Check for updates

Modeling and Analysis

Biofpr Biofuels Bioproducts & Biorefining

Biorefinery siting and sizing to achieve the US Billion-Ton Bioeconomy vision: A case study using a gasification–Fischer–Tropsch process

Dipti Kamath, Oluwafemi Oyedeji , Scott Curran , Matthew Langholtz , Ingrid Busch, Timothy Theiss, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA

Received July 24 2025; Revised December 29 2025; Accepted January 19 2026;
View online at Wiley Online Library (wileyonlinelibrary.com);
DOI: 10.1002/bbb.70136; *Biofuels, Bioprod. Bioref.* (2026)

Abstract: Achieving a secure, abundant, and affordable energy future requires a robust and adaptable energy strategy, with bioenergy playing a pivotal role. Biomass-based energy presents a promising pathway to use domestic resources while fostering economic opportunities in rural areas. Despite the potential to source more than 1 billion dry short tons of biomass annually in the US, significant infrastructure and economic barriers hinder full utilization for energy production. This study used the Biofuel Infrastructure, Logistics, and Transportation (BILT) model to assess biorefinery siting and scale and determine the number and size of facilities required to maximize use of the US biomass potential. A spatially agnostic approach first assessed the effects of facility capacity and transportation constraints on biomass use. Then, a spatially explicit analysis integrated county-level biomass availability from the US Department of Energy's 2023 Billion-Ton Report and technoeconomic assessments to evaluate different biorefinery deployment scenarios. The results indicate that an optimized mix of facility sizes is essential to leverage biomass resources fully across varying regional production densities to maximize use of the US biomass potential. Larger biorefineries or co-located smaller facilities significantly enhance biomass use while reducing costs through economies of scale. These findings underscore the importance of strategically balancing facility capacity and spatial distribution to optimize the bioenergy supply chain. This study provides critical insights for advancing the US bioenergy economy by aligning biorefinery deployment with biomass resource availability and economic viability. © 2026 Society of Industrial Chemistry and John Wiley & Sons Ltd.

Correspondence to: Oluwafemi Oyedeji, Oak Ridge National Laboratory, 1 Bethel Valley Rd., Oak Ridge, TN 37830, USA.
E-mail: oyedejia@ornl.gov

Disclaimer: This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

Supporting information may be found in the online version of this article.

Key words: bioenergy; biorefinery capacity; biomass use; Billion-Ton Report; BILT model; spatial optimization; supply-chain analysis

Introduction

Bioenergy plays an important role in strengthening the US energy mix for secure, reliable, and affordable energy sources that support different technologies across the key sectors of transportation, industry, and residential/commercial buildings. Bioenergy production in the US has increased substantially over the last few decades (Fig. 1). According to the US Energy Information Administration (EIA), 93.7 quads of primary energy were consumed in the US in 2023, with petroleum, natural gas, coal, and nonfossil energy contributing 35.5, 33.7, 8.2, and 8.3 quads, respectively.[1] In the context of the current energy mix, in which fossil fuels are predominant, bioenergy represents a scalable, nonfossil domestic energy source.

Biomass-based energy, which includes waste (4.7%), wood (23.4%), and biofuels (32.2%), accounted for a combined 60.4% of total nonfossil energy consumption in 2023. Biomass sources – such as food waste, municipal solid waste, animal waste, agricultural and forest residues, and dedicated energy crops – offer domestic alternative energy sources while also creating economic opportunities in rural areas. However, the full potential of biomass-based energy remains largely untapped because of infrastructure gaps, high initial investment costs, and the need for technological advancements. The US Department of Energy's (DOE's) 2016 Billion-Ton Report,[2] and its most recent update, the 2023 Billion-Ton Report,[3] estimate that the US has an economically and environmentally sustainable production capacity of 0.7–1.7 billion dry tons (i.e., ~2–4 times current biomass use) of biomass annually from across the contiguous US states, presenting a major opportunity to expand the bioenergy economy.

Expanding the US bioenergy economy to use the approximately 1 billion tons of potentially renewable biomass will require investments in new energy crops, infrastructure for transporting and processing biomass, and biorefineries and conversion technologies to maximize the energy production potential of biomass-based energy sources. To exploit the potential of biomass-based energy resources fully, the economics of the entire supply chain – from growing biomass across different regions to conversion, and to delivery to different end-use sectors – must be considered by strategically deploying new investments. This necessitates a comprehensive approach that accounts for each step of the bioenergy supply chain. A key consideration in achieving these goals is the optimal scale of biorefineries. This factor involves leveraging the spatial distribution of existing and potential future biomass resources across different feedstock types and locations while taking advantage of economies of scale. By identifying the appropriate biorefinery size, the US can enhance operational efficiency, reduce costs, and strategically utilize biomass resources to their full potential.

A model biorefinery of 2205 tons per day (2000 metric tonnes per day) has become a standard reference for

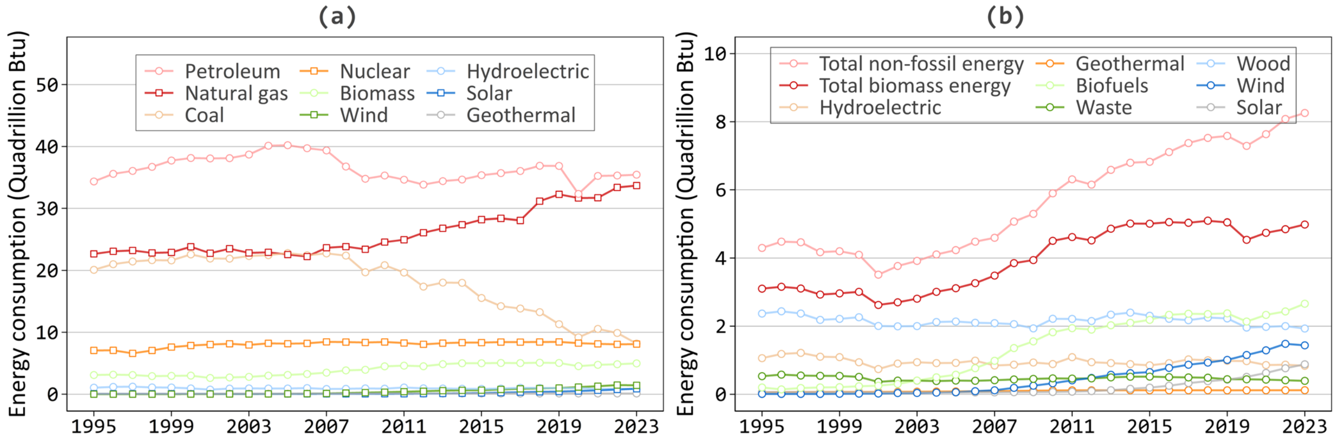


Figure 1. United States' primary energy consumption (1995–2023). (a) Primary energy consumption by source. (b) Primary nonfossil energy consumption by source and total consumption. Data from the US Energy Information Administration (EIA).[1]

conceptual designs and economic assessments for early-stage bioenergy conversion processes.[4–7] Limited analysis has been conducted (a) to understand whether this biorefinery size can fully utilize available biomass resources and (b) to account for the pronounced heterogeneity in the spatial distribution and production density of US biomass. Further studies are needed to evaluate the number and size of biorefineries – in terms of operational capacity and spatial distribution – to cost-effectively exploit US biomass resources and energy sources. Larger scale facilities may be feasible and economically viable in regions with dense and consistent biomass supply. To put this in perspective, the production capacity of 2205 tons per day biorefineries (about 23–64 million gal of gasoline equivalent (2.9–8.1 million GJ) per year)[6,8–12] is significantly smaller than the capacity of large existing corn ethanol plants (about 100–270 million gal of gasoline equivalent (12.7–34.2 million GJ) per year).[13]

Research at the DOE's Idaho National Laboratory (INL), Michigan State University (MSU), and Michigan Biotechnology Institute (MBI) has extensively examined the role of intermediate biomass processing depots in enabling large-scale, cost-effective biorefinery deployment.[14–16] These studies demonstrated that decentralizing certain preprocessing steps – such as densification, pretreatment, or feedstock stabilization – can reduce transportation costs, mitigate feedstock variability, and expand the feasible siting radius for conversion facilities. Such 'depot-enabled' supply systems were shown to influence both biorefinery scale and location decisions, providing a foundation for the evolution of a mature bioeconomy infrastructure.

