reduction in overall feedstock heating value due to the partial dry matter loss in conversion (Bergman, 2005; Bergman et al., 2005; Uslu et al., 2008). Dry, densified material results in reduced transport cost for feedstock delivery. Torrefaction and densification of feedstock reduce the volume of storage needed at a biorefinery, improve feedstock stability in storage, at least where dry storage is provided, and reduce onsite handling costs, which potentially result in higher economic performance in the fuel conversion process. Torrefaction increases the friability, which is advantageous for downstream size reduction via grinding or other comminution techniques (Bergman, 2005). In addition to these potential cost implications, higher efficiency in transport, storage, and processing can also reduce greenhouse gas and air pollutant emissions (Bergman, 2005; Uslu et al., 2008; Deutmeyer et al., 2012).

Nonetheless, torrefaction has not been broadly commercialized, and its economic benefit in the supply chain is still uncertain (Uslu et al., 2008; Van der Stelt et al., 2011). The purpose of this study was to evaluate the economic utility of torrefaction combined with densification in a biofuel supply chain to assess overall feasibility, recognizing that larger scale pilot facilities are still needed to reduce the uncertainty for commercial scale investments (Bergman, 2005; Koppejan et al., 2012). Specifically, we identify the size and location of TOP pretreatment in an optimized feedstock supply chain reflecting the specific geography of forests and transportation infrastructure in California as a model location. We use results of prior modeling work cited above as a basis for establishing the locations of biorefineries using woody biomass feedstocks. The results are used to derive the economic transport distance, at which pretreatment results in net reduction or breakeven in feedstock procurement costs compared to unprocessed feedstock, and to identify variable costs in the supply chain to which the solution is particularly sensitive.

The estimates were made using a spatially explicit supply chain optimization model based from those noted above and employing a cost-minimization objective. The model is general in approach and can be applied to other regions beyond California where sufficient data exist.

Materials and methods

To assess the economic impact of torrefaction and pelletization on woody biomass supply chains, a mixed-integer linear programming model was developed using transportation cost data from a geographical information system (GIS) analysis along with torrefaction and densification costs estimated for five pretreatment capacities or production scales. The optimization model was designed to assess whether such pretreatment could substantially reduce delivered costs of feedstock to biorefineries and if so, where and at what scale in the supply chain the pretreatment facilities should be located. The model was also employed to evaluate sensitivity of the optimal solution to the input assumptions.

Biomass feedstock supply chain network

The optimization model was based on the previous work of Parker et al. (2010) and Tittmann et al. (2010) modified to include an additional pretreatment stage within the model framework. In this case, the biomass supply chain network consists of three layers of nodes representing (i) feedstock supply, (ii) intermediate pretreatment, and (iii) biorefineries. Wood chips are compared with TOP feedstock delivered to or manufactured at the conversion facility. Wood chips are procured at feedstock source locations, typically log landings on industrial forest operations. TOP feedstock is assumed to be generated by conversion of wood chips at the log landing, at an intermediate location, or at the biorefinery.

The two primary benefits from the use of torrefied pellets in transportation are the higher mass and energy densities compared to bulk chips. For example, torrefied biomass has a higher heating value of 21.5 GJ per Mg dry basis compared with 17.5 GJ per Mg for dry wood chips, both on lower heating value basis. The higher mass density increases the transportation efficiency by reducing the unit shipment cost ($ per (GJ per km)) on dry basis, especially for rail transportation. Details of the multimodal transportation cost estimates are discussed in the input data section. Torrefied pellets can also offer advantages at the biorefinery (e.g., due to extra savings for storage
and maintenance, reduced energy demand for drying and size reduction of biomass feedstock before final conversion) for which a higher price at plant gate may be justified compared to green wood chips, offsetting the costs of pretreatment.

A schematic representation of the supply chain network is shown in Fig. 1. Note that potential pretreatment sites (\(J\)) include the biomass feedstock supply locations (\(I\)), intermediate potential locations (\(J_p\)), and biorefineries (\(J_b\)). Feedstock can be (i) delivered as wood chips to the biorefinery and used without pretreatment, (ii) pretreated at the landing and shipped as TOP material to the biorefinery, (iii) hauled as wood chip to an intermediate pretreatment facility and then shipped to the biorefinery as TOP material, or (iv) hauled as wood chip to the biorefinery and pretreated there. In this way, all the feedstock shipments start from sets \(I\), go through sets \(J\) (contains \(J_f\), \(J_p\), and \(J_b\)), and end in sets \(K\). We can formulate the problem as a mixed-integer linear program.

