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Adoption of biofuels for marine shipping decarbonization: A long-term price and scalability assessment

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Received December 04 2021; Revised February 02 2022; Accepted February 24 2022; View online April 18, 2022 at Wiley Online Library (wileyonlinelibrary.com); DOI: 10.1002/bbb.2350; *Biofuels, Bioprod. Bioref.* 16:942–961 (2022)

Abstract: This study assessed the long-term annual biofuel production capacity potential and price in the United States and shed light on the prospect of biofuel adoption for marine propulsion. A linear programming model was developed to assist the projections and provide insightful analyses. The projected long-term (2040) maximum annual capacity of biofuels in the United States is 245 million metric tons (Mt) or 65 billion gallons of heavy fuel oil gallon equivalent (HFOGE) when based on the median feedstock availability. Between 2022 (near-term) and 2040, the potential biofuel capacity increases by over 40%, attributed to increased feedstock availability. At a price range up to \$500/t, biodiesel is the main product, and the annual capacity (12 Mt) is limited to feedstock availability constraints. Biodiesel and corn ethanol are the main biofuels at a price range up to \$750/t. At a higher price point (above \$750/t), the biofuel types and annual capacities increase substantially (218 Mt per year). Biofuels above this price include gasoline-, jet-, and diesel-range blendstocks, as well as bio-methanol, bio-propane, and biogas. This study concludes that the US domestic feedstock availability coupled with advanced conversion technologies can produce substantial amounts of biofuels to achieve a critical mass and be impactful as alternative marine fuels. There is also a need to improve the biofuel price for marine shipping adoption. Policies and economic incentives that provide temporary financial support would help facilitate maritime biofuel adoption. © 2022 Alliance for Sustainable Energy, LLC. Biofuels, Bioproducts and Biorefining published by Society of Industrial Chemistry and John Wiley & Sons Ltd.

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

Key words: biorefinery; decarbonization; marine biofuels; renewable energy; scalability; sustainability; techno-economic analysis

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Introduction

One of the biggest challenges in the 21st century is that of transforming the transportation sector into a low-carbon-based sustainable industry, including maritime shipping. Marine shipping is the most energy-efficient form of freight transport and is the backbone of global trade, responsible for transporting 80% of the world's goods by volume and over 70% of global trade by value.[1–3] The marine shipping sector depends heavily on liquid fuel and is one of the largest petroleum fuel consumers. The primary fuel used by the marine shipping sector is heavy fuel oil (HFO), a residual of the refinery process that contains many undesirable impurities separated from other refinery products.[4] Other marine fuels include marine gas oil (MGO), marine diesel oil (MDO), intermediate fuel oil, and marine fuel oil. Marine fuels are categorized based on their blending properties.[5] The annual global marine fuel consumption is around 400 million metric tons (Mt) (2.5 billion barrels), which is higher than the world's yearly jet fuel consumption of 220 Mt (1.4 billion barrels).[3,6] The overall demand for marine fuels is expected to double by 2030 due to increased global trade.[7,8]

Moreover, ocean shipping is one of the most significant contributors to air emissions of sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter. Global shipping contributes 13% of human-caused emissions of SO_x and 2.6% of anthropogenic carbon dioxide (CO_2) emissions.[9,10] As a major source of pollutant emissions, the marine industry is facing several challenges related to emissions regulations. The industry recently complied with the emissions targets set by the International Maritime Organization (IMO), reducing global marine fuel sulfur content from the previous 3.5% m/m (mass by mass) to current 0.5% m/m, which started on 1 January 2020.[11] Moreover, in the United States, the California Air Resources Board (CARB) and other state agencies have established regulations limiting the sulfur content of fuel used in coastal regions to 0.1% m/m.[6,12] These regulations will require shipowners to find alternative fuel pathways. The options include low-sulfur HFO, low-sulfur MGO, installing sulfur scrubbers, or other alternative fuels and powertrains.[11] In addition to sulfur emissions reduction targets, the IMO has also established a framework for reducing the carbon intensity of shipping explicitly – a 40% reduction relative to 2008 levels by 2030 and a 70% reduction by 2050.[4,13]

Biomass-derived fuels can play an essential role in the transition to move maritime shipping toward carbon neutrality. As renewable alternatives of marine propulsion, they can also offer potential synergistic benefits when blended with petroleum fuels, i.e. smoothing the transition to biofuels by reducing alternative fuel costs while still lowering greenhouse gas (GHG) emissions.[3] With inherently zero- or low-sulfur content and renewable carbon sources, biofuels will help mitigate marine shipping sulfur emissions, improve overall emissions profiles, and enable the decarbonization transition. For example, bio-oil derived from biomass such as forest residues is expected to reduce the well-to-propeller life-cycle greenhouse gas emissions up to 90% compared to fossil equivalents and virtually eliminate SO_x emissions without any requirement for engine modifications.[3,14] Marine biofuels performed favorably across most emission categories, exhibiting improved life-cycle GHG emissions compared to HFO, with reductions ranging from 40% to 93%, and mitigation of sulfur oxides and particulate matter emissions.[3]

As biofuel for marine propulsion is still at its nascent stage, knowledge gaps exist, including the life-cycle environmental impacts, compatibility of biofuel blending with conventional marine fuels, scalability, and cost.[6] For the benefits of biofuels to be realized and impactful, a significant fraction of marine fuel use will need to be met with biofuel.[15] This necessitates that biofuel production volume should be high enough to meet demand. Furthermore, the potential of biofuel adoption also depends on future biofuel prices. Hence, marine biofuel's long-term price and availability are two critical factors for establishing the feasibility of marine biofuel adoption for operating vessels and they set the stage for this analysis. The objective of this study is to assess the long-term price and production capacity of various biofuels in the United States based on the projected domestic biomass resource availability and potential biofuel production technologies reported in the literature. The study aims to shed light on the prospect of biofuel adoption for maritime shipping.

Methods

The long-term biofuel price and scalability depend on the assessed feedstock cost and availability and biofuel production technologies. The basic assumptions for the total biofuel annual production and price projections were based on (i) feedstock availability and costs reported in the United States and (ii) existing potential biomass-to-fuel conversion technology analyses in the public domain. Using a bottom-up approach, all projected available feedstocks in the United States were integrated with the selected potential promising and top-performance conversion pathways (i.e., based on yields and production costs).

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Biomass feedstock availability and cost evaluation

We made use of the biomass feedstock cost and availability using recent yield and cost data, predominantly based on the *2016 Billion-Ton Report* (BT16), a study for the US Department of Energy (DOE) to identify one billion tons per year of domestic biomass availability for bioenergy consumption.[16] Biomass is defined by a broad spectrum of organic materials including herbaceous materials (corn stover, soybean hulls, and switchgrass), woody materials (logging residues, whole tree biomass, and construction and demolition waste), waste materials (animal manure, municipal solid waste, and paper and paperboard), and algae (microalgae and macroalgae). The present study's base case assumed all available feedstocks would contribute to the production of biofuels. This assumption did not consider market forces in which feedstocks would be used for other industries, such as biopower, biochemicals, and bioplastics. Additionally, the study did not explore the potential logistic challenges associated with the delivery of marine biofuel from biomass conversion regions to coastal ports.

This study considered the feedstock outlook for a near-term scenario (2022) and a long-term scenario (2040). The BT16 provided feedstock production constraints such as economic incentives, land availability, and overall yield that were applied to determine the total available biomass at the farmgate (agricultural resources), roadside (forestry resources), or sorting facility (waste resources) for both a near-term and long-term scenario. The long-term projections from BT16 include a base case and high-yield scenario in which each scenario has a low, median, and high cost and availability scenario. In this study, the long-term base case and high-yield case were consolidated for the potential biofuel capacity and price projection. In doing so, the base case assumptions were assumed for both the minimum and median availability cases, and the high-yield availabilities were assumed for the maximum availability case. Given that both the "lowest" case and the "highest" case will be analyzed, it is implied that the excluded cases will lie within the bounds of the calculated results.

For the highest-cost scenario, this study further assumed that given a high enough delivered cost to the biorefinery, all the potential biomass resources could be utilized.[15] The difference between the feedstock availability at the roadside, farmgate, or sorting facility and the biorefinery's total availability can be attributed to feedstock transportation and handling logistics and losses. This difference is referred to as the unused portion of the biomass. The unused portion was further broken down into three categories: unused due to cost limitations, unused due to over-contracting, and unused due to supply-chain losses (e.g., biological degradation or mechanical losses). Per BT16, a 10% over-contracting buffer was applied to the near-term woody feedstock scenario to protect biorefinery production from variability in the supply chain (e.g., fire, drought, pests).[16] Similarly, an over-contracting buffer of 25% was applied to the near-term herbaceous scenario. The losses attributed to over-contracting could not be recovered for the short-term scenario; however, for the long-term scenario, advanced collection and distribution systems would eliminate the need for over-contracting and therefore, there would be no over-contracting loss. The near-term scenario's supply-chain losses were assumed to equal the percentage ash content for a given feedstock, but an optimistic assumption was utilized for long-term scenarios in which the only limitations are feedstock cost and there are no supply-chain losses (i.e., biorefinery accepting higher delivered feedstock cost and advancement in feedstock logistics system). Thus, this study assumed that, given a high enough delivered cost to the biorefinery, and with advanced and improved feedstock logistic systems, all the potential biomass resources (including the unused portion) could be consumed for the long-term scenario.