The present analysis differs in scope and focus. Rather than modeling depot networks directly, it explores the system-level implications of varying biorefinery scales, spacing, and economies of scale under a mature-market scenario in which feedstock logistics are assumed to be reliable and relatively uniform. The results complement the earlier depot studies by examining the upper level spatial and economic outcomes that could emerge once feedstock aggregation constraints have been alleviated through logistical innovations.

This study employs the Biofuel Infrastructure, Logistics, and Transportation (BILT) model, developed by DOE's Oak Ridge National Laboratory, to better understand optimal siting for biorefineries to exploit the potential US biomass supply fully. This approach integrates county-level resolved feedstock availability and technoeconomic analysis data to ensure that facility placement minimizes economic costs while maximizing biomass potential supply utilization. A spatially agnostic approach – one that assumes homogeneous feedstock distribution and does not account for actual variations in biomass availability – is used to provide a broad overview and serve as a preliminary analysis before application of the more detailed, spatially explicit modeling approach.

Approach

Two approaches were employed to analyze the siting of biorefineries needed to harness about 1 billion dry tons of biomass in the US annually. The future scenario assumed no funding constraints on the number of biorefineries and used only the gasification–Fischer–Tropsch process as a case study. First, a spatially agnostic approach was applied, as detailed in the following subsection of this paper. Next, a spatially explicit approach using the BILT model was employed, as detailed in the subsequent subsection.

Spatially agnostic siting approach

A simplified analysis was conducted to estimate the characteristics of biorefinery facilities required to use the full potential US biomass supply without considering the spatial distribution of biomass feedstock or regional feedstock supply characteristics. As a result of its inherent simplifications, this spatially agnostic analysis offers only a rough approximation of the requisite number and size of biorefinery facilities. Nevertheless, it provides an initial framework for evaluating biorefinery siting needs and supports subsequent detailed analyses using the BILT model. The number of biorefinery facilities needed and the resulting interfacility distance were calculated as expressed in Eqns (1) and (2), respectively.

$$N = \frac{1}{C \times t} \sum_{i=i}^{k} S_i \tag{1}$$

$$d = \sqrt{\frac{2 \sum_{i=i}^{k} A_i}{\sqrt{3}\,N}} \tag{2}$$

where N is the number of biorefinery facilities needed to consume the potential biomass feedstock supply, d is the average interfacility distance (miles), C is the nominal daily biorefinery facility capacity (tons per day), t is the number of operating days per year, k is the number of US counties with sufficient biomass supply to meet the feedstock demand of a biorefinery facility, S_i is the potential biomass feedstock supply of the ith county (tons per year), and A_i is the land area of the ith county (square miles).

This analysis considered only the mature-market scenario of BT23 for the potential biomass supply. The mature-market scenario estimates that about 857 million tons (775 million tonnes) of potential biomass will be available at a price of ≤$100 per ton. This supply estimate includes only potential forest resources, agricultural residues, and woody and herbaceous energy crops but does not include wet waste resources, macroalgae, and 'currently used biomass' resources. The potential wet waste resources are expected to be used for biogas production, which is not considered in this analysis. The demand for, and use of, the 'currently used biomass' resources are expected to be preserved, with no significant changes to their current allocation profile.

The following baseline assumptions were made of commercial-scale facilities: capacity of 2205 tons per day, maximum feedstock supply radius of 50 miles (80.47 km), and operating period of 330 days per year. Hence, a biomass production density of at least 93 tons per square mile (35.9 tons per square km) is required to meet the feedstock demand of the biorefinery facilities. Only counties with a potential biomass supply of at least 93 tons per square mile were considered for this baseline assumption. The spatially agnostic approach was also used to assess how biorefinery siting criteria change with variations in facility capacity and feedstock supply radius.

Spatially explicit siting approach using the BILT model

The BILT model is an accounting and optimization model that tracks the entire biomass supply chain to its end use, including biomass production, transportation, and processing, across potential feedstocks and conversion pathways. It constructs an objective metric cost curve by determining the maximum (or minimum) value of a target metric and then solving a series of cost-minimization subproblems, each seeking to determine the least cost way to achieve a specified level of that metric. It allows for an analysis of routes and end uses that compete for shared resources. A differentiating feature of the BILT model is the spatial resolution of inputs and outputs, including the distribution of biomass, infrastructure, and siting of potential facilities for different stages of the biomass-to-biofuel/bioproduct conversion process. Figure 2 illustrates the accounting framework used for biofuel production – in this case, for the gasification–Fischer–Tropsch process – accounting for crop cultivation through biofuel use. Based on the assumptions described in subsequent sections, the BILT framework sites biorefineries and optimizes their locations to achieve the selected optimization metric at minimum cost. In this study, the optimization metric is maximization of biomass utilization. This approach provides results in number of biorefineries and locations similar to the results of other optimization metrics, including those reported by Oyedeji *et al.*[17] Other optimization metrics, such as maximizing total fuel production, could be applied but are not expected to materially alter the siting results of this study.

In addition to unveiling the geographical distribution of biorefineries and the cost of biofuels, this spatially explicit modeling approach yielded comprehensive insights into the breakdown of feedstock consumption by type, location, and production volumes of diverse biofuels.

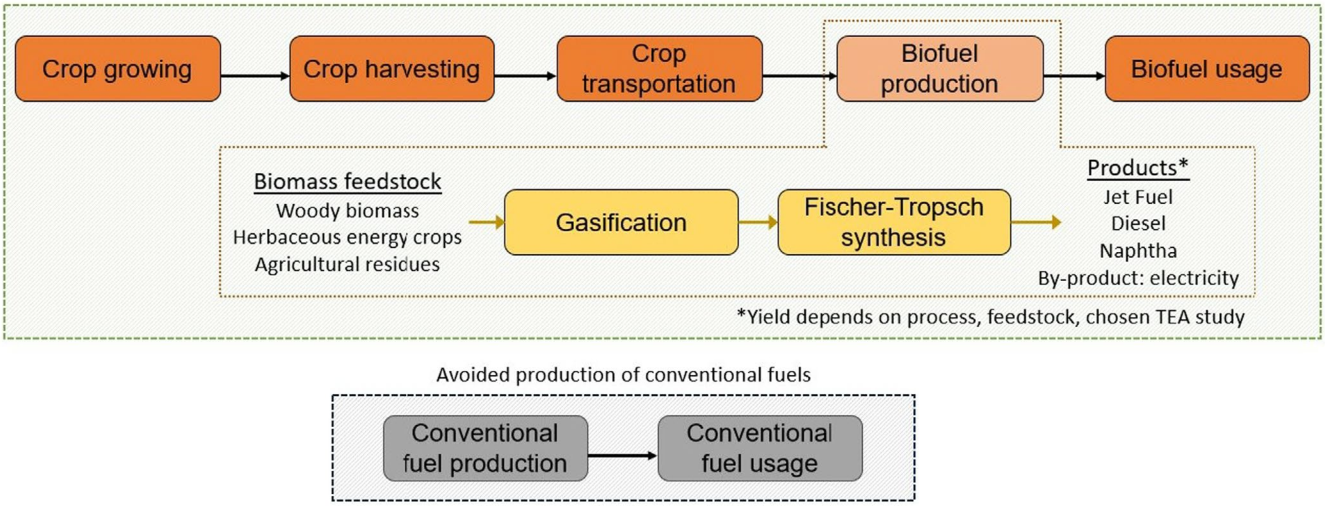


Figure 2. The system boundary for biofuel production through the gasification–Fischer–Tropsch pathway, and displaced conventional fuels.

