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Policy Analysis

Implications of Biorefinery Policy Incentives and Location-Specific Economic Parameters for the Financial Viability of Biofuels

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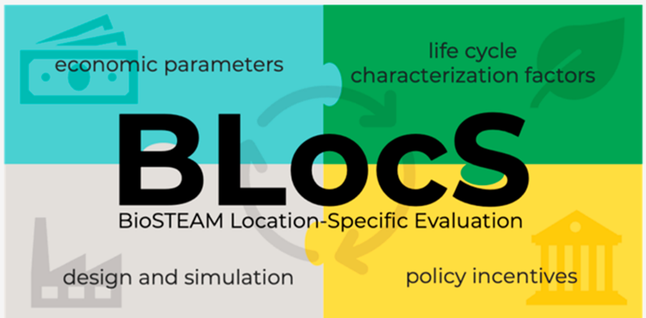

ABSTRACT: Cellulosic biofuels are part of a portfolio of solutions to address climate change; however, their production remains expensive and federal policy interventions (e.g., Renewable Fuel Standard) have not spurred broad construction of cellulosic biorefineries. A range of state-level interventions have also been enacted, but their implications for the financial viability of biorefineries are not well understood. To address this gap, this study evaluated the efficacy of 20 state-level tax incentives from 14 states and their interactions with other location-specific economic parameters (e.g., state income tax rates, electricity prices). To characterize implications of location-specific policies and parameters on biorefinery cash flows, we developed a new BioSTEAM Location-Specific Evaluation (BLocS) module for the open-source software BioSTEAM. Leveraging BLocS and BioSTEAM, we characterized the minimum ethanol selling price (MESP) for a cellulosic biorefinery (using corn stover as feedstock) and two conventional biorefineries (using corn or sugarcane as feedstock) for comparison. Among state-specific scenarios, nonincentivized MESPs for the corn stover biorefinery ranged from 0.74 $\$\cdot L^{-1}$ (4.20 $\$\cdot$gallon gasoline equivalent [gge]$^{-1}$) [0.69−0.79 $\$\cdot L^{-1}$; 3.91−4.48 $\$\cdot gge^{-1}$; Oklahoma] to 1.02 $\$\cdot L^{-1}$ (5.78 $\$\cdot gge^{-1}$) [0.95−1.09 $\$\cdot L^{-1}$; 5.39−6.18 $\$\cdot gge^{-1}$; New York], while the tax incentive-induced MESP reduction ranged from negligible (Virginia) to 5.78% [5.43−6.20%; Iowa]. Ultimately, this work can inform the design of policy incentives for biorefineries under specific deployment contexts.

KEYWORDS: *biofuels, biorefinery location, bioenergy policy, tax incentives, techno-economic analysis*

■ INTRODUCTION

With support from government policy, the volumetric production of bioethanol and biodiesel in the United States increased by approximately 8-fold and 200-fold, respectively, from 2001 to 2019.[1] Cellulosic biofuels, in particular, can provide energy for transportation with lower greenhouse gas emissions compared to fossil fuels,[2] especially when produced from perennial feedstocks on marginal land.[3−5] Ethanol produced from corn stover can reduce greenhouse gas emissions by 57−95% compared to gasoline,[6] and the environmental benefits of biofuels produced from perennial grasses (e.g., switchgrass, giant miscanthus) extend to maintaining biodiversity compared to native grassland, reducing the need for nitrogen fertilizer, improving soil microbiomes compared to annual crops, and reducing human health externalities.[7,8] However, cellulosic biofuels remain technologically challenging and expensive to produce.[9,10] Early adopters of novel bioenergy crops and new biorefining technologies often face significant financial risks in implementation, which stem (in part) from uncertainty in financing (e.g., raising capital from investors), financial assistance (e.g., loan terms), and feedstock supply.[11] This financial risk is particularly relevant to commercial cellulosic ethanol refineries as they are significantly more capital intensive than conventional biorefineries. For example, while an existing cellulosic plant with a production capacity of 25−30 million gallons of ethanol per year costs \$225−250 million to construct, a similarly sized corn ethanol plant costs only \$80 million.[11] To support market development in these sectors, government entities have offered financial incentives to mitigate risk and spur the growth of the domestic biofuel industry (e.g., the federal Volumetric Ethanol Excise Tax Credit, renewable identification numbers [RINs] as part of the Renewable Fuel Standard). Despite existing incentivization, production of nonconventional biofuels remains lower than federal targets established by the U.S. Renewable Fuel Standard (RFS). For example, the RFS originally required the production of 10.5

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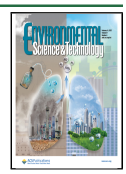

Table 1. Tax Incentives Evaluated in This Study[a]