**Model formulation**

For convenience, all the notations used in the model are listed in Table 1.

**Model objective.** The model objective is to minimize the annualized total cost of supply given biomass demand and supply constraints for the biorefineries. System costs include procurement, pretreatment, transportation, as well as the avoided refining costs, if any, from utilization of torrefied pellets instead of wood chips at the biorefinery.

\[
\min \text{Cost}_{\text{pretreatment}} + \text{Cost}_{\text{transport}} + \text{Cost}_{\text{procurement}} - U 
\]

**Pretreatment cost.**

\[
\text{Cost}_{\text{pretreatment}} = \sum_{i \in J_f} \sum_{j \in J_p} F_{ij} \cdot X_{ij} \tag{2}
\]

Cost\(_{\text{pretreatment}}\) represents the costs to build and operate pretreatment facilities at different scales and locations.

**Transportation costs.**

\[
\text{Cost}_{\text{transport}} = \sum_{i \in J_f} \sum_{j \in J_p} \text{TO}_i Y_i^T + \sum_{j \in J_p} \sum_{k \in K} \text{TD}_j Z_j^T + \sum_{i \in J_f} \sum_{k \in K} \text{OD}_i Y_i^W \tag{3}
\]

\(\text{TO}_i\), \(\text{TD}_j\), and \(\text{OD}_i\) are unit costs for transporting one Mg (wet basis) of material through network edges (\(i, j\), \(j, k\), and \(i, k\)). Note that Cost\(_{\text{transport}}\) includes the transportation cost of both wood chips (TO, OD) and torrefied pellets (TD).

**Procurement costs.**

\[
\text{Cost}_{\text{procurement}} = C \cdot (\sum_{i \in J_f} \sum_{j \in J_p} Y_i^T + \sum_{i \in J_f} \sum_{k \in K} Y_i^W) \tag{4}
\]

\(C\) is the unit procurement cost. This cost reflects the assumption that wood used as feedstock for bioenergy applications would be a residual product from logging operations conducted to produce high-value solid wood products. Thus, for this analysis, the procurement cost is assumed to be only the cost of chipping and loading logging residuals piled at the log landing and does not include a production cost associated with growing or harvesting the trees, although the latter cost could be added for generality.

**Avoided costs due to use of TOP material.**

\[
U = \kappa \sum_{j \in J_p} \sum_{k \in K} \mu_j \cdot Z_j^T \tag{5}
\]

\(\mu_j\) is the LHV on a wet basis of torrefied pellets, and \(\kappa\) is the price premium paid ($ GJ^{-1}$) for dry torrefied pellet utilization by the receiving biorefineries.

**Model constraints**

**Supply and demand constraints.**

\[
\sum_{j \in J_f} Y_i^T + \sum_{k \in K} Y_i^W \leq S_i, \forall i \in I 
\]

\[
\sum_{j \in J_p} (1 - \lambda_j) \cdot Z_j^T + \sum_{k \in K} (1 - \lambda_k) \cdot Y_k^W \geq D_k, \forall k \in K \tag{6}
\]

\(\mu\) is the equivalence ratio between dry wood chips and torrefied pellets, and this ratio is calculated based on their energy content (dry basis, GJ per Mg) and the net efficiency of the pretreatment process (Bergman, 2005).
Technical characteristics of the TOP process. Torrefaction is a thermal process performed mostly at atmospheric pressure in the absence of oxygen, at temperatures ranging between 200° and 300 °C. Under these conditions, water and some dry matter (mostly due to hemicellulose decomposition) are volatilized and the resulting solid product becomes more friable. The process results in improved fuel quality for combustion and gasification applications. Torrefaction has not been widely commercialized; however, existing literature shows that torrefaction significantly increases energy density, hydrophobicity, friability, flowability, and combustion characteristics of biomass (Uslu et al., 2008; Ciołkosz & Wallace, 2011; Tumuluru et al., 2011; Van der Stelt et al., 2011; Deutmeyer et al., 2012; Koppejan et al., 2012; Shah et al., 2012). Grindability is improved such that size reduction to fine particles useful in entrained flow reactors and pulverized fuel units is achieved at lower energy input and lower cost and with greater uniformity. On a dry basis, torrefied biomass typically contains 70% of its initial weight and 90% of its initial energy content (Bergman, 2005). As torrefied biomass loses relatively more oxygen and hydrogen than carbon, the calorific value of the product usually increases due to the greater heating value of carbon compared with carbohydrate.
Torrefied biomass prior to densification possesses some undesirable properties for transportation and storage, including increased porosity and lower bulk density, decreased mechanical strength, and increased dust formation (Uslu et al., 2008). Densification has been widely suggested to ameliorate these issues. Pelletization densifies raw materials under pressure to improve uniformity and increase density. During pelletization, lignin present in wood or torrefied product typically weakens and flows, becoming a binding agent. Performance data for the TOP process as reported by ECN are listed in Table 2 (Bergman, 2005; Fiala & Bacenetti, 2012).