Data and assumptions used in the BILT model

This study addressed the range of biorefinery facility sizes required to utilize effectively the approximately 1 billion tons of biomass available annually, considering its spatial distribution throughout the contiguous US. The gasification–Fischer–Tropsch process was chosen because of its advanced technology readiness level for biofuel production and its ability to use multiple feedstocks. The availability of peer-reviewed economic factors for the process also facilitated a comprehensive dataset for this analysis.

Feedstock availability and data sources

The US potential biomass availability data were extracted from BT23. The report is not a projection but instead estimates the biomass resources that could be available in the contiguous US if markets for biomass resources develop. The report details methods for quantifying biomass wastes, agricultural residues, forestland resources, and biomass crops and provides county-level resource information as a function of price, scenario, and time. The present analysis used county-level cellulosic biomass resources from the base case modeled as potentially available in a mature market at prices up to \$100 per dry ton, at the roadside (farm gate), before transportation, in 2022 US dollars, as described in the report, indicating up to 850 million tons of biomass nationally. Marginal supplies were calculated in \$10 increments to allow resource availability to be modeled as a function of price.

Biorefinery siting criteria

Initializing potential facility locations involved delineating specific criteria that an appropriate site must meet. The Oak Ridge-Siting Analysis for Power Generation Expansion tool (OR-SAGE) was used to generate landmass areas over the 48 contiguous US states that satisfy each criterion (Supporting Information, Fig. S1). There were six exclusion criteria and one inclusion criterion. The exclusion criteria were areas with high population density (more than 500 people per square mile (193 people per square km)), wetlands or open water, protected lands, slope greater than 12% grade, landslide hazard, and 100-year floodplain. The inclusion criterion required that biorefineries be located within 20 miles (32.19 km) of a cooling water source with a flow rate of at least 125 000 gal min^{-1}.

The landmass areas generated by OR-SAGE were adapted into a more manageable format to provide the BILT model with a predefined set of potential locations. The adaptation process involved a 'blanketing' procedure in which the US was systematically surveyed in 6.21 mile (10 km) increments both horizontally and vertically. The surrounding area of each testing site was assessed to determine the percentage of suitable locations within a specified radius. Only sites with at least 75% suitability within the radius progressed to the next step (Supporting Information, Fig. S2). Finally, the process generated a grid of suitable points (Supporting Information, Fig. S3).

The locations were further adapted to reduce the number of discrete points. A process was developed to streamline this set of locations while ensuring that the resulting usable set of locations was representative of the original suitability areas produced by OR-SAGE. An outline of the process follows:

1. Place all location points into set A, and create an empty set, set B. Designate a threshold distance, d (typically 50 miles).
2. Determine the point in set A that is farthest from any other point in set A. Remove this point from set A and place it in set B.
3. Calculate the distance from each point, p, in set A to each point, q, in set B and call this distance $d(p,q)$.
4. For each p in set A, determine the minimum distance to a point in set B and call it $d(p)$.
5. Choose the point, p', in set A that maximizes the minimum distance to a point in set B. That is, p' achieves Eqn (3):

$$d(p') = \min_{p \in A} \max_{q \in B} d(p,q) \tag{3}$$

6. If $g < d$ (the threshold distance from step 1), then quit. Set B is the set of potential facility sites.
7. Add p' to set B and go to step 3.

This process, with a threshold distance (d) set to 50 miles, resulted in the set of potential locations shown in Fig. 3. The threshold distance is not an intersite distance but, rather, is a termination criterion for the process. That is, the process stops when the next point to be added is within this distance (typically 50 miles) of another site already designated as a potential site. Any site not in set B is necessarily within distance d of a site in set B.

Biofuel production cost assumptions

Biorefineries in this study are assumed to produce a mix of biofuels (jet fuel, diesel, and naphtha) as the main products and electricity as a byproduct of the gasification–Fischer–Tropsch process, as shown in Fig. 2. The broad feedstock categories considered are woody biomass, herbaceous energy

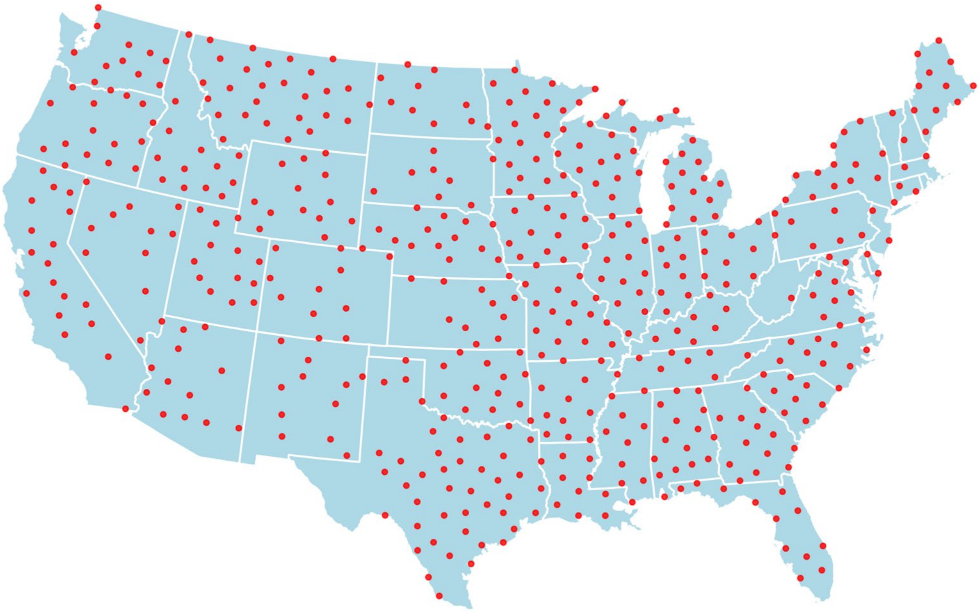


Figure 3. The set of potential facility locations identified based on landmass areas generated by OR-SAGE and further adaptation procedures (threshold distance = 50 miles).

crops, and agricultural residues. Multiple peer-reviewed journal articles were reviewed to obtain the yields of the different biofuels and the associated cost (capital expenditure and operating cost).[18–22] All costs were converted to 2022 US dollars using relevant consumer price indices and foreign currency rates. The biorefineries were all assumed to have an average lifetime of 25 years, with an availability of 330 days per year.[6,10,12,23]

The analysis was conducted by running specific scenarios in the BILT model to determine how all available biomass could be utilized. The following scenarios were considered:

1. Baseline scenario (model biorefinery). This scenario assumes biorefineries with a capacity of 2205 dry tons per day, consistent with values commonly reported in the literature. The threshold interfacility distance is assumed to be 50 miles.
2. Scenario 1 (large biorefinery). This scenario assumes larger capacities in addition to the baseline size – specifically 1×, 3×, 5×, and 10× the standard 2205 dry tons per day capacity. The threshold interfacility distance remains 50 miles. As biorefinery capacity increases, levelized capital and operating costs are assumed to decrease with an economies of scale factor of 0.7.[10,12]
3. Scenario 2 (co-located biorefinery). This scenario assumes standard 2205 dry tons per day biorefineries co-located in groups of 1×, 3×, 5×, and 10×. Biorefinery costs do not change, indicating a lack of economies of scale.
4. Scenario 3 (model biorefinery with lower threshold distance). This scenario follows the baseline scenario but reduces the threshold interfacility distance to 25 miles, allowing for a greater number of locations.
5. Scenario 4 (large biorefinery with higher threshold distance). This scenario is the same as Scenario 1 but increases the threshold interfacility distance to 75 miles, allowing for a smaller number of locations.