Table 1 summarizes feedstock availability for all feedstock at the roadside, farmgate, or sorting facility at their respective costs. The BT16 provided minimum and median cost scenarios for both herbaceous and woody feedstocks, and the maximum cost scenario ($131/t) was assumed for this assessment. For currently utilized feedstocks, the

Table 1. Feedstock cost (dry basis) assumptions for each feedstock type derived from BT16. Bold values were determined with additional assumptions applied in this study. See supporting information for BT16 values

	Minimum	Median	Maximum
Production/procurement costs ($/t)			
Currently utilized	–	$66	–
Herbaceous	$44	$66	$88
Woody	$44	$66	$88
Waste	$44	$55	$66
Delivered costs ($/t)			
Currently utilized	**$53**	**$66**	**$79**
Herbaceous	$92	$109	**$131**
Woody	$92	$109	**$131**
Waste	**$77**	**$91**	**$109**

Note. Cost values in 2016 US dollars and rounding to nearest dollar.

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median delivered price was assumed to be \$66/t, which is consistent with the value provided in BT16. The median procurement cost is \$55/t for waste feedstocks versus \$66/t for herbaceous and woody feedstocks. However, only the procurement cost (\$55/t) but not the delivered cost was provided for waste feedstocks in BT16. This study used the median delivered cost of \$91/t, which was determined by assuming the waste feedstock logistic cost contribution to the total delivered cost (40%) is identical to herbaceous and woody feedstocks. Similarly, the minimum and maximum waste feedstock costs are also consistent with herbaceous and woody feedstocks, with factors of 84% and 120% of the median cost, respectively.

Macroalgae availability values were sourced from the report Roesijadi *et al.*[17] Potential seaweed yields and production costs, which included cultivation and harvesting, were provided based on previous data in terms of annual dry and ash-free weight per hectare.[18] To determine the potential biomass availability from yield information, it was necessary to estimate the area of the exclusive economic zone (EEZ) that could realistically be utilized for algal biomass in near-term and long-term scenarios. The US EEZ usable area was determined to be 468 000 km,[219] in which 0.09% of the EEZ, or about 10 895 km^2 would be a reasonable utilization target.[17] Given the uncertainty in time required to develop the market and infrastructure required for this biomass cultivation level, the 0.09% EEZ metric was set as the long-term target case to be conservative in this analysis. The near-term case was then estimated as 10.7 times less than the target case (1018 km^2, 0.008% of the EEZ); this assumes all productivity goes to biofuel production. These EEZ utilization areas were then multiplied by productivity values to generate predictions for the near-term and long-term scenarios. A fixed factor of ±20% was also applied to both the cost and availability of each macroalgae type for the minimum and maximum cases.

The total available biomass breakdown by resource category for the three median cases investigated is shown in Fig. 1. Increases in herbaceous energy crops are expected to drive feedstock availability in long-term cases. Waste materials and currently utilized resources are not expected to significantly grow in availability over time. Their relative contributions over time are expected to decrease from 8% in the 2022 base case to 6% in the 2040 base case. Woody biomass is also expected to increase over time but not to the same extent as herbaceous feedstocks. Finally, microalgae contributions are not projected to increase significantly over time. However, with significant infrastructure development and the pursuit of macroalgae technologies, it is predicted that macroalgae can become a significant contributor to feedstock availability in the long term. The detailed long-term feedstock availability scenario is provided in Fig. 2, and all feedstock availabilities and costs are summarized in Tables S1–S3 in the supporting information (SI).

Biomass conversion technology assessment

This section reviews the existing biomass-to-fuel conversion technology analyses available in the public domain, largely leveraging the portfolio of conversion pathways developed under the US Department of Energy's Bioenergy Technologies Office (BETO). BETO has focused on enabling the development of technologies to produce infrastructure-compatible, cost-competitive liquid hydrocarbon fuels from various feedstocks such as lignocellulosic biomass. The program's portfolio is expanding to include research and development of advanced biofuels that will enable a range of technologies to be deployed to produce infrastructure-compatible hydrocarbon fuels.

The conversion pathways used in this study vary by feedstock type, conversion technologies, and product slates, as well as market maturity. For example, sugar and starch crops treated by hydrolysis yielding sugars for fermentation to ethanol is a well established industry, which had 17 378 million gallons of ethanol per year nameplate capacity in the United States as of January 2020.[20] On the other hand, there are technologies where limited commercialization has been attempted, or it has been constrained to the bench scale because of the need for further technological advancement. Two of these technologies are hydrothermal liquefaction of wastewater sludge and fermentation of macroalgae. Some pathways were explored but eliminated from this study early due to their final fuel not being usable for direct combustion (e.g., straight vegetable oil). According to the DOE's Vehicle Technologies Office, using straight vegetable oil leads to reduced engine life because of the buildup of carbon deposits in the engine and vegetable oil buildup in the engine lubricant.[21–23]

The selected biofuel production technologies used in this study are summarized in Table 2, including their feedstock types, conversion technologies, and final fuels. Pathway numbering with source references is summarized in SI (Table S4). The crucial process performance metrics such as feedstock used, fuel yield, hydrocarbon product slate, capital costs, and operating costs were gathered and used for the linear programing model for the biofuel production capacity and price projections (Table 3). Detailed description of each pathway can be found in a recent report.[15] As not all reports used in this study were published in the same year, the costs were converted and normalized to the same cost year (in 2016 US dollars), and performance metrics were normalized by equating fuel products to heavy fuel oil gallon equivalent

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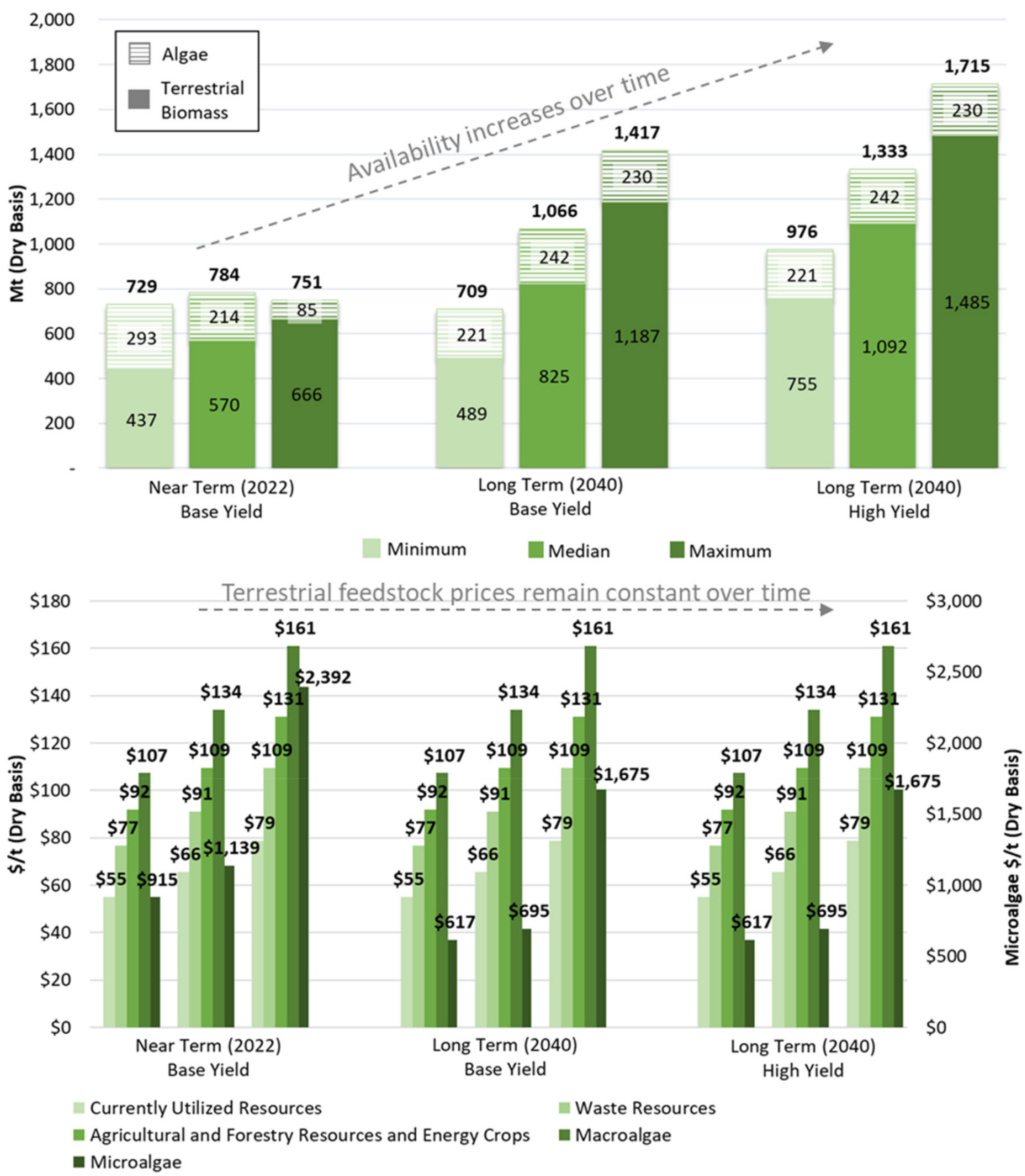

Figure 1. Summary of total feedstock contributions by scenario. Only median feedstock prices are shown. See Tables S1–S3 in the supporting information for the minimum and maximum feedstock prices.

(HFOGE). Once the data were compiled and harmonized, the economic and performance metrics were utilized in linear modeling. The biofuel production processes were segmented by their feedstock group into one of seven feedstock types for analysis in this section: (i) fats, oils, and greases; (ii) corn grain; (iii) lignocellulosic biomass; (iv) microalgae; (v) wastewater sludge; (vi) municipal solid waste; and (vii) macroalgae.