**Costs of TOP material production**

The economy of scale is a crucial factor influencing production cost and efficiency (Jenkins, 1997). The scale effect and the existence of an optimal investment cost for capital-intensive biomass pretreatment technologies have been investigated by Uslu et al. (2008). Lacking empirical economic data on pretreatment technologies at industrial scales, the economic evaluation of the TOP process from Bergman (2005) is referred to in this study as the base or reference case (Table 3). The formula \( C_0 = \left( \frac{M}{C_1} \right)^s \), where \( C \) (S) is the installed capital cost of a facility of capacity \( M \) (MWh), and \( C_0 \) (S) is the installed capital cost of the base plant facility of capacity \( M_0 \) (MWh), and a constant scaling factor of \( s = 0.7 \) is applied to model the scale effect on the TOP process, noting that a constant value may not adequately represent the economy of scale at very large sizes (Jenkins, 1997). Five representative biorefinery capacities with different capital investment costs were assumed as candidates for different locations along the supply chain in the following scenarios (Table 4).

**Biomass supply chain**

**Transportation network.** The transportation network in this study was modeled using data from the National Transportation Atlas Database (2011) of the Bureau of Transportation Statistics (Bureau of Transportation Statistics, 2011). The network includes multiple transport modes (highway, railway, and marine) for bulk biomass transportation as well as intermodal facilities and allows for unloading/loading (transloading) of biomass to shift between transportation modes. For biomass transportation between two specific nodes (e.g., forest landing to pretreatment facility or to biorefinery), rail or marine transportation could be used on long routes for economic benefit assuming transloading is an option. The network allows for direct deliveries to biorefineries via rail or marine routes if biorefineries are proximal to rail or marine routes, otherwise biorefineries must take delivery by truck.

**Feedstocks.** Forest biomass feedstock data used in this analysis are derived from Sethi & Simons (2005). The original data were generated at a 30-m spatial resolution. For the purposes of this analysis, 30-m pixels were aggregated to 1.6-km harvest units to reflect the likely size of operational units. Feedstock availability was estimated based upon forest type and ownership. Supply was annualized based upon an expected rotation of 60 years on private lands and 75 years on public lands. Forest land area with administrative restrictions (wilderness areas, roadless, etc), riparian buffer zones, and slopes >35% were excluded. The total feedstock resource in the original forest supply database was about 14 Tg, which was further reduced to approximately 12 Tg for this study by excluding feedstock points with <1000 Mg supply.

**Biorefineries.** Tittmann et al. (2010) identified optimal biorefinery locations in California based on supply chain and fuel

| **Table 2** Technical characteristics of the TOP process (Bergman, 2005; Fiala & Bacenetti, 2012) |
|-----------------------------------------------|
| **Properties** | **Unit** | **Green wood chips** | **TOP pellets** |
| Moisture content (wet basis) | wt% | 57% | 3% |
| Bulk density (wet basis) | kg m\(^{-3}\) | 326 | 800 |
| Bulk energy density (wet basis) | GJ m\(^{-3}\) | 2.0 | 16.6 |
| Heating value (LHV) | MJ kg\(^{-1}\) | 6.2 | 20.8 |
| LHV on dry basis | MJ kg\(^{-1}\) | 17.5 | 21.5 |

**Table 3 Economic characteristics of the TOP process (Bergman, 2005)**

| Item | **Unit** | **TOP process** |
|------|----------|-----------------|
| Feedstock type | | Green wood chips |
| Feedstock input | 1000 Mg per yr | 170 |
| TOP production capacity* | 1000 Mg per yr | 56 |
| Total capital investment | M$ | 9.3 |
| Total production cost† | $ per Mg | 62.5 |

*The ratio of feedstock input and TOP output will be used among all the representative scales in Table 4.
†Assumptions for this economic evaluation include 10-year depreciation period and 8000-h load factor.