Conventional fuel assumptions

Table 1 reports the cost data for fossil fuel-derived jet fuel, diesel, naphtha, and electricity, which serve as direct counterparts to products from the gasification–Fischer–Tropsch process. Cost data for each fossil fuel-derived product displaced by a biomass-derived alternative were compiled from the literature. A notable limitation was the absence of publicly accessible production cost information for these fossil fuel-derived products. Price proxies were therefore used after the review of available sources. Specifically, average spot prices for 2012–2021 were used to approximate production costs for fossil fuel-derived jet fuel, diesel, and gasoline.[24] The production cost of fossil fuel-derived electricity was estimated using the average levelized cost of electricity generation, weighted by the production share of each generation source.[25–28] Annual demand for each fossil fuel-derived product was derived from the EIA,[28] establishing product-specific maximum permissible displacement thresholds.

Table 1. Assumptions regarding cost factors and annual demand for conventional fuels and electricity.

Product	Unit	GGE (GGE per unit)[29]	Production cost ($ per unit)	Annual demand (billion units)[28]
Jet fuel	gal	0.903	1.84	23.00
Diesel	gal	0.873	1.98	44.61
Naphtha	gal	0.960	2.20	31.51
Electricity	kWh	32.879	0.11	4010.00

Abbreviation: GGE, gasoline gallon equivalent.

Results and discussion

Spatially agnostic siting approach

Figure 4 shows (a) the number of facilities that could be located, (b) biomass used, and (c) average interfacility distance as a function of different facility capacities (1102.5–22 050 tons per day) and maximum transportation distance assumptions (50–500 miles), based on the county-level potential biomass production density under the mature-market scenario of BT23. Observations include the following:

- The number of facilities that could be located decreased with increasing facility capacity (Fig. 4a), reflecting the spatial distribution of biomass resources. The relationship between facility number and capacity followed a relatively stable power-law trendline across maximum transportation distance assumptions.
- The total annual biomass use rate decreased as the facility capacity increased (Fig. 4b). Larger facilities require higher biomass production density, excluding low-density regions from use. This effect diminishes as the maximum transportation distance (i.e., feedstock supply area) increases and is particularly pronounced for larger facilities with limited supply areas. The results underscore the importance of matching facility capacity to biomass production density, ensuring that smaller facilities are sited in regions where biomass supply is insufficient for larger ones. Example α in Fig. 4b represents a facility capacity of 22 050 tons per day and a maximum transportation distance of 50 miles and illustrates the markedly low total annual biomass use under these conditions.
- The average interfacility distance increased with increased facility capacity (Fig. 4c). This trend was consistent across the different maximum transportation distances studied. However, the upward shift in this trend becomes more prominent as the maximum transportation distance increases. Economies of scale generally would improve with increasing facility capacity. Hence, the facilities with lower capacity have lower economies of scale, despite their higher proximity. This suggests a need to merge proximate smaller facilities into larger ones, especially for the 1102.5–2205 tons per day range, where the interfacility distance is less than 60 miles.

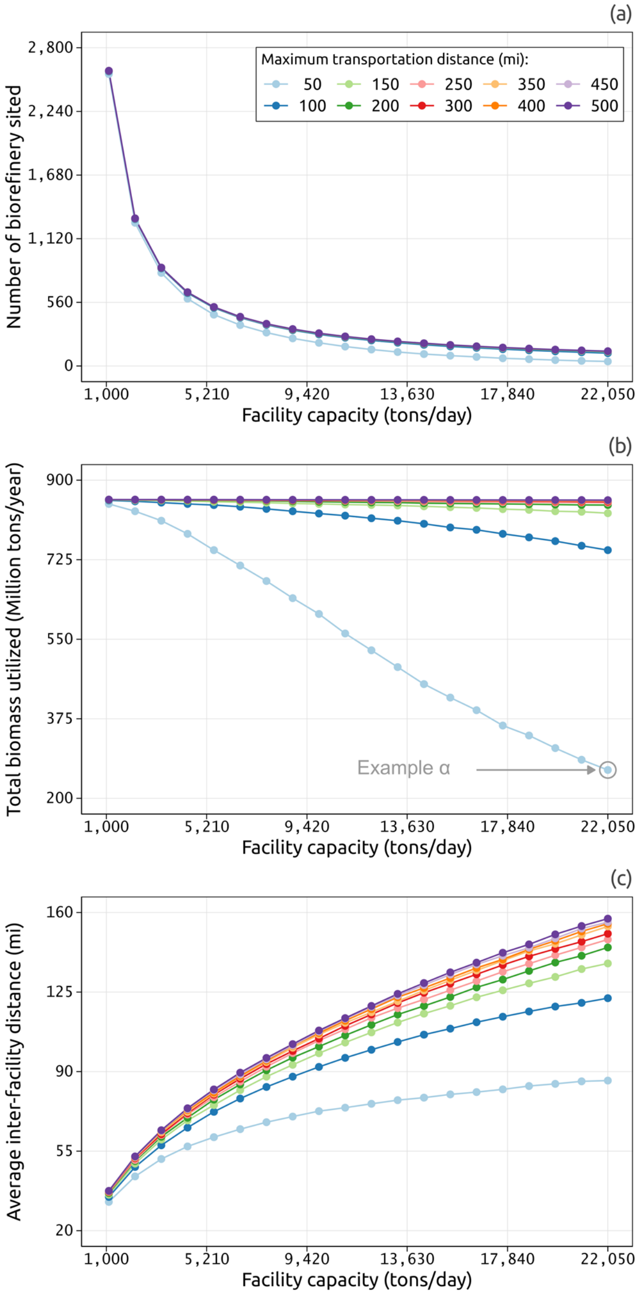


Figure 4. Effects of different facility capacity and maximum transportation distance assumptions on (a) the number of facilities that could be located, (b) annual total biomass use rate, and (c) average interfacility distance, using the mature-market scenario of BT23.

To use the available biomass supply efficiently, facility sizes should be optimized to balance biomass use and economies of scale. A ‘one-size-fits-all’ approach is suboptimal. A mix of facilities with varying capacities allows full exploitation of biomass resources while maximizing economic benefits. Figure 5 shows the mix of facility capacities needed to consume the unused biomass supply from Example α (Fig. 4b). In this sequential approach, larger facilities are sited first, followed by smaller facilities to utilize the remaining biomass. This analysis did not account for spatial factors (explored above in the section on spatially explicit siting approach using the BILT framework), and results should be interpreted with caution. Nevertheless, Fig. 5 demonstrates the importance of deploying facilities of