#	state	name	type	parameter group	portion of parameter incentivized; maximum value [$\$\cdot yr^{-1}$]; duration [yr]	type of tax
E1	IA	Alternative Fuel Production Tax Credits	exemption	FCI	100%; –; 20	property
E2	KS	Biofuel Production Facility Tax Exemption	exemption	FCI	100%; –; 10	property
E3	MT	Ethanol Production Facility Property Tax Exemption	exemption	SEM	100%; –; 10	property
E4[†]	NE	Ethanol and Biodiesel Tax Exemption	exemption	ATA	100%; –; biorefinery lifetime	fuel producer
E5[†]	OR	Biofuel Production Property Tax Exemption	exemption	FCI	100%; –; biorefinery lifetime	property
D1[†]	NM	Biofuel Production Tax Deduction	deduction	SEM	100%; –; biorefinery lifetime	sales
C1	AL	Biofuel Production Jobs Tax Credit	credit	TCI	1.5%; –; 10	income
C2	CO	EZ Investment Tax Credit Refund for Renewable Energy Projects	credit	TCI	3%; 750 thousand; 22	income
C3	HI	Renewable Fuels Production Tax Credit	credit	ethanol	0.20 $\$\cdot gal^{-1}$; 3 million; 5	income
C4	IA	Alternative Fuel Production Tax Credits	credit	TCI	5%; –; 5	income
C5[†]	KY	Alternative Fuel Production Tax Incentives (Kentucky Business Investment Program)	credit	ATA	100%; –; 15	income
C6	KY	Ethanol Production Tax Credit	credit	ethanol	1.00 $\$\cdot gal^{-1}$; 5 million; biorefinery lifetime	income
C7	LA	Provision for Green Jobs Tax Credit	credit	TCI	18%; 1 million; 2	income
C8	SC	Biofuel Production Facility Tax Credit	credit	TCI	25%; –; 7	property
C9	SC	Biomass Energy Tax Credit (Corporate)	credit	SEM	25%; 650 thousand; 15	income
C10	UT	Alternative Energy Development Incentive (Corporate)	credit	ATA	75%; –; 20	income
C11	VA	Green Jobs Tax Credit	credit	jobs	500 $\$\cdot job^{-1}$; 175 thousand; 5	income
R1	IA	Alternative Fuel Production Tax Credits	refund	SEM	100%; –; 1	sales
R2	KY	Alternative Fuel Production Tax Incentives (Kentucky Enterprise Initiative Act)	refund	SEM	100%; –; 1	sales
R3	MT	Ethanol Production Incentive	refund	ethanol	0.20 $\$\cdot gal^{-1}$; 6 million; biorefinery lifetime	income

[a]Table S2 includes full state names along with the abbreviations used in this table, as well as simplifying assumptions, notes, and links to database entries for each incentive. Incentives were grouped based on the biorefinery parameter they incentivize: total capital investment (TCI), fixed capital investment (FCI), specific equipment and/or material (SEM), volume of ethanol produced by the biorefinery (ethanol), amount of tax assessed on a biorefinery (ATA), and the number of jobs at the biorefinery (jobs). The majority of incentives do not indicate the maximum amount of money that may be paid to a biorefinery, which is indicated by "–". "†" indicates representative incentives evaluated across ranges of tax rates.

billion gallons of cellulosic biofuel in 2020, but this requirement was retroactively lowered to 510 million gallons (<5% of the original value) by the U.S. Environmental Protection Agency (EPA; which administers the RFS) when the target was not met.[10]

To better support and expedite the adoption of nonconventional biofuels, it is important to understand the efficacy of existing and proposed policies on biorefinery finances. Although existing techno-economic analyses (TEAs) have evaluated the financial benefits of government policies including the RFS,[12,13] credits for carbon capture and storage,[13−16] and various other existing and expired tax incentives,[12,17] these studies have generally been limited to programs and incentives offered at the federal level. For studies that have investigated state-level policies, the focus has been on California's Low Carbon Fuel Standard, with some limited comparison to Oregon's Clean Fuels Program.[13,14] Other state-level policies such as tax incentives, especially those in key bioenergy feedstock production states (e.g., Iowa, Kansas, Nebraska), have been largely overlooked in the literature. These tax incentives can be structured in different ways: for example, as tax exemptions based on a biorefinery's capital investment or as tax credits whose value is determined by the amount of biofuel the biorefinery produces. However, the efficacy of such incentives at reducing fuel production costs, as well as their interactions with biorefinery characteristics (e.g., feedstock, fuel yield), have not been investigated.