Figure 3 summarizes the conversion pathway screening assessment for potential marine biofuel production pathways. Eight metrics were developed for each pathway that was evaluated. The pathway metrics were compiled, harmonized, and then compared for their technical and economic viability. The metrics include: (i) feedstock agnostic, which is the variability of feedstock the conversion technology can handle; (ii) feedstock scalability, which takes into account total feedstock available and feedstock expected growth on the long-term horizon; (iii) feedstock production and logistics, which accounts for cultivation, collection, and transportation of feedstock from its origin to the biorefinery; (iv) technological maturity, which encompasses the

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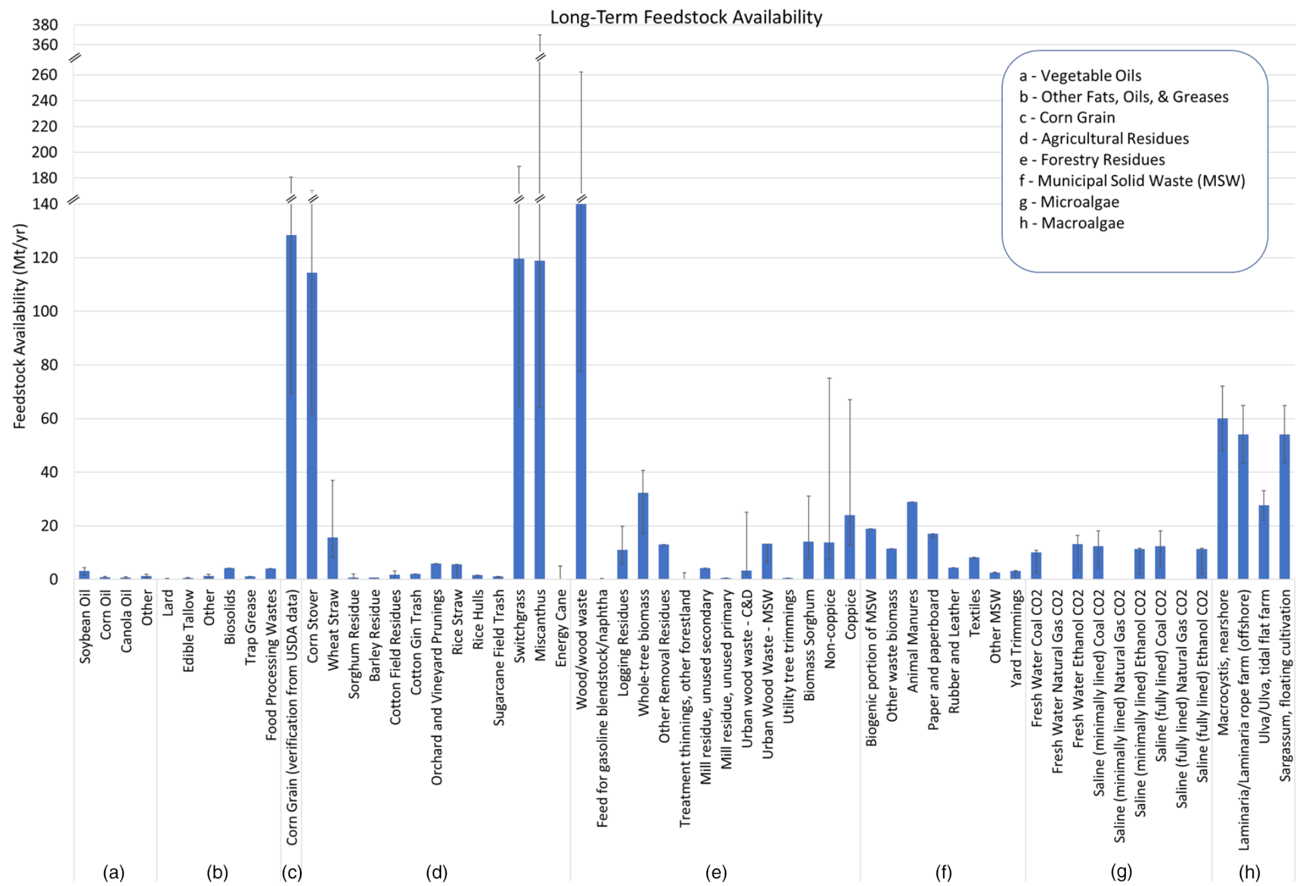

Figure 2. Summary of long-term feedstock availability by feedstock type. The feedstock types are grouped with lower case letters (a–h). Error bars indicate the maximum and minimum feedstock availability for each feedstock.

technological readiness level that accounts for the proven scale of the technology including pilot plants, commercial demonstration, and market penetration; (v) carbon conversion efficiency, which is the carbon content from the biomass that makes it into the final fuel(s); (vi) yield, which is the energy produced per dry metric ton and is related to carbon conversion efficiency but can include the electricity and heat produced on site from the biomass that is not part of the carbon conversion efficiency (i.e., hydrocarbon blendstocks); (vii) feedstock cost, which is the feedstock cost assumed in the technology reports that the information was taken from; and (viii) minimum fuel sell price (MFSP), which is the plant-gate price that represents the minimum selling price of biofuel that meets the specified economic parameters to sell the main fuel product for as calculated in the technology reports from which the information was taken. The pathways were given relative qualitative scores based on various metrics (Table S5). Each technology pathway was assessed and determined to be favorable, neutral, or unfavorable with respect to each metric. Note that these metrics are directly related to the marine biofuel production capacity and price. Environmental and fuel properties are excluded, as they are outside the scope of this study.

It is evident from Fig. 3 that the majority of the metrics are either favorable or neutral for most pathways. The feedstock availability for fats, oils, and greases poses a challenge for Pathways 1–7. Technology maturity associated with Pathways 12–18 and 23–30 is not favorable for the near term. For the technology maturity metric, all cases were compared based on their state of technology. Macroalgae pathways exhibit the most unfavorable metrics.

Biofuel production capacity and cost projections

A linear optimization model was developed for the biofuel production capacity and cost projection. The model consists of two sub-models: (i) a database of biomass conversion pathway techno-economic cost inputs and a discounted cash flow rate of return (DCFROR) solver that calculates MFSP for the fuel output for each pathway and (ii) an optimization

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Table 2. Feedstock groups, fuel intermediates, and processing technologies with associated pathway number assignments

Feedstock	Initial processing	Fuel precursor	Secondary processing	Biofuel	Pathway #
Oil crops (a)	Pressing/ extraction	Vegetable oil	Esterification	Biodiesel (FAME)	1
			Hydroprocessed esters and fatty acids (HEFA)	Sustainable aviation fuel (SAF) + renewable diesel	2,3,4,5
			Direct	Straight vegetable oil (SVO)	N/A
Waste fat, oil, and grease (FOG) (b)	Collection	Waste fat, oil, and grease (FOG)	Esterification	Biodiesel (FAME)	6
			Hydroprocessed esters and fatty acids (HEFA)	Sustainable aviation fuel (SAF) + renewable diesel	7
Sugar/starch crops (c)	Hydrolysis	Sugar	Fermentation	Ethanol, butanol	8
Lignocellulosic biomass (d and e)	Hydrolysis	Sugar	Fermentation	Ethanol, n-butanol	9
				Ethanol	10
				Isobutanol	11
	Hydrothermal liquefaction (HTL)	Bio-oil	Catalytic refining	Renewable diesel	12
	Fast pyrolysis		Hydrotreating	Renewable diesel	13
	Catalytic fast pyrolysis (CFP)		*In situ* catalytic upgrading	Renewable gasoline	14
			Ex situ catalytic upgrading	Renewable diesel	15
	Gasification	Syngas	Catalytic synthesis	High-octane gasoline (HOG)	16
			Catalytic synthesis	Methanol	17
			Catalytic synthesis	Methane, DME	18
			Fischer-Tropsch (FT)	Renewable diesel/SAF	19,20,21
			Mobil olefines to gasoline and distillates (MOGD)	Renewable gasoline	22
			C2+ alcohols + Guerbet reaction	Renewable diesel/SAF	23
			Syngas fermentation + Guerbet reaction	Renewable diesel/SAF	24
			Oxygenates + carbon coupling	Sustainable aviation fuel (SAF)	25
			C2+ alcohols + carbon coupling	Sustainable aviation fuel (SAF)	26
			Catalytic synthesis + MTG	Gasoline	27
			Mixed alcohol synthesis	Ethanol	28
Micro algae (g)	Oil extraction	Green crude	Catalytic upgrading	Renewable diesel	29
Municipal solid waste (MSW) (f)	Hydrothermal liquefaction (HTL)	Bio-crude	Catalytic refining	Upgraded bio-oil	30
	Anaerobic digestion	Direct	N/A	Methane	31
Macro algae (h)	Hydrolysis	Sugar	Fermentation	Ethanol, butanol	32,33,34,35
	Anaerobic digestion	Direct	N/A	Methane	36

solver that varies the amount of biomass routed to each pathway and calculates the biofuel output and plant-gate cost for each biomass conversion pathway and biomass feedstock combination, as depicted in Fig. 4, with the detailed list of feedstock and pathway technology summarized in Table S6 and S4, respectively.