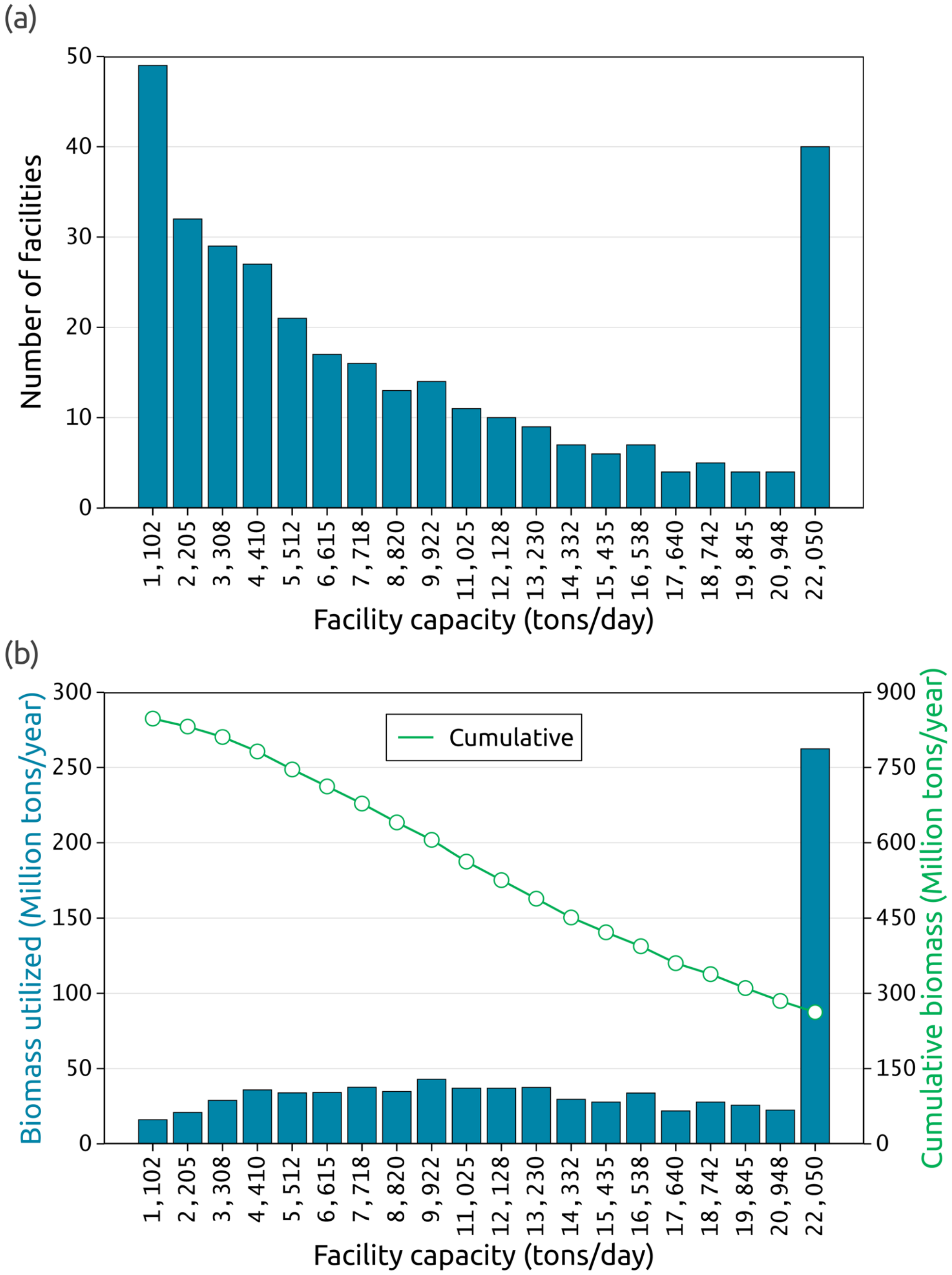


Figure 5. Distribution of (a) facility capacities required to consume the potential biomass supply in the US and (b) their corresponding annual total biomass use rates, assuming a maximum transportation distance of 50 miles and a maximum facility capacity of 22 050 tons per day.

varying capacities optimized for local biomass production density.

Spatially explicit siting approach using the BILT framework

This section details the BILT model results for five scenarios, with spatially resolved feedstock by type at the county level across the contiguous USA. Previous sections provide details of the assumptions and scenarios.

Biomass utilization under different scenarios

Figure 6(a,b) shows the feasible limits of biomass use in the baseline scenario compared with the biomass use in Scenario 1. In both cases, agricultural residues and woody biomass

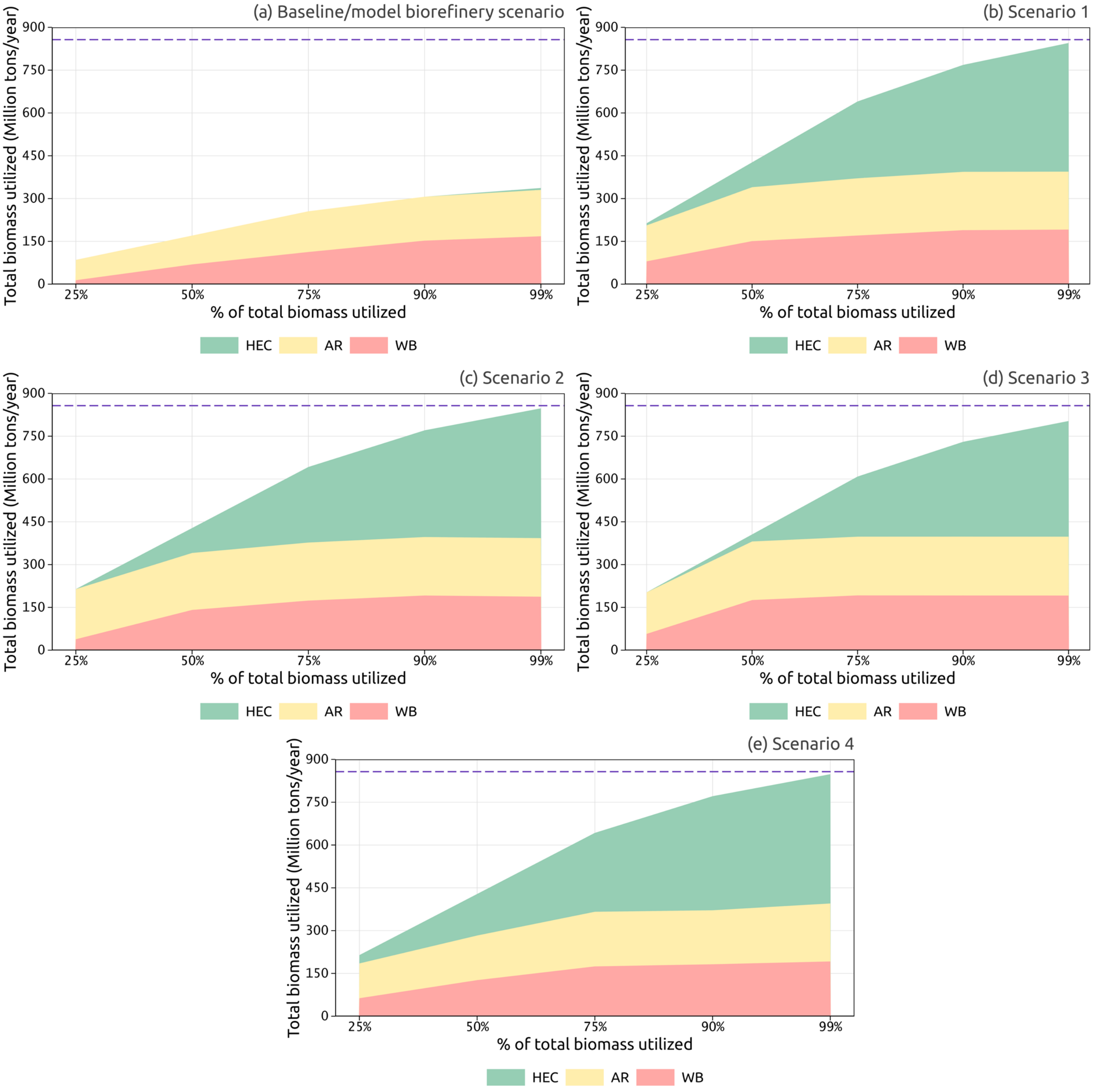
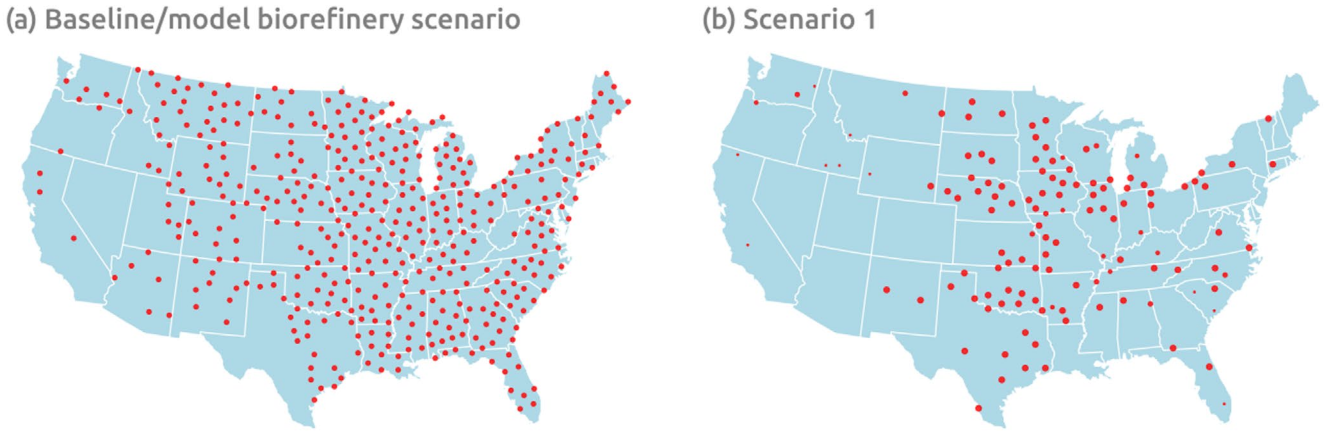