**Table 4 Representative conversion scales for the TOP process**

| Scale/ID | Plant size | Specific investment cost ($ per Mg) |
|----------|------------|-----------------------------------|
| Distributed/Dist35* | 3.5 | 73.3 |
| Small | 28 | 39.9 |
| Medium 1/Med56 | 56 | 31.7 |
| Medium 2/Med105 | 105 | 26.4 |
| Large/Large210 | 210 | 21.5 |

* Distributed scale pretreatment is a mobile or portable process located at the primary collection point where wood chip van loading would take place (Renewable Fuel Technologies, LLC, 2010).
distribution costs but without considering the pretreatment options evaluated here. In the previous analysis, biorefineries could use feedstock from a range of sources (e.g., forest and agricultural residues). From the locations selected in the previous analysis, we identified the locations of all biorefineries using >10 dry Mg per yr of forest-sourced material, resulting in 20 distinct locations, from which we randomly selected 10 locations meeting the above criteria for this study. The baseline model considered 1.2 Tg per yr to be the maximum throughput in terms of feedstock at each biorefinery.

Potential locations for biomass pretreatment facilities. We assume that the selection of potential optimal locations for biomass pretreatment facilities would be significantly influenced by transportation accessibility and the geographical features of the transport network. The mean shift method (Fukunaga & Hostetler, 1975) was used to perform a clustering on all junction nodes in the road network. Junction nodes exist where two road segments intersect. Clustering was needed as in many cases multiple nodes were located in close proximity to a freeway interchange or overpass. The clustering resulted in 90 (of 5177) points selected as potential locations for pretreatment facilities. For the purpose of simplicity, we did not consider any other restrictions in selecting potential locations for biomass pretreatment facilities, such as labor and land use.

Transportation cost. Biomass transportation costs are modeled by the same cost function used by Tittmann et al. (2010) for three modes: truck, rail, and marine (Table 5).

The costs of trucking consist of two different components: a distance-dependent component and a time-dependent component. We assume that these two components do not vary by feedstock type.

Normally, trucks used for biomass transport have a weight limit of 25 Mg and a volume limit of approximately 120 m³ (Searcy & Hess, 2010). For both wood chips and torrefied pellets, the truck load is constrained by weight rather than volume. Greater advantage would accrue to trucks of higher weight capacity, but currently regulations do not provide for this. So, without any further information on truck transport, we assume that road transportation of torrefied pellets has the same unit cost ($) per Mg-km) compared with shipping green wood chips.

Rail transportation cost is derived from a mileage-based rate schedule for agricultural products. According to a freight transportation and logistics organization, a common rail car has a weight limit of about 100 Mg and a volume limit of about 150 m³ (EnviroModナル, 2012). The transportation of green wood chips in rail cars is volume limited as the total weight of 150 m³ (0.326 Mg/m³ × 150 m³ = 50 Mg) is less than the weight limit of a rail car (100 Mg). For TOP pellets with a mass density of 0.8 Mg/m³, the total weight is 120 Mg, which exceeds the 100 Mg limit; thus, rail cars carrying TOP pellets are weight-limited. Because rail car payloads for green wood chips and TOP pellets differ significantly, the unit transport cost for green wood chips was assumed to be twice as high as for pellets given the ratio of maximum weight per car all other costs being constant.

Similar to rail transportation, costs of marine shipment were derived from published rate schedules (Tidewater Inc., 2007). The size and capacity of barges provide that the actual payload for green wood chips and TOP pellets would both be weight-limited, so no difference in the unit transportation cost was assumed.

Table 5  Transportation cost components (on wet basis)

| Mode       | Cost component       | Green wood chips | Pelletized biomass |
|------------|----------------------|------------------|--------------------|
| Road       | Loading/unloading    | $ 5 per Mg       | $ 9.7 per Mg       |
|            | Time dependent       | $ 29.21 per h per truckload* | $ 0.008/(Mg-km)   |
|            | Distance dependent   | $ 1.10 per km per truckload† | $ 0.143/(Mg-km)   |
|            | Truck payload        | 25 Mg            | 100 Mg             |
| Rail       | Loading/unloading    | $ 5 per Mg       | $ 9.7 per Mg       |
|            | Fixed cost           | $ 19.5 per Mg    | $ 0.008/(Mg-km)   |
|            | Distance dependent   | $ 0.143/(Mg-km)  | $ 0.008/(Mg-km)   |
|            | Rail car capacity    | 50 Mg            | 100 Mg             |
| Waterway   | Loading/unloading    | $ 5 per Mg       | $ 9.7 per Mg       |
|            | Fixed cost           | $ 3.85 per Mg    | $ 0.008/(Mg-km)   |
|            | Distance dependent   | $ 0.027/(Mg-km)  | $ 0.008/(Mg-km)   |
|            | Barge capacity       | 3600 Mg          | 100 Mg             |

*Including capital cost of $ 18.80 per h and labor cost of $ 10.41 per h.
†Including fuel $ 0.83 per km, repair and maintenance $ 0.04 per km, and permits and licensing $ 0.21 per km; the truck fuel economy is assumed to be 1.42 km per L.