A majority of evaluated pathways coproduce both jet- and diesel-range hydrocarbon blendstocks (Table 2). Processes modeled with the focus on producing jet fuel that meets the jet fuel specifications (e.g., high flash point and good cold-flow properties) were accomplished with the hydrocracking and isomerization steps. However, the product slate of these

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Table 3. Summary of conversion process performance, product distribution, capital cost, and operating costs

Pathway	Feedstock type	Yield (HFOGE/dry t)	Distribution					Total capital investment (MM$)	Total operating costs (MM$/year)*	Biorefinery capacity (t/day)
			Gasoline (%)	Diesel (%)	Jet (%)	Other (%)	Other (type) (%)			
1	Vegetable oils	237.81	0	100	0	0		$9.76	$68.40	137
2		268.50	28	2	66	4	Propane	$320.40	$139.33	715
3		276.85	34	2	64	0		$320.40	$461.04	715
4		258.72	28	14	58	1	Propane	$320.40	$254.14	715
5		280.06	32	0	67	1	Propane	$320.40	$489.12	715
6	Fats, oils, and greases	237.81	100	0	0	0		$6.98	$17.05	99
7		277.66	32	0	67	1	Propane	$320.40	$202.46	715
8	Corn grain	62.74	0	0	0	100	Ethanol	$123.03	$76.27	1029
9	Agricultural residues or forestry residues	31.86	0	0	0	100	Butanol	$456.74	$35.55	2000
10		47.51	0	0	0	100	Ethanol	$435.61	$78.36	2000
11		57.34	0	0	0	100	Butanol	$441.28	$107.65	2000
12	Agricultural residues, forestry residues, or MSW	71.82	42	40	0	18	Heavy oil	$482.52	$101.65	2000
13	Agricultural residues or forestry residues	59.82	48	52	0	0		$647.97	$114.78	2000
14		55.68	73	27	0	0		$504.95	$103.58	2000
15		58.05	45	55	0	0		$545.33	$97.83	2000
16	Agricultural residues, forestry residues, or MSW	40.67	100	0	0	0		$396.90	$78.77	2000
17		49.13	0	0	0	100	Methanol	$301.26	$66.07	2000
18		47.76	0	0	0	100	Methanol (15 wt%) and dimethyl ether (85 wt%)	$345.28	$68.23	2000
19		45.13	36	20	44	0		$633.15	$67.58	2276
20		42.33	39	19	42	0		$690.84	$64.10	2427
21		48.80	36	26	38	0		$534.03	$79.72	2000
22		48.08	58	21	21	0		$531.34	$115.14	2000
23		42.23	0	53	47	0		$680.54	$92.03	2000
24		46.03	0	51	49	0		$442.93	$78.80	2000
25		49.32	24	10	66	0		$398.43	$102.48	2000
26		30.92	24	10	66	0		$462.07	$76.21	2000
27		42.26	100	0	0	0		$205.69	$56.50	2000

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Table 3. (Continued)

Pathway	Feedstock type	Yield (HFOGE/ dry t)	Distribution					Total capital investment (MM$)	Total operating costs (MM$/ year)*	Biorefinery capacity (t/day)
			Gasoline (%)	Diesel (%)	Jet (%)	Other (%)	Other (type) (%)			
28	Microalgae	50.39	0	0	0	100	Ethanol	$531.84	$64.65	2000
29		49.96	23	77	0	0		$333.90	$144.51	568
30	MSW	72.57	24	76	0	0		$481.80	$55.28	1100
31	Macroalgae	20.40	0	0	0	100	Biogas	$32.06	$2.34	196
32		28.31	0	0	0	100	Ethanol	$154.11	$183.47	2000
33		13.70	0	0	0	100	Ethanol	$435.61	$158.51	2601
34	Macroalgae or MSW	37.12	0	0	0	100	Ethanol	$228.77	$27.62	1522
35	Macroalgae	32.92	0	0	0	100	Biogas	$1.14	$0.20	9
36		68.00	0	0	0	100	Ethanol	$54.04	$19.75	400

[a]Assumed 7884 h/year operation.

processes can be adjusted for higher marine fuel-range hydrocarbon production with properties that resemble those of marine diesel oil. Both jet- and diesel-range biofuels are potential marine biofuels (e.g., marine diesel oil).

The optimization model calculates fuel production costs and fuel production rates under two optimization strategies – minimize the cost of produced fuel and maximize the total fuel produced. The maximum biofuel production calculation was solved using a fast linear solver. The weighted average plant-gate price calculation is more complex, and a nonlinear solver was required. The system-wide (i.e., the combination of all feedstocks and all pathways) MFSP value is a weighted average of the costs for each biomass feedstock and conversion pathway combination according to the equation:

$$\text{weighted average MFSP} = \sum_{b=1}^{B}\sum_{p=1}^{P}\left(C_{bp} \times DT_b \text{yield}_p\right) \div \sum_{p=1}^{P}\left(DT_b \text{yield}_p\right) \quad (1)$$

where: B = feedstocks; P = conversion technology pathways; C_{bp} = cost ($/HFOGE) for output fuel from each biomass/pathway combination; DT_b = mass of biomass feedstock routed to each pathway; yield_p = pathway yield (HFOGE/t).

Microsoft Excel's solver function was used for the optimizations, and a set of visual basic macros was used to set up the solver problem and loop through the sensitivity cases. Excel's GRG nonlinear solver engine was used to calculate the minimum cost, and the Simplex LP linear engine was used to calculate the maximum biofuel production. Moreover, two constraints were used for all cases: all of the available biomass feedstock must be used, and all values must be positive. The optimization model was run for the baseline case for each technology pathway and feedstock combination set, as well as sensitivity cases for yield, biomass feedstock price, capital cost, and plant operating cost excluding feedstock cost. The model was set up by first selecting the biomass feedstocks, the feedstock supply curve (minimum, median, or maximum availability), and the analysis timeframe, either near term or long term. These values determine the total availability and the price for each selected biomass feedstock. The pathways that will be evaluated in the optimization are selected in another database. This database serves as a lookup table for the yield values, baseline capital and operating costs, and the linear equation parameters needed to calculate the cost of fuel output for each conversion pathway-biomass feedstock combination.

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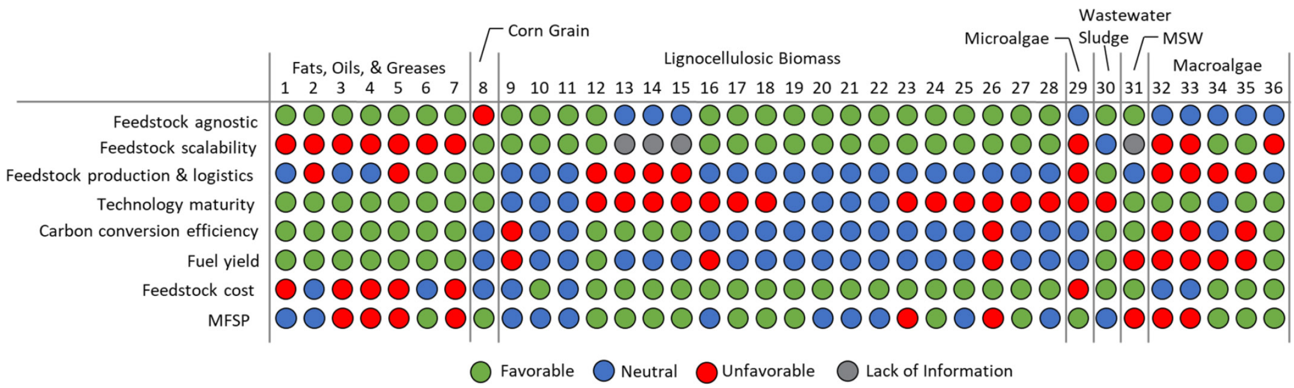

Figure 3. Conversion pathway screening assessment

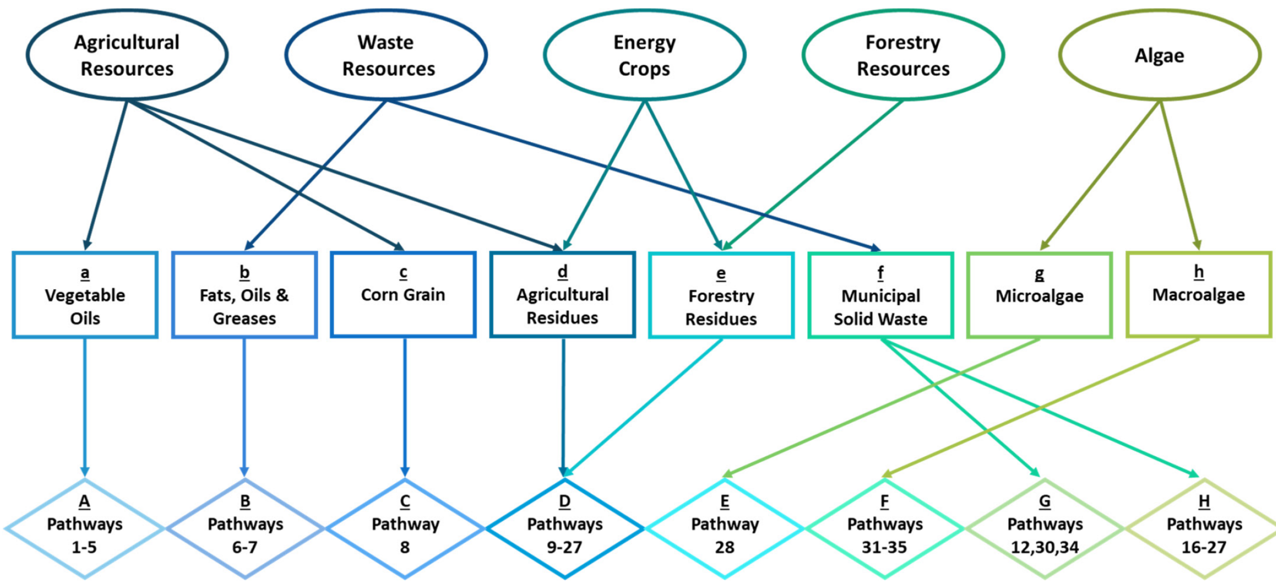

Figure 4. Schematic representation mapping feedstock groups (a–h) with conversion pathways (1–34) for production capacity and price projections. Technology groups are designated with upper case letters (A–H)

Results

Biofuel production capacity and cost projections

Figure 5 shows the results from two optimization cases: maximize total biofuel production capacity and minimize the biofuel production cost. The error bars indicate biofuel capacity at the maximum and minimum feedstock availability, respectively, and the median case serves as the baseline. Each scenario was also assessed to either include or exclude the contributions of microalgae and macroalgae. Figure 5(b) shows the projected biofuel plant gate price corresponding to the projected biofuel capacity (Fig. 5(a)) and was determined as a weighted average of the individual technology group cost. The same results as those in Fig. 5, but on a heavy fuel oil gallon equivalent (HFOGE) basis instead of a per metric ton basis, are shown in Fig. S1. The conversion factors used for this study are that 1 HFOGE is equal to 140 353 Btu and 1 metric ton of heavy fuel oil is equal to 267 HFOGE.[24]

For the scenario to maximize biofuel production (Fig. 5(a) and (b)), the projected short-term and long-term annual capacity of biofuels in the United States are 173 million Mt (or 46 billion HFOGE) at $1798/t and 245 Mt (or 65 billion HFOGE) at $1157/t, respectively, when based on the median feedstock availability. If both microalgae and macroalgae derived biofuels are excluded, the projected annual capacity decreases from 173 to 132 Mt for the near-term scenario and from 245 to 189 Mt for the long-term scenario.