In addition to local policies and technical characteristics of a given biorefinery, a number of other location-specific economic parameters (e.g., feedstock prices, tax rates) can significantly affect financial viability.[18,19] For example, in a given time frame across U.S. states, corn grain prices may range from 130 to 183 $\$\cdot$metric ton^{-1};[20] average electricity prices may range from 0.05 to 0.26 $\$\cdot kWh^{-1}$,[21] and state income tax rates may range from 0% to 12%.[22] Despite these substantial differences, the implications of this spatial variation for biorefinery economics and final fuel selling price are not well understood. Ultimately, this gap in understanding leads to a lack of generalizable guidance in policymaking and impedes the tailoring of tax incentives to a given biorefinery location, technology, or feedstock. The 2022 Supreme Court opinion in *West Virginia v. Environmental Protection Agency*[23] that found limitations to the EPA's authority to regulate greenhouse gas emissions at the federal level further underscores the need to understand the efficacy of state-level climate change mitigation policy.

The objective of this work was to evaluate the influence of biorefinery and biofuel-related tax incentives on biofuel production costs across the United States and to characterize the interaction of incentives with location-specific economic parameters. To this end, the BioSTEAM Location-Specific Evaluation (BLocS) module,[24] an open-source library in Python contributing to the BioSTEAM platform,[25,26] was developed and leveraged to characterize the state-specific economic implications of tax incentives on biorefineries and minimum fuel selling prices. A total of 82 state-specific scenarios were evaluated for relevant feedstocks to elucidate the value of tax incentives when combined with tax rates consistent with federal and state statutes. Specifically, corn stover, corn, and sugarcane to ethanol biorefineries were evaluated with seven location-specific economic parameters (state income, property, sales, and fuel producer taxes; feedstock price; electricity price; location capital cost factor).

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Table 2. Location-Specific Parameters Considered in This Study

parameter	definition	observed distribution [minimum, mode, maximum]	source
State income tax	assessed on biorefinery's net income (or gross receipts in Ohio and Texas; federal income tax deducted from income in Alabama and Louisiana; 50% of federal income tax deducted from income in Iowa and Missouri)	0%, 6.5%, 12%	Federation of Tax Administrators[22]
Property tax	assessed on monetary value of the biorefinery's physical property	0.37%, 1.36%, 7.4%	Tax-Rates.org,[31] Tax Foundation[32]
Sales tax	assessed on the biorefinery's purchases (e.g., equipment and feedstock)	0%, 5.875%, 7.25%	Sales Tax Institute[33]
Fuel producer tax	assessed on wholesale value of fuel produced	5% (NE only)	National Conference of State Legislatures[34]
Electricity price	purchase cost of electricity from grid and selling price of excess electricity sold to grid	0.0471, 0.0685, 0.2610 $\$\cdot kWh^{-1}$	EIA[21]
Corn stover price	purchase cost of corn stover feedstock	81.60, 99.17, 107.91 $\$\cdot$metric ton^{-1}	Bioenergy KDF[35]
Corn price	purchase cost of corn feedstock	130.17, 149.95, 182.89 $\$\cdot$metric ton^{-1}	USDA National Agricultural Statistics Service[20]
Sugarcane price	purchase cost of sugarcane feedstock	20.02, 33.23, 41.84 $\$\cdot$metric ton^{-1}	USDA Economic Research Service[36]
LCCF	ratio of construction costs in area of interest to baseline area	0.82, 1.02, 2.56	Whole Building Design Guide[37]

Ethanol was the focus of this study because of its current and historical dominance in U.S. biofuel production,[1] but the approach outlined in this study can be extended to other biofuels. The relative importance of incentive specifications (e.g., type of incentive, duration for which incentive is provided) compared to location-specific parameters (e.g., tax rates, electricity prices) was evaluated. Conclusions from this study can be leveraged to inform policymakers of the financial efficacy of different tax incentive structures, to identify location-specific parameters particularly salient to biorefineries, and to suggest locations with promising economic conditions for biorefinery deployment. Further, the open-source BLocS software developed in this study can be used to evaluate the implications of incentives on other feedstocks (with results presented here serving as benchmarks) and integrated with BioSTEAM's life cycle assessment (LCA) capability to integrate economic and environmental sustainability evaluations.

METHODS

Tax Incentives and BLocS. Information on state-level tax incentives related to biofuels and renewable electricity production available to biorefineries was collected from two databases: the Database of State Incentives for Renewables & Efficiency (DSIRE)[28] and the Alternative Fuels Data Center (AFDC).[29] Out of over 6,000 incentives in DSIRE and AFDC as of February 2020, only 24 were tax incentives applicable to electricity and ethanol produced from biomass by industrial entities. After excluding expired incentives and incentives pertaining to equipment used in other industries (e.g., "property used for an air quality improvement project"), a total of 20 were analyzed in this study (Table 1). Each incentive was assigned a number, and the incentives were grouped based on the biorefinery parameter they incentivize: total capital investment (TCI), fixed capital investment (FCI), specific equipment and/or material (SEM), volume of ethanol produced by the biorefinery (ethanol), amount of tax assessed on a biorefinery (ATA), and the number of jobs created by the biorefinery (jobs; Supporting Information (SI) Section S1.3 provides further explanation of these parameter groups). Important information collected for each incentive includes the state providing the incentive, eligibility criteria (if any), formula to determine the monetary value of the incentive (and maximum value, if any), the type of tax to which the incentive is applied, and the duration of the incentive.