Scenarios

Sensitivity analysis was used to assess the impact of input parameters on the optimal solution. Variables evaluated were pretreatment capacity, diesel fuel price for portable and mobile equipment operation, unit transport cost of rail shipment, feedstock procurement cost, and potential cost savings for torrefied pellets with biomass conversion.

The pretreatment capacity is critical to the total investment cost and thus can significantly change the optimal supply system configuration. Besides the five representative candidate pretreatment scales selected in the baseline scenario, we set pretreatment capacity as a sensitivity variable with a range...
from 10 Gg to 210 Gg per yr and a much finer increment of 5000 Mg per yr to examine impact on the system.

Diesel fuel price is historically quite variable. Between July 2008 and March 2009, for example, diesel price ranged from $1.26 to $0.54 L$^{-1}$ (US Energy Information Administration, 2014). To represent this fluctuation and reflect the uncertainty in diesel fuel price, three price levels – $0.53, $0.93, and $1.32 L$^{-1}$ were used in the sensitivity analysis.

Rail transport costs are difficult to accurately predict. Bulk rail rates depend on the volume being transported; unit trains carrying a single commodity in 100–150 cars result in substantially lower cost than mixed load trains. Previous analyses have used a published rate schedule (Union Pacific Railroad, 2007) for mixed trains. This rate is estimated to be higher than what would likely be paid (Searcy et al., 2007). Sensitivity analysis was therefore conducted to reflect uncertainty regarding rail transport rates. For the fixed rail cost described in Table 5, we set its range from $5.5 per Mg to $26.5 per Mg with an increment of $7 per Mg on a wet basis.

The procurement cost range reflects the variability in costs associated with different harvest scenarios. Many industrial timber harvesting operations produce biomass at the landing in the form of tops and limbs. The low end procurement cost that is used in the base model makes the assumption that the limbs and tops at the landing are available at no cost and thus the only cost associated with procuring that material is incurred from chipping and loading. The high cost estimate assumes that all the costs from harvesting, yarding, chipping, and loading must be paid. Costs for high and low cases were calculated using the Fuels Reduction Cost Simulator (Fight et al., 2006).

The cost savings at biorefineries attributed to the utilization of torrefied pellets arise from reductions in energy demand for drying and size reduction of biomass feedstock at the biorefinery before final conversion. Not all conversion processes may benefit from the torrefaction of the feedstock, however. Other types of capital investment such as outside storage might also be lowered by pellet utilization due to the higher density in storage, although the need for more permanent structures to protect the quality of pellets might increase costs above more conventional outside storage of chips. While such cost savings are widely mentioned in literature (Bergman, 2005; Uslu et al., 2008; Deutmeyer et al., 2012; Koppejan et al., 2012), an accurate quantitative measure of such benefit is difficult due to limited empirical data. A range from 0 to $5 per GJ for the cost saving parameter is used, where $5 per GJ roughly corresponds to the point of 100% torrefied pellet utilization in our model analysis.

Results

The model was applied to California as a case study and solved using the Gurobi optimization solver (Gurobi Optimization, Inc, 2013). In this section, we first review the model baseline results with default assumptions specified in the input data section. Then, we present results of the sensitivity analysis conducted on the baseline model, followed by some scenario results to demonstrate the impact of integrating pretreatment into the bioenergy supply chain.

Baseline results

Here, we consider the baseline scenario using all 10 biorefineries and discuss pretreatment impacts on the forestry biomass supply system in California.

The feedstock supply system design. The optimal design of the baseline scenario makes use of three of the five possible pretreatment facility scales (Fig. 2). The relatively wide range of scales is partially due to large spatial variation in feedstock supply throughout the study region. Most of the pretreatment facilities are located close to some feedstock procurement location to take advantage of the reduced transportation cost of feedstock. For biorefineries that have abundant forest resources in the vicinity (such as the northern biorefineries in Fig. 2), all or at least a major proportion of biomass demand is met by green wood chips, while in cases of biorefineries that are located far from forest resources such as the central part of the state, long-distance pellet shipments becomes necessary.