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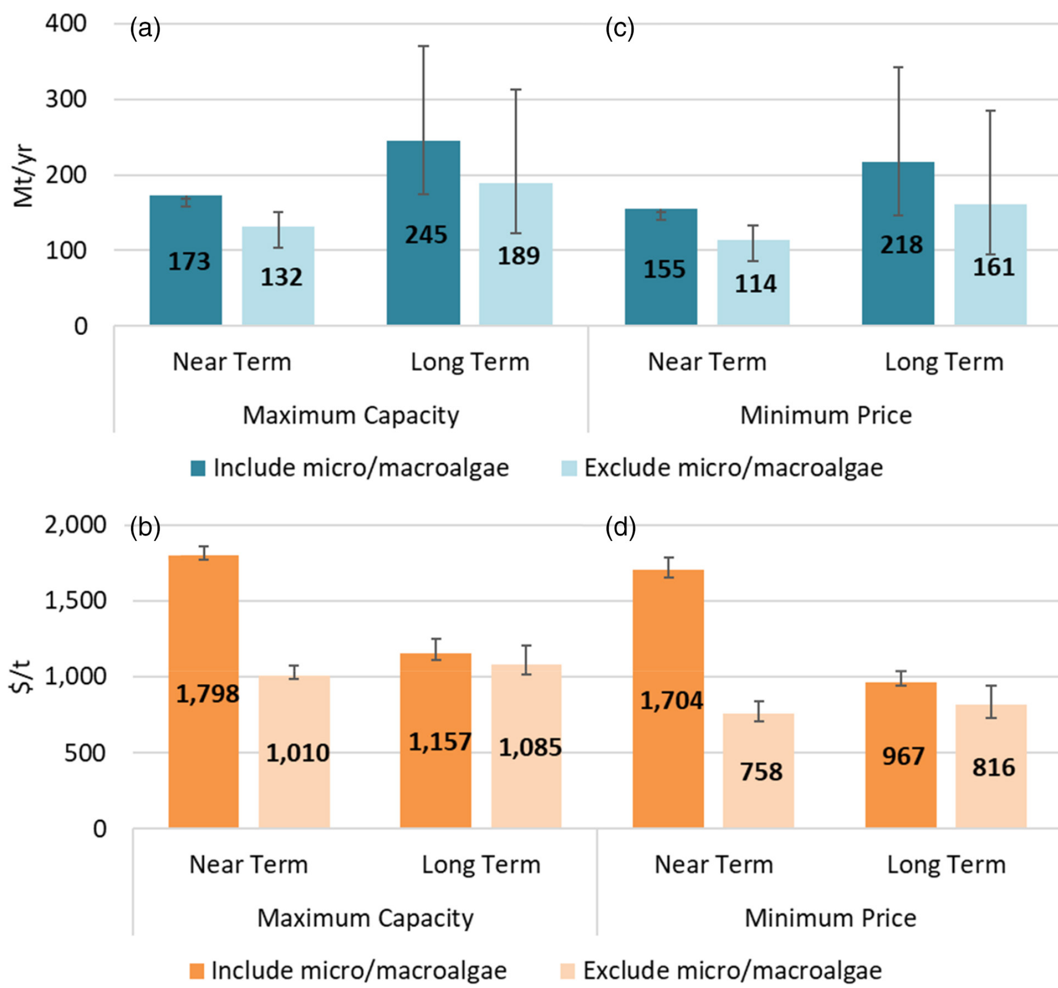

Figure 5. (a) Projected maximum biofuel production capacity in million metric tons per year and the corresponding price (b), in US dollars per metric ton for maximum capacity scenario. Projected biofuel capacity (c) and price (d) on a per-metric-ton basis for minimum cost scenario

Similarly, a second optimization scenario was also carried out in which the cost of biofuel was minimized. The summarized results of this scenario are presented in Fig. 5(d) . Correspondingly, the error bars indicate the maximum and minimum feedstock availability compared to the median availability baseline. In this scenario, the cost optimization objective function was to minimize the overall biofuel production cost, and constraints were not placed on the product distribution. The corresponding projected annual biofuel production capacity at the minimum biofuel cost scenario was also determined (Fig. 5(c)). When based on the median feedstock availability for the scenario to minimize the biofuel price, the projected annual capacity for the near-term and long-term scenarios are 155 Mt at $1704/t and 218 Mt at $967/t, respectively. When both microalgae and macroalgae feedstocks are excluded, the corresponding annual capacity for the near-term and long-term scenarios are 114 Mt at $758/t and 161 Mt at $816/t, respectively. The same summarized results of the cost optimization scenario are also presented in Fig. S1 on an HFOGE basis.

Biofuel contribution by technology groups

Technology groups were determined by matching feedstock categories with conversion technologies, as depicted in Fig. 4. Each technology group was analyzed independently to determine the pathway that optimized either the total biofuel produced or the biofuel price. The quantity of biofuel produced is dependent on feedstock availability and yield of the selected conversion technology. A high-level summary of maximum biofuel yield for the near-term and long-term scenarios is broken down by technology group contributions in Fig. 6. The summary shown in Fig. 6 is for

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the median feedstock availability scenario for both near-term and long-term scenarios. It is evident that Technology Group D – biofuels derived from lignocellulosic biomass via sugar, bio-oil, and syngas fuel precursors – contribute greater than 50% of the biofuel production capacity in all scenarios.

In this analysis, biofuel price depends on feedstock cost and conversion cost, specific to the selected pathway. The majority of the feedstock analysis, excluding algae, was determined at a fixed feedstock cost with a range applied to give a minimum and maximum cost and availability scenario. In the optimization scenario, maximizing the total biofuel production, conversion cost was not used as a criterion for the solver in selecting the optimal pathway. The resulting cost at the annual biofuel capacity for each technology group was then calculated after the pathway was selected. The results of this calculation are also presented in Fig. 6. Conversion of microalgae to biofuels (Technology Group E) consistently resulted in the highest fuel price due to high feedstock and conversion costs, whereas conversion of fats, oils, and greases (Technology Group B) was consistently the lowest due to lower feedstock cost and more mature technologies.

Biofuel product distribution

Another critical aspect of the biofuel production analysis is the type of biofuel produced by the selected conversion pathways. Figure 6 displays the resulting product slate for