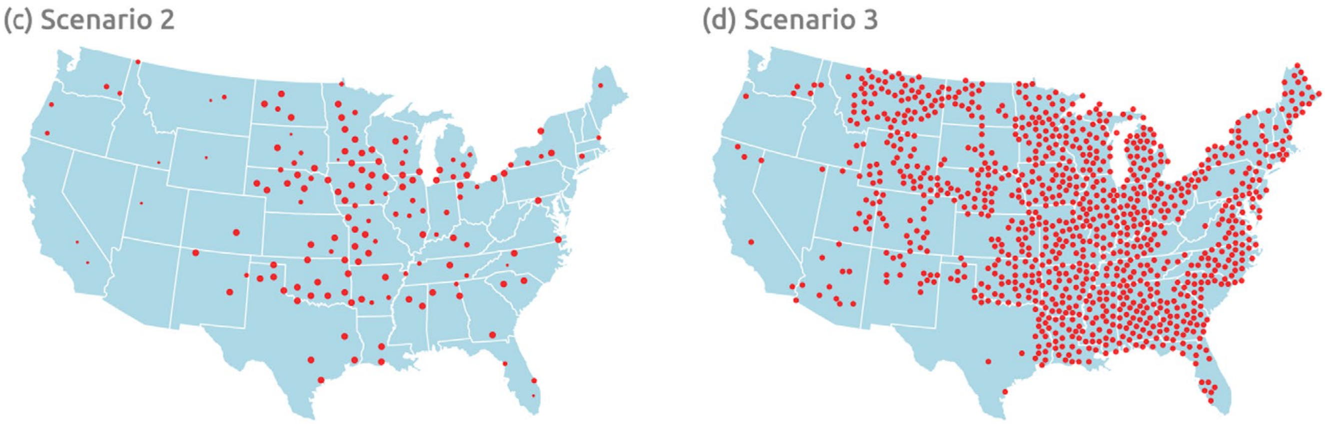
Figure 6. Biomass use under the three broad feedstock categories in each scenario. AR, agricultural residues; HEC, herbaceous energy crops; WB, woody biomass. The purple dashed line indicates the total biomass available.

(specifically the logging residues) were used first, followed by herbaceous energy crops. The prioritization of feedstock use is attributable to farm-gate feedstock cost and energy conversion costs.

The baseline scenario uses only one-third of the available biomass, demonstrating that the standard biorefinery capacity of 2205 dry tons per day is inadequate to utilize the potential biomass supply efficiently. One approach to address this limitation is to increase the capacity of the biorefineries, as demonstrated in Scenario 1, by using larger biorefineries. Larger facilities can process more biomass, enhancing overall use rates and efficiency. Another crucial


(a) Baseline/model biorefinery scenario

(b) Scenario 1


(c) Scenario 2

(d) Scenario 3


(e) Scenario 4

Figure 7. Biofuel Infrastructure, Logistics, and Transportation (BILT) model results of biorefinery sites for each scenario. Dots indicate locations of the biorefinery facilities at 90% of biomass utilization; dot size denotes biorefinery size, with the smallest denoting 1× or one 2205 tons per day biorefinery facility, and the largest denoting 10× or ten 2205 tons per day biorefinery facilities.

siting factor that can be adjusted is the interfacility distance. By reducing the interfacility distance constraint below the baseline of 50 miles, more facilities can be sited to increase biomass use. This observation aligns with findings in the spatially agnostic analysis (Fig. 4c), in which the average interfacility distance for the 2205 tons per day facility was significantly lower than 50 miles, enabling use of a larger portion of the available biomass supply. However, leveraging economies of scale through larger facilities fosters economic and logistical benefits, presenting a more compelling option.[30]

Overall, the biomass use curves reveal that only Scenarios 1, 2, and 4 – which have biorefinery capacities exceeding the baseline of 2205 tons per day – can substantially utilize the potential US biomass supply. Scenario 2, with co-located biorefineries, can be an alternative to single large facilities when the aim is full biomass utilization. Scenario 4 further shows that large biorefineries operating with an expanded

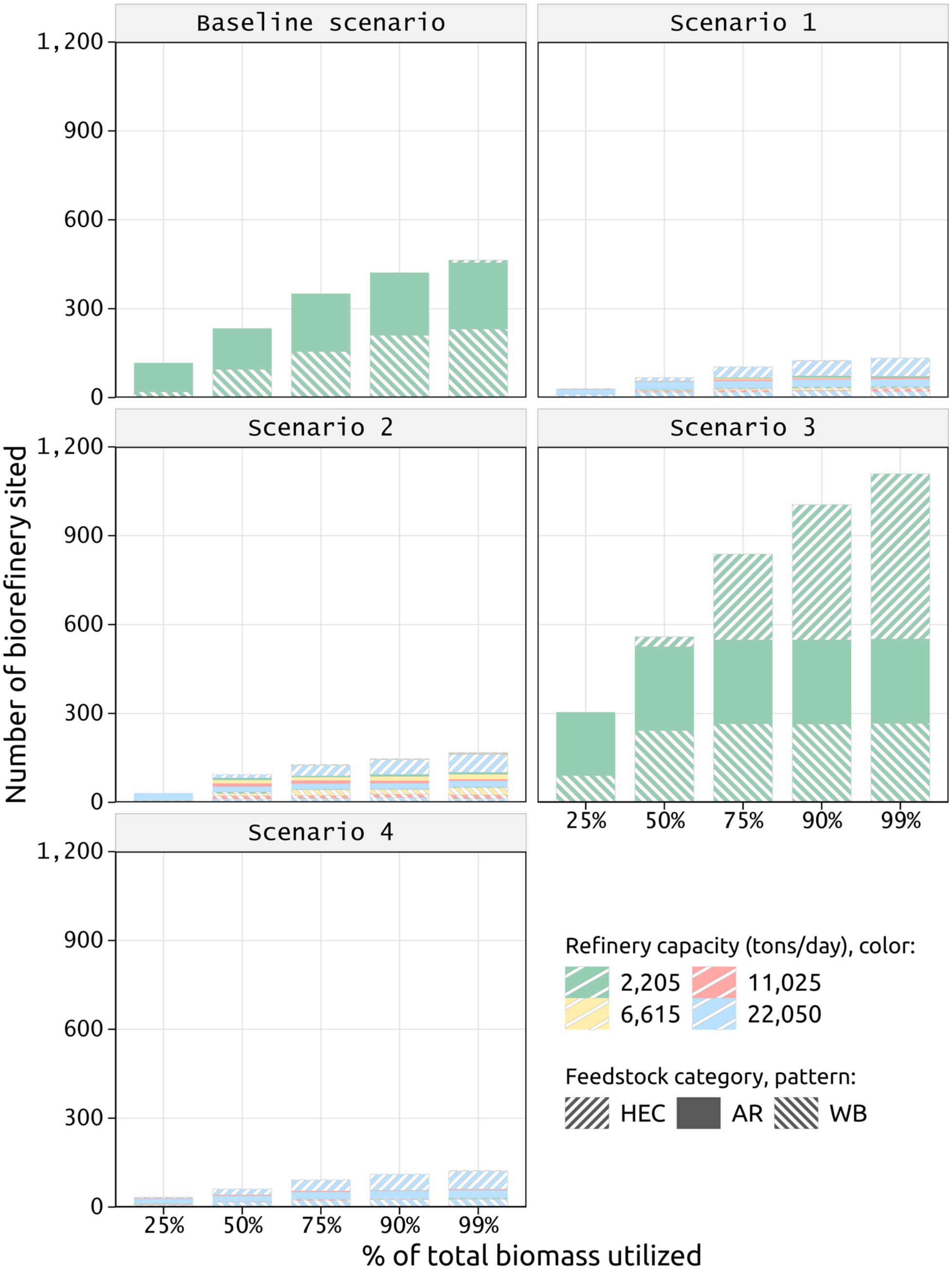


Figure 8. The number of facilities located across each scenario at each level of biomass utilization possible based on the assumptions, categorized by the size of the sited biorefineries.