Delivered costs. The total delivered cost is comprised of three components: feedstock procurement cost, pretreatment cost, and transportation cost.

Table 6 shows the average system cost breakdown for 1 GJ (dry basis) of biomass utilization at the biorefinery. The average total delivered cost with feedstock pretreatment is $4.36 per GJ, which is about $0.24 per GJ lower than a system without any pretreatment process. In the baseline scenario, 12.8% of the final biomass energy supply to refineries is pretreated, and the procurement cost is slightly higher than the no-pretreatment system due to the extra feedstock required to compensate for the material loss in pretreatment. The pretreatment production cost takes about 8% of the total system delivered cost. The transportation cost decreased from $4.14 per GJ to $3.54 per GJ and shows the potential of cost saving by biomass pretreatment.

Transportation modal split. In the biomass supply system, 35% of the feedstock energy shipped is by rail transportation, and 65% is truck transportation. For the same set of input data, the corresponding no-pretreatment system results in 25% of rail transportation usage and demonstrates the particular advantage of rail transport for high mass density material that results in a shift from volume limitation to weight limitation in transport, a feature not associated with the truck and marine transport in this analysis.
Feedstock supply curve. To further illustrate the impact of biomass pretreatment on the feedstock supply system, we compare the aggregated biomass supply curves for two system scenarios (Fig. 3). For the system without pretreatment, raw woodchip is the only option for biorefineries, and for the system that has a pretreatment option, refineries can choose to construct preprocessing facilities when necessary. As shown at the left bottom of Fig. 3, the average delivered costs of both systems are almost the same when the total biomass supply amount is small as only green wood chips in the vicinity of biorefineries are needed. As more biomass is required, the delivered costs of both systems start to increase, but for the system supplemented with torrefied pellets, the growth of delivered cost is not as rapid as in the system where only untreated biomass supply is provided. The

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difference in delivered cost grows to about $3 per GJ when the total feedstock supply is about 5 Tg per yr.

**Sensitivity analysis of the baseline model**

Iterative model runs were conducted with each changing a particular variable to evaluate the sensitivity of the results. Note that some of the input parameters directly affect the optimal solution; for example, unit feedstock procurement cost and TOP pellet utilization savings were taken as model inputs but also are part of the average delivered cost breakdown. So, we only examined the total delivered cost and the transportation cost components in the sensitivity analyses, instead of all four components of the system cost.

**Impact of pretreatment scale**

Figure 4 shows how average delivered cost ($ per GJ), average transport cost ($ per GJ), the proportion of energy in pellets delivered, and the fraction of rail transportation among all biomass shipments (energy basis) change with respect to changes in the pretreatment facility capacity. The total delivered cost and transport cost decrease from $4.6 to $4.4 per GJ and from $4.0 to $3.5 per GJ, respectively. Above approximately 100 Gg per yr, the transportation cost starts to fluctuate due to variable modal shift and the cost ceases to decline substantially. The fraction of biomass supply met by pellets has an increasing trend (from 2.3 to 14.5%) as pretreatment production capacities increase. Nonetheless, there are still fluctuations between 70 and 140 Gg per yr capacities.

Although preferred due to the economy of scale, larger facilities also require a greater amount of feedstock and will be ultimately limited by the feedstock availability and the rapid increase in delivered cost when approaching the limit of supply. There may also be technical and financial risks at very large sizes that are not represented in an assumption of constant scale factor (Jenkins, 1997).

The proportion of rail shipment also has an increasing trend from 24.5 to 38.3%. Although rail transport exhibits a cost benefit due to higher energy and mass

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**Table 6** System cost breakdown

| Average cost component | System with pretreatment process\* | System without pretreatment process |
|------------------------|-----------------------------------|-----------------------------------|
|                        | ($ per GJ, dry basis)              | ($ per Mg, wet basis)              |
| Total delivered cost   | 4.36                              | 4.60                              |
| Procurement            | 0.47                              | 0.46                              |
| Transportation         | 3.54                              | 4.14                              |
| Pretreatment (for pellets) | 2.74                          | –                                 |

\*The percent of feedstock pretreated is 12.8%.
†On torrefied pellets.
densities for torrefied pellets, building a pretreatment facility at an intermediate location still leads to extra biomass handling and transportation costs that depend on local network characteristics such as railway accessibility. For California, the fairly high percentage of railway transportation in all pretreatment-scale scenarios shown in Fig. 4 demonstrates how biomass pretreatment could benefit from rail transportation for long-distance shipment when a large amount of feedstock is required.