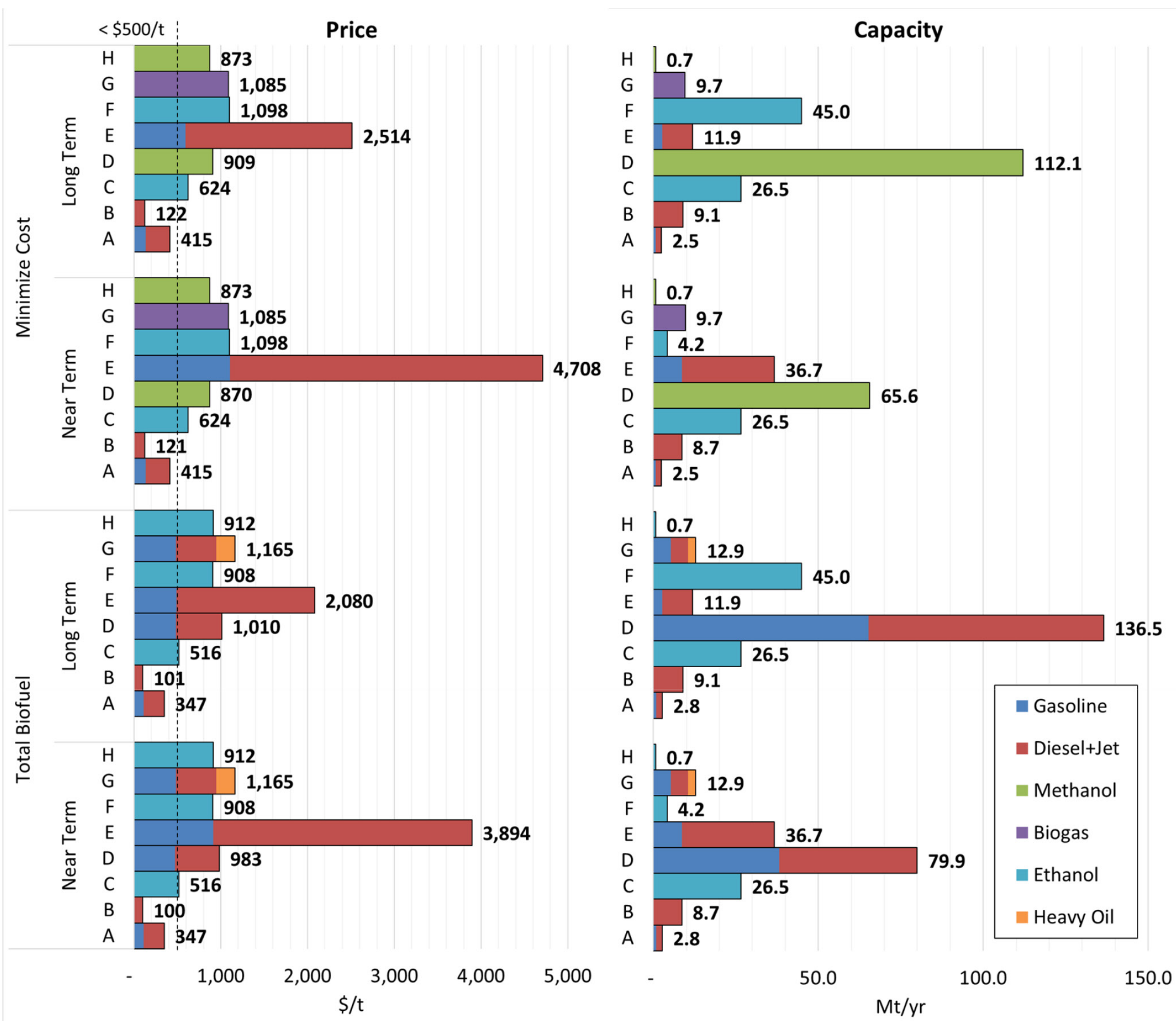

Figure 6. Projected biofuel prices and annual production capacities for the evaluated technology groups based on median feedstock availability. Note that for the price figure, fuel distribution is a percentage, not additive contributions, to total fuel cost

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the median feedstock availability scenario. The results for the minimum and maximum feedstock availability scenarios are presented in Tables S7 and S9. For each feedstock availability scenario, the lowest cost biofuels are predominantly methanol, ethanol, and biogas (also referred to as renewable natural gas). This is consistent with the results shown in Fig. 5(a), (b) – that is, although the minimum cost scenario produces considerable amounts of biofuel, the tradeoff is in product distribution. The maximum total biofuel optimization case primarily produces mainly gasoline, diesel, and ethanol.

Biofuel capacity and price sensitivity study

Sensitivity studies were conducted to provide insight into areas of uncertainty and to identify the key factors impacting projected biofuel production capacity and cost. Figure 7 shows the biofuel production sensitivity analysis conducted for maximum total biofuel production. The results are shown for the near-term and long-term scenarios, either including or excluding algal biofuel contributions. In each case, the median (baseline) scenario is indicated by bold text. In this analysis, a factor of ±20% was applied to the overall yield of the conversion pathways. As the conversion pathway yield scales linearly with biofuel production, the overall biofuel production increases or decreases with the extent of the yield change accordingly. Feedstock availability is another sensitivity parameter. The baseline is median feedstock availability, and the minimum and maximum feedstock availability cases are the lower and the upper bounds, respectively. Feedstock availability also scales linearly with the biofuel production. However, feedstock availability depends on both the minimum, median, and maximum designation, as well as near-term versus long-term factors. An interesting phenomenon occurs in the near-term scenario that includes algae, in which the median scenario is projected to have produced the most biofuel for the maximum total biofuel case. This is due to the inverse accounting scheme utilized for algae compared to terrestrial biomass (i.e., more algae are available at a lower cost). In reference to Fig. 1, the increase in terrestrial biomass availability between the median and maximum case in the near term is smaller in magnitude than the decrease in availability of algae between the same median and maximum case. Compounded with the respective yields of each pathway, this results in the perceived pattern.

Biofuel price sensitivity scenarios were completed to analyze the biofuel production cost as a function of yield, feedstock cost (in the conversion pathway), capital expenses, operating expenses, and feedstock availability and cost (Table 3). In the long-term scenario including algae (Fig. 8), the baseline weighted average biofuel cost was \$967/t. The largest cost driver was yield, resulting in a cost increase of 25% when the yield was decreased by 20% and a cost decrease of 13% when the yield is increased by 20%. The yield was followed by feedstock cost (from the conversion pathway).

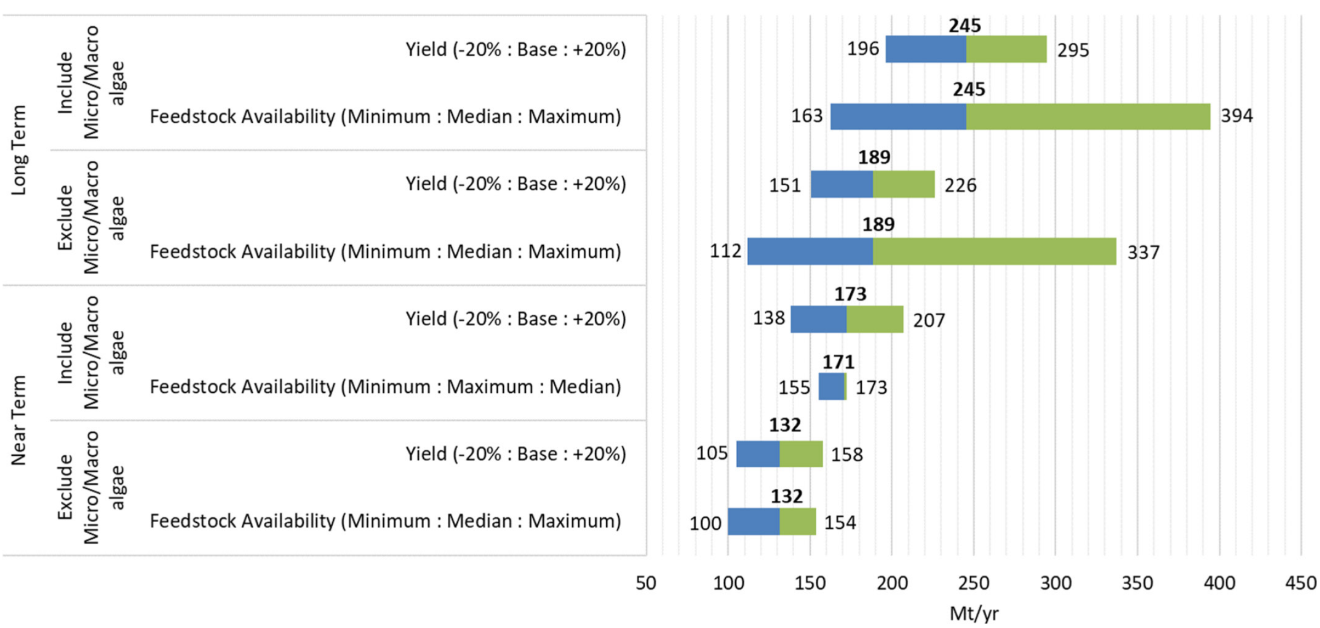

Figure 7. Sensitivity analysis for the maximum total biofuel production scenario. Median (baseline case) for each scenario is shown in bold

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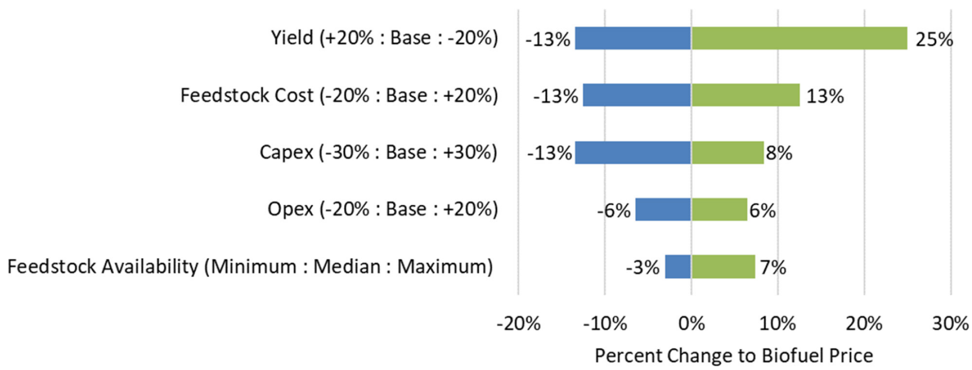

Figure 8. Long-term minimized biofuel price scenario sensitivity analysis for the total biofuel production including micro/macroalgae. Baseline: $967/t. capex: Capital expenses; Opex: Operating expenses

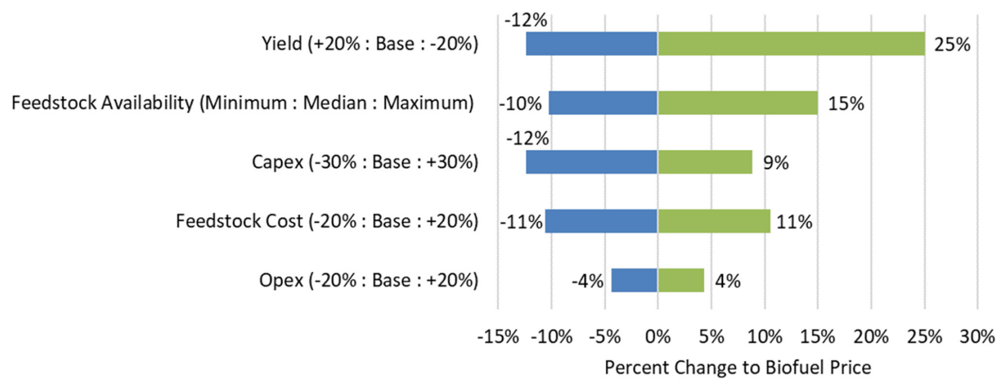

Figure 9. Long-term minimized biofuel price scenario sensitivity analysis for the total biofuel production excluding micro/macroalgae. Baseline: $816/t. capex: Capital expenses; Opex: Operating expenses

Figure 9 reveals that the baseline weighted average biofuel cost is significantly lower $816/t (a 16% reduction from the case that includes algae). In this scenario, yield also exhibited the largest impact on cost variability. The sensitivity profiles for the near-term cases follow the same trend as the long-term cases, as shown in Figs. S2 and S3.