threshold distance of 75 miles (as opposed to 50 miles in Scenario 1) can still use nearly all available biomass. In Scenario 3, even with lower threshold distances (25 miles), model biorefineries could only use about 734 million tons of biomass, compared with approximately 850 million tons of biomass available. These results indicate that either large biorefineries or co-located model biorefineries are required to fully utilize the available biomass supply.

Number and spatial distribution of biorefinery facilities by scenario

Figure 7 shows the locations of the biorefineries across the different scenarios considered in this study. Each dot on the map represents a unique biorefinery at 90% biomass utilization. The locations of the biorefineries mirror the density of the biomass availability, with more biorefineries located where a larger quantity of biomass is available.

Figure 8 breaks down the number of facilities sited under the five scenarios, each determined by a unique set of specified constraints. The number of facilities is categorized by the types of biomass consumed by the facility and capacities of the sited biorefineries. Predictably, as the percentage of maximum biomass utilization is allowed to increase in the BILT model, more facilities and/or higher capacities are needed.

Scenario 3 yields the largest number of facilities, with a maximum of 1014 unique facilities sited to use approximately 734 million tons of biomass each year, representing 86% of the potential biomass supply. For comparison, this total is approximately eight times more than the current number of operable petroleum refineries in the USA[31] and about six times the current number of fuel ethanol production plants.[13] The baseline scenario results in 457 unique facilities at maximum use capacity of approximately 332 million tons of biomass each year, or 38% of the potential biomass supply. These results suggest that deploying sufficient 2205 ton per day biorefineries to fully realize the US Billion-Ton bioeconomy vision would require an unprecedented and likely impractical expansion of infrastructure. Establishing more than 1000 unique facilities would face considerable challenges, including prohibitive capital investment, workforce limitations, site permitting constraints, supply chain complexity, and a lack of scale economies.

Scenarios 1, 2, and 4, which incorporate multitiered biorefinery capacities, require substantially fewer facilities while achieving near-complete use of potential future biomass resources. This observation reinforces the insights in the section above on the spatially agnostic siting approach, emphasizing the need to implement facilities of varying capacities, aligned with local biomass production density, to realize the US Billion-Ton bioeconomy vision. A strategic emphasis on larger scale biorefineries, when conditions (e.g., feedstock availability) permit, can improve economies of scale and reduce the total number of facilities required nationally, increasing the overall feasibility of large-scale biomass deployment.

These results contribute to the body of research on the potential logistical configurations of biorefineries in the USA. Lamers *et al.*[16] and Kim and Dale[14] showed that depots could lower delivered feedstock cost and increase siting flexibility; however, the current findings suggest that, beyond a certain threshold, increasing biorefinery scale yields diminishing returns when interfacility distances become large. Together, these insights highlight that both feedstock preprocessing strategies (as studied by Idaho National Laboratory, Michigan State University, and Michigan Biotechnology Institute) and strategic scaling of conversion facilities (as examined here) are critical, complementary levers for optimizing the spatial efficiency and financial performance of a national biofuel system. Consistent with Kim and Dale,[15] the results of the current study indicate that a range of sizes is needed for widescale deployment, and very large scales may be advantageous under some conditions.

Conclusions

This study highlighted the critical role of strategic biorefinery siting in maximizing the use of the potential US biomass supply while minimizing economic costs. By employing both spatially agnostic and spatially explicit modeling approaches, the study demonstrated that an optimized mix of facility sizes is essential to leverage biomass resources fully across varying regional production densities.

The results show that the standard model biorefinery capacity of 2205 dry tons per day is insufficient to utilize the full potential of available biomass. Larger biorefineries and co-located facilities substantially improve biomass use rates by capitalizing on economies of scale. Increasing the maximum feedstock transportation distance also enhances use rates but gives rise to logistical complexities and costs, emphasizing the need for a balanced approach.

Across the siting scenarios evaluated, configurations with larger capacities or co-located facilities achieved the highest biomass use rates. These results underscore the importance of integrating county-level feedstock availability and technoeconomic analysis into bioenergy infrastructure planning to bring about an economically viable, secure, and resilient bioenergy future.

Future work should focus on refining cost assumptions, incorporating additional supply chain constraints, and developing technological advances to further optimize biorefinery deployment.

Acknowledgements

This work is supported by the US Department of Energy, under Department of Energy Contract No. DE-AC05-00OR22725. The authors would like to thank Dr. Mark Elless (technology manager).

Data availability statement

The 2023 Billion-Ton Report data used in this study are available on the Bioenergy Knowledge Discovery Framework (https://bioenergykdf.ornl.gov). Detailed data from siting analysis will be made available on request.