Impact of transportation cost parameters. The baseline result of the 10-biorefinery scenario indicates that transportation cost accounts for more than 80% of the total delivered cost.

In this section, we test the system with $0.53, $0.92 and $1.32 L⁻¹ diesel fuel prices. These different prices lead to about $0.50 per GJ differences in delivered cost and about $0.4 per GJ differences in transportation cost of the system. Higher diesel prices also encourage more TOP material utilization and rail transport. Note that although trucking of greenwood chips and pretreated biomass had the same unit costs as both were weight-limited, pellet utilization would still reduce the total tonnage of biomass transported due to the higher energy density and thus reduce the total feedstock transportation cost. The diesel price increment brings about 5–10% increase in TOP utilization and about 10–15% more rail transportation, measured in Mg-km.

Rail cost change has less impact on the system cost, partially due to the assumption that rail is less expensive than trucking for biomass delivery on a $ per GJ-km basis. A $21 per Mg increase in fixed rail cost only leads to about $0.5 per GJ increase in delivered cost and about $0.40 per GJ increase in transportation cost. On the other hand, a $21 per Mg rail cost difference results in about 5 to 10% decrease in TOP utilization and as much as 30% decrease in the proportion of transportation by rail.

Impact of procurement cost and TOP utilization savings. Lastly, we explored the impact of procurement cost and TOP utilization savings to the system.

Procurement cost has a negative impact on TOP pellet utilization, as higher procurement cost of feedstocks on a wet basis makes torrefied pellets less affordable due to the energy and material loss in the pretreatment process. In our test, the difference between a $3.5 per Mg and $40.0 per Mg procurement cost could lead to a 20% difference in TOP utilization and 10% difference in the proportion of transportation by rail.

The increase of pellet-derived savings at biorefineries, on the other hand, can lead to a significant rise in TOP utilization and rail transportation. Our investigation indicates that a $5 per GJ TOP cost saving would lead to only pellets being used and the fraction transported by rail would reach about 40%.

Model scenarios

Single-biorefinery scenario. We first studied two single-biorefinery systems, of which one has access to abundant feedstock resources within short distances (Redding biorefinery, Fig. 2) and one that does not (Scotts Valley biorefinery, Fig. 2). In both cases, the demand of the biorefinery was increased from 1.2 Tg per yr to 12 Tg per yr on a wet basis. The average delivered or transportation cost, proportion of torrefied pellet utilization, and rail transport under various biomass demands for the two single-biorefinery scenarios are plotted in Fig. 5.

For the biorefinery at Redding (Fig. 5a) note that before pretreatment becomes preferred, the gap between average delivered cost and transportation cost remains about the same, which means that the increase in total delivered cost is mostly due to the rise of transportation cost of biomass deliveries over longer distances. Pretreatment starts to be utilized when the demand exceeds 6.6 Tg per yr, and the proportion of torrefied pellets on an energy basis grows to about 33% at the largest demand. Railway transport for biomass delivery starts at 9 Tg per yr and increases to about 37% on a wet Mg-km basis.

For the biorefinery at Scotts Valley (Fig. 5b) where local biomass resource is scarce, pretreatment starts at 3 Tg per yr demand and reaches about 65 percent at 12 Tg per yr demand. Railway transport starts to be used at 5.4 Tg per yr and grows to about 50% at the largest demand. As a major share of the feedstock is procured from longer distances compared to the Redding biorefinery, both pretreatment and rail transport become part of the solution at smaller demands and reach higher proportions. Note that the average transportation cost has a noticeable decline right after pretreatment becomes preferred, a trend absent from the Redding analysis. Pretreatment reduces the transportation cost more significantly on long-distance deliveries, and the Scotts Valley biorefinery also receives more torrefied pellets than the Redding biorefinery.

The single-biorefinery scenario illustrates that TOP pretreatment can help in logistics by providing feedstock to a facility that needs to source feedstock from a long distance, and particularly, it takes advantage of rail transportation for long-distance feedstock shipments.