Discussion

Feedstock scalability assessment and future work

Domestic feedstock utilization for marine biofuel applications is highly dependent on feedstock availability. Other market forces could potentially compete for a share of the biomass feedstocks. Some of those markets include aviation fuels, road vehicle fuels, and biobased plastics.[25–27] Feedstocks share with other biofuel markets will likely depend on biofuel price and fuel type yield from each conversion technology (i.e., which fuel is most compatible with which market). Biobased plastics is a growing but relatively small market. Current data indicate about 2.1 million metric tons of global biobased plastic production in 2019, nearly a sixfold increase since 2007 (0.36 million metric tons globally in 2007).[27,28] Despite recent growth in the biobased plastic market, this sector's land use requirement was only about 1.6% of the biofuel's land use in 2019.[28] With the continued increase in biomass availability through feedstock diversification and improved production and distribution methods projected by BT16 and outlined in this study, the coexistence of these two markets is likely feasible. The future pursuit of these works could expand the scope of the study by including more detailed projections of competitive markets, coupled with modified biofuel production projections, to better understand how target biofuel and bioproduct production can be achieved across multiple sectors.

An additional consideration for the large-scale utilization of the US domestic biomass is the co-development of conversion facilities. Domestic biomass potential may increase due to (i) improved production, harvesting, and distribution technologies, (ii) consistent demand, and (iii) grower incentives from the biorefinery to the producer

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to maintain a supply. Large-scale deployment of these feedstocks and biorefineries also needs to consider further the regional distribution of these products. Current biorefinery process designs are often limited in scale due to the regional availability of biomass to the biorefinery. Increasing daily throughput may be feasible if more feedstocks can be delivered to a single biorefinery at lower economic and environmental burdens than is currently achieved. This increase could potentially lower fuel production costs due to the benefits of economies of scale; however, this would also introduce new logistical considerations at the biorefinery that would need to be considered, including feedstock delivery and storage.[29–31]

Strategies to lower biofuel price

The choice of biofuel adoption to enable the shipping industry to comply with low-sulfur regulations and achieve long-term decarbonization is primarily dependent on the vessel owner's financial decisions. Fuel costs represents more than 50% of total operating expenses, making it challenging for shippers to absorb additional operating expenses and stay operational.[32] The projected long-term biofuel prices average $1157/t for the maximized total biofuel scenario (Fig. 5(b)) and $967/t for the minimized price scenario (Fig. 5(d)), which are higher than the current marine fossil fuel prices. To put this into perspective, the average 2019 MGO price was $700/t, and at the time of writing, the average MGO price in North America was about $800/t.[33] Note that these projected prices are weighted averages from all evaluated technology groups (i.e., culminating from various feedstock and production pathway combinations). To consider all potentially available feedstocks in the United States for the total biofuel capacity projection, it is inevitable that certain expensive feedstocks and pathways, such as algal pathways, are also included in the analysis, resulting in the overall high fuel price. Still, there are pathways and technology groups that produce biofuels that are price competitive with fossil fuels. For example, Technology Groups A, B, and C in Fig. 6 exhibit biofuel prices similar to or even better than fossil fuels (less than $500/t). Moreover, when higher cost algae pathways are excluded, the weighted biofuel price can be around $730/t (Fig. 5), which is very close to the 2019 MGO price (pre-COVID-19 pandemic) and lower than the current price.

Scaling up biofuel production at a given time point (i.e., near-term, or long-term scenario) appears to have an inverse relationship to price. That is, the more biofuel produced, the higher the biofuel price. As scaling up will require more biomass feedstock, the higher feedstock demand will introduce new logistical challenges that would need to be considered, including feedstock harvesting, delivery, and storage.[16] Thus, feedstock availability and cost are largely dictated by the feedstock handling technologies that handle the logistical constraints within a given time point. As higher feedstock availability is associated with higher feedstock cost (Fig. 1), scaling up (utilizing more feedstocks) will lead to higher biofuel production costs. However, when the perspective shifts from scaling up within a given time point to scaling up over time, logistical limitations are overcome with improved technologies; it is plausible to achieve much larger capacities of biofuel production at similar or potentially lower costs. For example, Fig. 10 shows that for the maximum total biofuel production scenario, the potential biofuel capacity increases by over 40% between near term and long term, which is attributed to increased feedstock availability. During the same period, the projected biofuel price decreases by 36%. Although both the near-term and long-term feedstock prices for terrestrial biomass remain constant in each feedstock availability scenario (i.e., minimum, median, maximum) within a given feedstock group, microalgae prices are projected to reduce over time. Thus, including microalgae as a feedstock can also decrease the overall biofuel price in the long run.

The biofuel product slate is also related to biofuel prices. There is a tradeoff between price and product distribution (Fig. 6). For each feedstock availability scenario, the minimized cost scenario produces more methanol, ethanol, and biogas than the cases that are optimized for biofuel production. The maximum total biofuel optimization case primarily produces gasoline, diesel, and ethanol. Figure 6 shows that technology Groups A and B can produce low-price biofuels (up to about $500/t), predominantly dominated by biodiesel from vegetable oils and fats, oils, and greases. However, due to low feedstock availability, the projected annual capacity for biodiesel is a mere 12 Mt. This is also in agreement with a recent study that feedstock availability for biodiesel could be an issue in the future.[34] When the price point increases to $750/t, the capacity increases to 29 Mt, of which about 17 Mt is attributed to corn ethanol. Incidentally, the corn ethanol price was around $2.22/gal ($4.08/HFOGE or $1090/t) at the time of writing.[35] At a higher price point, both the biofuel types and annual capacity increase substantially (218 Mt/year), as depicted in Fig. 11. Essentially, all the second- and third-generation biofuels are greater than $750/t. Consequently, lowering the biofuel price to a more acceptable level holds the key for the maritime sector to tap into the projected biofuel capacity.

Biofuel production cost correlates strongly with feedstock cost and conversion cost. Feedstock cost is the key cost contributor to biofuel production. The strategies to reduce feedstock costs include the utilization of waste and low-quality feedstocks, the adoption of integrated landscape

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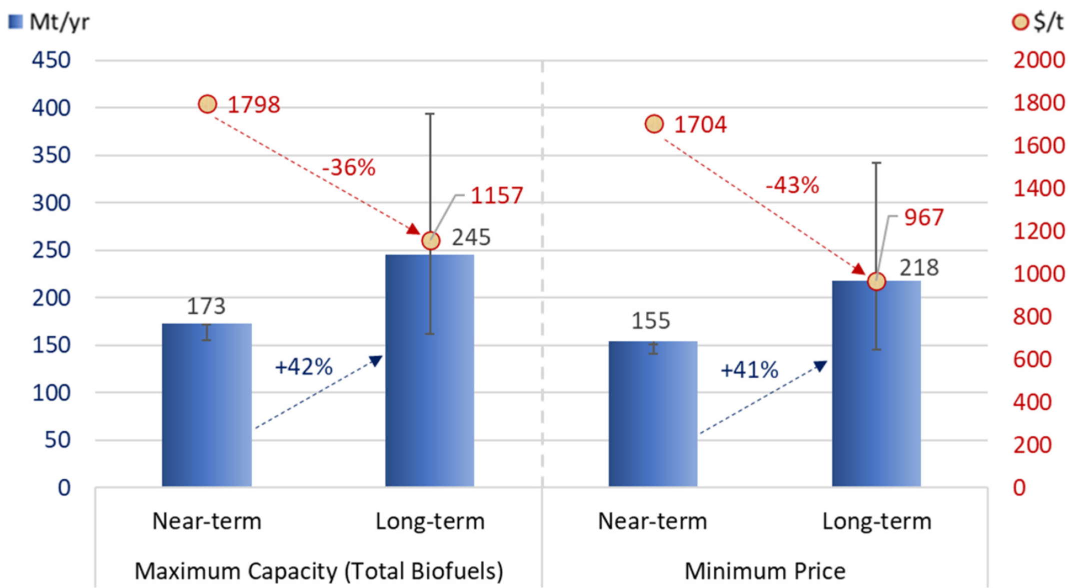

Figure 10. Summary of near-term and long-term projected annual biofuel capacity in million metric tons [Mt] and price (in $/t) based on the US feedstock availability. Error bars are the range of annual capacities corresponding to minimum and maximum feedstock availability. 1 gal HFO = 140,353 Btu; 1 t = 267 gal HFO