References

1. EIA, *Annual Energy Review*. U.S. Energy Information Administration, Washington, DC (2025). Available: https://www.eia.gov/totalenergy/data/annual [3 March 1998].
2. U.S. Department of Energy, *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks*. Oak Ridge National Laboratory, Oak Ridge, TN (2016. Report No.: ORNL/TM-2016/160.). https://doi.org/10.2172/1271651.
3. U.S. Department of Energy, *2023 Billion-Ton Report: An Assessment of U.S. Renewable Carbon Resources*. Oak Ridge National Laboratory, Oak Ridge, TN (2024. Report No.: ORNL/SPR-2024/3103.). https://doi.org/10.23720/BT2023/2316165.
4. Riley C and Schell D, *Technical and Economic Analysis of an Enzymatic Hydrolysis Based Ethanol Plant*. Solar Energy Research Institute, Golden, CO (1991).
5. Wright MM, Satrio JA, Brown RC, Daugaard DE and Hsu DD, *Techno-Economic Analysis of Biomass Fast Pyrolysis to Transportation Fuels*. National Renewable Energy Laboratory, Golden, CO (2010. Report No.: NREL/TP-6A20-46586.). https://doi.org/10.2172/993332.
6. Swanson RM, Satrio JA, Brown RC, Platon A and Hsu DD, *Techno-Economic Analysis of Biofuels Production Based on Gasification*. National Renewable Energy Laboratory, Golden, CO (2010. Report No.: NREL/TP-6A20-46587.). https://doi.org/10.2172/994017.
7. Lin Y, Roni MS, Burli PH, Hartley DS and Thompson DN, *Herbaceous Feedstock 2021 State of Technology Report*. Idaho National Laboratory, United States (2021. Report No.: INL/EXT-21-64635.). https://doi.org/10.2172/1908668.
8. Dutta A, Sahir A, Tan E, Humbird D, Snowden-Swan LJ, Meyer P *et al.*, *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels. Thermochemical Research Pathways with In Situ and Ex Situ Upgrading of Fast Pyrolysis Vapors*. National Renewable Energy Laboratory, Golden, CO (2015). https://doi.org/10.2172/1215007.
9. Davis R, Bartling A and Tao L, *Biochemical Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels and Products: 2020 State of Technology and Future Research*. National Renewable Energy Laboratory, Golden, CO (2021). https://doi.org/10.2172/1784889.
10. Dutta A, Mukarakate C, Iisa K, Wang H, Talmadge M, Santosa D *et al.*, *Ex Situ Catalytic Fast Pyrolysis of Lignocellulosic Biomass to Hydrocarbon Fuels: 2020 State of Technology*. National Renewable Energy Laboratory, Golden, CO (2021). https://doi.org/10.2172/1805204.
11. Harris K, Nash C, Ruddy D, Dutta A, Dupuis D, Christensen E *et al.*, *High-Octane Gasoline from Lignocellulosic Biomass via Syngas and Methanol/Dimethyl Ether Intermediates (2021 State of Technology)*. National Renewable Energy Laboratory, Golden, CO (2022). https://doi.org/10.2172/1842283.
12. Jones S, Meyer P, Snowden-Swan L, Padmaperuma A, Tan E, Dutta A *et al.*, *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Fast Pyrolysis and Hydrotreating Bio-Oil Pathway*. National Renewable Energy Laboratory, Golden, CO (2013. Report No.: NREL/TP-5100-61178.). https://doi.org/10.2172/1126275.
13. EIA, *U.S. Fuel Ethanol Plant Production Capacity*. U.S. Energy Information Administration, Washington, DC (2024). Available: https://www.eia.gov/petroleum/ethanolcapacity [1 March 2023].
14. Kim S and Dale BE, Comparing alternative cellulosic biomass biorefining systems: Centralized versus distributed processing systems. *Biomass Bioenergy* **74**:135–147 (2015). https://doi.org/10.1016/j.biombioe.2015.01.018.
15. Kim S and Dale BE, All biomass is local: The cost, volume produced, and global warming impact of cellulosic biofuels depend strongly on logistics and local conditions. *Biofuels Bioprod Biorefin* **9**(4):422–434 (2015). https://doi.org/10.1002/bbb.1554.
16. Lamers P, Roni MS, Tumuluru JS, Jacobson JJ, Cafferty KG, Hansen JK *et al.*, Techno-economic analysis of decentralized biomass processing depots. *Bioresour Technol* **194**:205–213 (2015). https://doi.org/10.1016/j.biortech.2015.07.009.
17. Oyedeji OA, Moore AM, Kamath D, Busch IK, Curran SJ, Henriksen M *et al.*, Economic and environmental performance of biomass gasification for renewable natural gas production in the context of the U.S. natural gas supply. *Biomass Bioenergy* **197**:107670 (2025). https://doi.org/10.1016/j.biombioe.2025.107670.
18. Li ML, Zhao WY, Xu Y, Zhao YX, Yang K, Tao W *et al.*, Comprehensive life cycle evaluation of jet fuel from biomass gasification and Fischer-Tropsch synthesis based on environmental and economic performances. *Ind Eng Chem Res* **58**(41):19179–19188 (2019). https://doi.org/10.1021/acs.iecr.9b03468.
19. Shahriar MF and Khanal A, The current techno-economic, environmental, policy status and perspectives of sustainable aviation fuel (SAF). *Fuel* **325**:124905 (2022). https://doi.org/10.1016/j.fuel.2022.124905.
20. Tan ECD, Hawkins TR, Lee U, Tao L, Meyer PA, Wang M *et al.*, Biofuel options for marine applications: Technoeconomic and life-cycle analyses. *Environ Sci Technol* **55**(11):7561–7570 (2021). https://doi.org/10.1021/acs.est.0c06141.
21. Tan ECD, Snowden-Swan LJ, Talmadge M, Dutta A, Jones S, Ramasamy KK *et al.*, Comparative techno-economic analysis and process design for indirect liquefaction pathways to distillate-range fuels via biomass-derived oxygenated intermediates upgrading. *Biofuels Bioprod Biorefin* **11**(1):41–66 (2017). https://doi.org/10.1002/bbb.1710.
22. Agusdinata DB, Zhao F, Ileleji K and DeLaurentis D, Life cycle assessment of potential biojet fuel production in the United States. *Environ Sci Technol* **45**(21):9133–9143 (2011). https://doi.org/10.1021/es202148g.
23. Dupuis DP, Grim RG, Nelson E, Tan ECD, Ruddy DA, Hernandez S *et al.*, High-octane gasoline from biomass: Experimental, economic, and environmental assessment. *Appl Energy* **241**:25–33 (2019). https://doi.org/10.1016/j.apenergy.2019.02.064.

24. EIA, *Spot Prices for Crude Oil and Petroleum Products*. U.S. Energy Information Administration, Washington, DC (2021). Available: https://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm [10 April 2024].
25. IEA, *Projected Costs of Generating Electricity*. International Energy Agency, Paris (2020).
26. NREL, *2022 Electricity ATB Technologies and Data Overview*. National Renewable Energy Laboratory, Golden, CO (2022). Available: https://atb.nrel.gov/electricity/2022/index [24 March 2024].
27. Statista, *Estimated Unsubsidized Levelized Costs of Energy Generation in the United States in 2023, by Technology*. Statista (2022). Available: https://www.statista.com/statistics/493797/estimated-levelized-cost-of-energy-generation-in-the-us-by-technology/ [24 March 2024].
28. EIA, *Annual Energy Outlook 2022*. U.S. Energy Information Administration, Washington, DC (2023). Available: https://www.eia.gov/outlooks/aeo/data/browser [1 March 2023].
29. EIA, *Appendix A: British Thermal Unit Conversion Factors*. U.S. Energy Information Administration, Washington, DC (2023). Available: https://www.eia.gov/totalenergy/data/monthly/pdf/sec12.pdf [1 March 2023].
30. Larnaudie V, Ferrari MD and Lareo C, Switchgrass as an alternative biomass for ethanol production in a biorefinery: perspectives on technology, economics and environmental sustainability. *Renew Sustain Energy Rev* **158**:112115 (2022). https://doi.org/10.1016/j.rser.2022.112115.
31. EIA, *Number and Capacity of Petroleum Refineries*. U.S. Energy Information Administration, Washington, DC (2025). Available: https://www.eia.gov/dnav/pet/pet_pnp_cap1_dcu_nus_a.htm [1 April 2025].

Dipti Kamath

Dipti Kamath is an R&D associate staff member at the Oak Ridge National Laboratory (ORNL) Manufacturing Energy Efficiency Research and Analysis Group, US. She conducts technoeconomic and life-cycle assessments for industrial transformation, with a focus on the pulp and paper sector, and is a US Department of Energy (DOE) Better Plants technical account manager.

Oluwafemi Oyedeji

Oluwafemi Oyedeji is a researcher with an interest in advancing biomass utilization and the technoeconomic analysis of biobased systems. His work integrates process modeling, materials characterization, and systems-level analysis to accelerate the development and commercialization of next-generation biobased technologies.

Scott Curran

Scott Curran leads the Fuel Science and Engine Technologies Research Group at Oak Ridge National Laboratory, US. His research areas include development of advanced combustion concepts, end-use alternative fuels utilization research, and biomass resource analysis with a focus on transportation.

Matthew Langholtz

Matthew Langholtz is a natural resource economist at Oak Ridge National Laboratory, US. He is Principal Investigator of the Biomass Supply Analysis Project. His research includes biomass resource economics, short-rotation woody crops, and bioenergy from forest resources. He received his PhD in forest economics from the University of Florida in 2005.

Ingrid Busch

Ingrid Busch is a transportation analyst in the Transportation Analytics and Decision Science Group at Oak Ridge National Laboratory, US. Her research interests are modeling and simulation, multimodal transportation analysis, freight modeling, network analysis, economic analysis, and geographic information systems (GIS).

Timothy Theiss

Timothy Theiss served from 2011 to 2023 as program manager for Oak Ridge National Laboratory's bioenergy technologies program, leading R&D in biomass supply, conversion technologies, biofuels, biomaterials, and bioenergy sustainability analysis.