Impact of increased feedstock demand on pretreatment location. In the 10-biorefinery baseline scenario, the biorefinery at Scotts Valley (Fig. 2) receives torrefied pellets from the pretreatment facilities in the far north of California. The long-distance shipment passes close to
several biorefineries in the north. The question arises: why not ship to closer biorefineries? This model result reflects the capacity constraint imposed on all biorefinery locations of 1.2 Tg per yr in the baseline scenario. Although closer locations would minimize transport cost, the total capacity constraint means that facility needs have already been met while additional feedstock is still available. To test how variability in demand at specific locations would impact the pretreatment and biomass procurement cost for more distant biorefineries, the baseline model was perturbed, increasing the capacity of the Chico refinery to 2.4 Tg per yr (Fig. 2). Due to this demand increase, biomass resources in the north no longer feed the refinery at Scotts Valley, and instead of building two pretreatment facilities in the north as included in the baseline scenario (Fig. 2), another pretreatment facility is deployed in the southern part of the state to ship torrefied pellets to the biorefinery at Scotts Valley in meeting the required demand there. Alternatively, the Scotts Valley biorefinery might not be constructed or requires strategies such as contracting with biomass providers to ensure feedstock supply in a competitive and uncertain market.

Figure 6 reflects supply curves for feedstock delivered to the Scotts Valley biorefinery under several scenarios. For the baseline configuration with and without pretreatment, a dramatic reduction (≈ $5 per GJ) in the cost of procuring feedstock is achieved with the introduction of pretreatment. In addition, when the demand for feedstock is doubled at the Chico refinery, the Scotts Valley facility is in a much better position to make up for lost supply at substantially less cost with pretreatment than without, although at higher and potentially uncompetitive cost overall.

Discussion

The model analysis shows that torrefied pellet utilization can under some conditions reduce the total cost of a biomass supply system, especially through reductions in transportation cost for long-distance feedstock deliveries. In the baseline scenario, the total delivered feedstock and transportation costs of an optimal biomass supply system including pretreatment facilities are 5.2% (0.24 $ per GJ) and 14.5% (0.84 $ per GJ) lower than the optimal system without biomass pretreatment.

Critical factors affecting the economic performance of the biomass supply chain with pretreatment were investigated through sensitivity analysis. The deployment of a pretreatment facility is crucially dependent on the demand and the spatial characteristics of the biorefineries and the feedstock supply. Economies of scale have significant impact at smaller pretreatment sizes, but have less effect beyond about 100 Gg per yr. Lower feedstock procurement and higher truck transportation costs both increase torrefied pellet utilization. Depending on the diesel fuel and fixed rail prices and the location of a pretreatment facility, rail transport could

Fig. 5 The impact of feedstock demand on the single-refinery systems. Note that the average delivered cost and transportation cost use the left axis, and the percentage of TOP utilization and rail transportation use the right axis. (a) Redding biorefinery. (b) Scotts Valley biorefinery.

Fig. 6 Aggregated feedstock supply curve of the Scotts Valley biorefinery.
handle as much as half of the total biomass energy or as little as 15% in the case of high fixed rail cost and low diesel price scenarios.

The model addresses the feasibility and design configuration with pretreatment included in the biomass supply system. The results provide insight into the potential for combined torrefaction and pelletization in reducing costs of bioenergy feedstocks from California forests. The modeling framework is flexible and could also be implemented in the investigation of other types of feedstock, pretreatment, and facility location.

The present model is limited in several ways. The additional cost savings at biorefineries brought about by torrefied pellet utilization is varied from zero in the baseline scenario to as high as $5 per GJ in the sensitivity analysis. This effect is highly uncertain; however, and for some processes, torrefied material may not represent a higher quality feedstock and hence could increase conversion costs if used. Additional information and research are needed to assess these quality implications. The model as currently implemented also ignores biomass imports and does not consider torrefied pellets as a commodity for sale on the market, including export, which may influence the feasibility and profitability of pretreatment facilities. Impacts on the transportation network, such as traffic congestion, statewide or regional railway capacities, and other factors, were also not considered.

Conclusions

Feedstock pretreatment through combined torrefaction and pelletization to produce TOP material is shown to enhance the flexibility and profitability of a biomass supply system when long-distance delivery is needed. For woody biomass supply in California, the TOP process reduces the total delivered cost and transportation cost by about 5% and 15%. Where transportation distances typically are <300 km, wood chips are, however, preferred over torrefied and pelleted material.

It is likely that initial investments in relatively small biofuel production facilities will be made in locations close to plentiful feedstock with relatively low transportation costs, making pretreatment unlikely. However, as the industry expands to meet a broader regional supply potential or draw feedstock from outside the region, larger facilities relying on diverse sources of feedstock with longer supply chains are more likely. In this later stage of industrial development, pretreatment such as evaluated here can result in lower procurement costs.

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