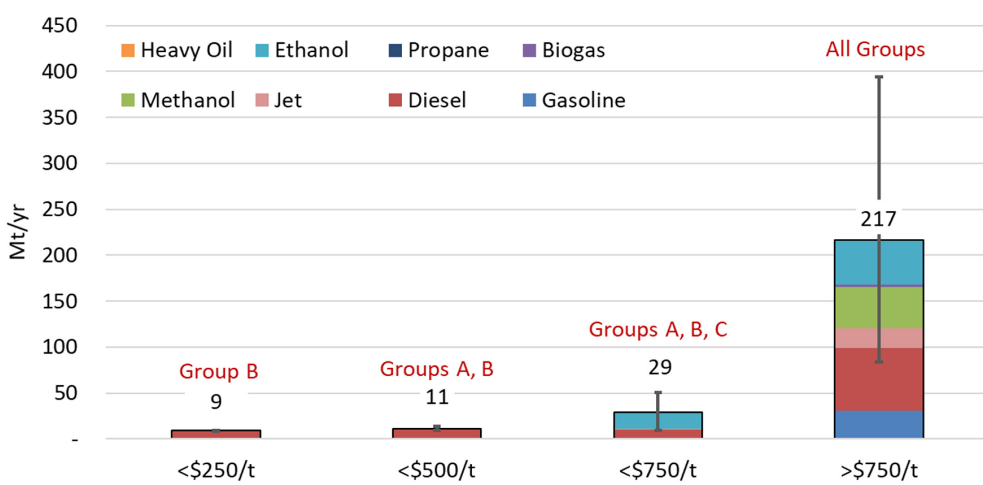

Figure 11. Consolidated long-term projected biofuel capacity and product slate at various price ranges

management strategies, and feedstock logistic enhancement. Improving material conversion and utilization efficiency and energy sustainability via process intensification can improve the biorefinery economy.[36] Co-processing biomass with fossil feedstock such as natural gas has also shown to be an effective synergistic approach to improve liquid fuel yields and lower production cost.[3,37] Furthermore, to enable biofuels to be economically viable, BETO has recently identified five integrated strategies needed to achieve lower biofuel production costs in an integrated biorefinery: developing atom-efficient biorefineries, intensifying process designs, utilizing existing infrastructure, reducing feedstock costs, and developing high-value products.[38]

Incentive schemes to facilitate maritime biofuel adoption

In addition to the technical solutions and strategies mentioned above to lower biofuel production costs, policies and economic incentives could act as economic support mechanisms to help facilitate biofuel development during the nascent stages of marine biofuel adoption. The potential for

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an additional price reduction coupled with incentives and policies would further enable biofuel adoption for maritime. There are a number of examples of policies geared directly toward the marine sector. A clear example is the 'Clean Inland Shipping and Sustainable Logistics in Rotterdam,' a temporary financial support incentive scheme supported by Expertise and Innovation Centre Inland Shipping (EICB) in cooperation with the Port of Rotterdam. The incentive scheme has accelerated the adoption of biofuels, as illustrated by the successful demonstration of the first inland vessel running on 100% drop-in replacement biofuel produced by GoodFuels for Heineken to transport its beers from its brewer in Zoeterwoude to the Port of Rotterdam.[39] A similar approach for ocean freight is underway, led by GoodFuels in collaboration with IKEA, the shipping company CMA CGM, and the GoodShipping Program.[40]

Other existing financial incentive schemes that help accelerate the adoption of clean fuel and technologies for maritime shipping include the Environmental Ship Index, Clean Shipping Index, GHG Emissions Rating, and Green Award.[41,42] Collaborating among multiple ports on major shipping routes and ship owners, these incentive programs encourage shipowners and operators to reduce air pollution from their ships by adopting green shipping practices, of which marine biofuel can play an important role. Qualified ships will receive incentives from all participating ports and other incentive providers participating in these programs. For example, qualified ships will be rewarded with decreased port dues that can offset the (bio)fuel costs. The US government, ports, and industry could benefit from participating in or adopting similar industry-initiated incentive programs. The ports of Los Angeles, New York, and New Jersey, have already joined the Environmental Ship Index program.[41]

There are also incentive programs within the United States that the marine sector could utilize. Other transportation sectors have considered policy strategies that could be altered for use in the marine sector. California's Low Carbon Fuel Standard (LCFS) was approved in 2009 and was intended to decrease the carbon intensity of fuels used in California by 10% by 2020 and 20% by 2030 from a 2010 baseline.[43] The program set a benchmark for the carbon intensity of gasoline, diesel, and fuels that replace them using life-cycle analyses (in grams of CO_2 equivalent per megajoule). Over 900 fuel production pathways currently have carbon intensity scores in the LCFS database, with over 180 of them producing either biodiesel or renewable diesel, both of which could be used in the marine sector.[43] Although LCFS regulation currently does not apply to fuels used in oceangoing vessels, this is one opportunity for the marine sector to utilize a credit system already in place.

The aviation industry has also investigated policy ideas that could target their sector, which the marine industry could emulate for their needs. Sustainable aviation fuel (SAF) has a higher carbon intensity than renewable diesel as scored by the LCFS, incentivizing the production of renewable diesel over SAF, even while ground diesel use has easier pathways to decarbonization than the aviation industry does.[43] Some ideas to work around this roadblock for SAF deployment include: (i) blending mandates requiring a certain volume of SAF to be used in comparison to all jet fuel, (ii) setting life cycle greenhouse gas emissions reduction requirements, (iii) providing an SAF fund that would reduce the prices of SAF funded by taxes or by government budgets, (iv) imposing a fuel tax based on CO_2 emitted per megajoule fuel, or (v) passing the extra cost of SAF to passengers (passenger taxes) based on distance traveled.[44] The marine sector could follow one of these policy ideas; however, further exploration into the advantages and disadvantages for the maritime industry is warranted.

Conclusions

Biofuels can play an important role in accelerating the energy transition and enabling the marine shipping industry to achieve decarbonization and low-sulfur targets. To meet both growing marine fuel demand and recently enacted aggressive air emissions targets, this study projected the potential long-term biofuel price and annual production capacity in the United States. Based on the median feedstock availability, for the scenario to maximize total biofuel production, the projected near-term and long-term annual biofuel capacities were estimated at 173 and 245 Mt, respectively (a 42% increase). Similarly, for the scenario to minimize the biofuel price, the projected annual capacity increases by 41%, from 155 Mt for the near-term to 218 Mt for the long-term. As a reference, the recent global marine fuel consumption was around 400 Mt.

The projected long-term weighted average biofuel prices are $1157/t for the maximized total biofuel scenario and $967/t for the minimized price scenario. By utilizing all available feedstocks in the United States for the biofuel production capacity projection, certain expensive feedstocks and pathways were also included in the analysis, resulting in the overall higher fuel price. Still, there are individual pathways and technology groups that produce biofuels that are price competitive with fossil fuels.

Scaling up will require more biomass feedstock and the higher feedstock demand will introduce new logistical challenges that would need to be considered, including feedstock harvesting, delivery, and storage, resulting in higher feedstock cost (a key cost driver for biofuels). The biofuel price will therefore be higher at any given time when more

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of it is produced. However, over time, the overall feedstock cost will decrease, or more feedstocks will be available at a similar cost and drive down the biofuel production cost. For example, for the scenario to maximize biofuel production, the annual biofuel capacity increases by 42% (due to the increased availability of biomass feedstocks) between 2022 and 2040, whereas the biofuel price decreases by 36% during the same period.

There are strategies to reduce biofuel production costs. Feedstock cost, a key cost contributor to biofuel production, can be lowered via the utilization of waste and low-quality feedstocks, adoption of integrated landscape management strategies, and feedstock logistic enhancements. Other strategies to achieve lower biofuel prices include co-processing biomass with fossil feedstock, developing atom-efficient biorefineries, intensifying process designs, utilizing existing infrastructure, and developing high-value coproducts. The potential for further price reductions coupled with economic incentives and policies would also help enable biofuel adoption for the maritime industry.

Acknowledgements

This work was authored in part by the National Renewable Energy Laboratory, managed and operated by Alliance for Sustainable Energy, LLC, for the US Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. This work is funded by the US Department of Transportation's Maritime Administration (MARAD) through the Maritime Environmental and Technical Assistance (META) program. The authors thank NREL's colleagues, Ryan Davis, Bruno Klein, and Avantika Singh, for their helpful suggestions and review of this work and Michael Deneen for editing support. The views expressed in the article do not necessarily represent the views of the DOE or the US government. The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for US government purposes.

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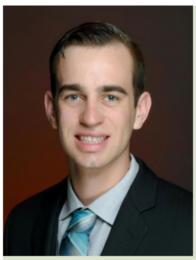

Stephen M. Tifft

Stephen Tifft is a cross-functional research engineer in the NREL's catalytic process development group, developing thermochemical and biochemical routes to convert sustainable biomass feedstocks into drop-in aviation and marine fuels on the bench scale and through high-level techno-economic analyses.

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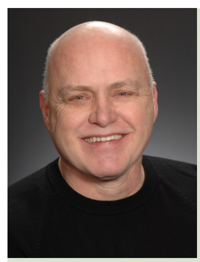
Darlene Steward joined the staff of the NREL in 2007. As a senior engineer, in more than 15 years at NREL she has been involved in a wide variety of projects focusing on environmental and energy systems techno-economic analysis, and lifecycle cost modeling, policy analysis, and research in sustainability and the circular economy. Prior to joining NREL, she worked as an environmental engineering consultant developing emissions inventories and tools for environmental compliance, techno-economic assessment, and cost estimating for private industry and government clients. Darlene holds bachelor's and master's degrees in chemical engineering from the University of Colorado at Boulder.

Christopher Kinchin

Christopher Kinchin joined NREL in 2007. Since then, he has specialized in process design, simulation, and economic analysis of biomass conversion and biofuels processes, primarily techno-economic evaluations of thermochemical biomass to liquid fuels routes, such as gasification, pyrolysis, and hydrothermal liquefaction. Kinchin also supports algae techno-economic evaluations and strategic energy analysis projects, such as biochemical market analysis. Prior to joining NREL, Christopher worked on biomass gasification and solid oxide fuel cell research at the Energy and Environmental Research Center in Grand Forks, North Dakota.



Thomas N. Thompson

Dr. Thomas N. Thompson recently retired as the maritime environmental and energy technical adviser at the US Maritime Administration (MARAD), an agency of the US Department of Transportation. His research interest is the decarbonization of fuels for the commercial shipping sector. His focus has been on both demonstration projects and proof of concept projects that show the viability of innovative technologies for the maritime sector.

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