To enable the evaluation of these 20 incentives (and with the potential to add new incentives), BLocS was developed as an open-source library for the BioSTEAM platform. For a given incentive and biorefinery simulation, BLocS calculates the monetary value of the incentive on a yearly basis according to the formulation of the incentive. BLocS directly incorporates these incentive revenues into streamlined cash flow analyses in BioSTEAM's TEA module. The code developed for the assessment of tax incentives and location-specific economic parameters was published and made available for other users to download and use on the BioSTEAM Development Group GitHub page (https://github.com/BioSTEAMDevelopmentGroup/BLocS).[24] Detailed documentation and examples are available in BioSTEAM's TEA tutorial.[30]

Location-Specific Data Collection. The following location-specific parameters were selected for evaluation in this study: state income, property, sales, and fuel producer tax rates; electricity price; feedstock price; location capital cost factor (LCCF; Table 2). Data on these economic parameters were collected on a state-level basis from the Federation of Tax Administrators,[22] Tax-Rates.org,[31] the Tax Foundation,[32] the Sales Tax Institute,[33] the National Conference of State Legislatures,[34] the Energy Information Administration (EIA),[21] the Bioenergy Knowledge Discovery Framework (KDF),[35] the U.S. Department of Agriculture (USDA),[20,36] and the Whole Building Design Guide.[37] SI Section S1.3 provides a further description of feedstock price data and dollar-year adjustments, property tax rate estimation methods, fuel producer taxes, LCCFs, and electricity price data.

Biorefinery Design, Simulation, and TEA. *Biorefinery Design and Simulation.* Biorefinery design and simulation was performed using BioSTEAM[26,27] version 2.31.18. BioSTEAM is a community-led platform for the design, simulation, and evaluation of biorefineries under uncertainty. This study used existing corn stover, corn, and sugarcane biorefinery models and TEA configurations in BioSTEAM.[38] Biorefineries were

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modeled at typical commercial sizes (0.876, 0.366, and 1.60 million metric tons of biomass per year for corn stover, corn, and sugarcane, respectively) consistent with those in refs 39−41. All three types of biorefineries produce ethanol as their main product. Both the corn stover and sugarcane biorefineries also sell excess electricity to the grid from burning waste biomass (the corn biorefinery is a net consumer of electricity).

Techno-Economic Analysis (TEA). The design and simulation results for each biorefinery are directly used in TEA. To account for the time value of money, discounted cash flow analysis was performed with BioSTEAM using biorefinery-specific assumptions for the estimation of fixed capital investment (e.g., construction expenses and contingency) and fixed operating costs (e.g., maintenance and labor costs) consistent with the literature.[39−41] All capital, material, and labor costs were adjusted to 2020 dollars using Bureau of Labor Statistics adjustment factors[42] and the Chemical Engineering Plant Cost Index, and the federal income tax rate reflects the reduction to 21% in 2017.[43] For each simulated year of biorefinery operation, the biorefinery's costs, including capital investment and taxes, are subtracted from its revenues from product sales and any tax incentives to determine its net profit or loss. This study considered the biorefinery's minimum ethanol selling price (MESP), which is the lowest price at which the biorefinery can afford to sell its fuel; therefore, a lower MESP indicates greater financial viability.

Characterization of Tax Incentives Across Biorefineries and Locations. *Setup.* The evaluation of tax incentives and location-specific economic parameters was conducted in three parts. First, a state-specific incentive analysis was conducted to evaluate the effects of specific combinations of location-specific tax incentives (Table 1) and economic parameters (Table S4). For each state-specific scenario, only feedstocks for which market price information for that state were available were simulated (e.g., sugarcane biorefineries were only simulated in 4 states where it is grown and sold). Second, the general (state-agnostic) efficacy of each tax incentive was characterized using the median values of location-specific economic parameters. Incentives were grouped based on their incentivized parameter (total capital investment, fixed capital investment, specific equipment and/or materials, volume of ethanol produced, amount of tax assessed, or the number of jobs created), and the effects of the magnitude of the incentivized parameter combined with the unique specifications of each incentive on the MESP were quantified. Lastly, representative incentives for each different type of tax (state income, property, sales, and fuel producer) were chosen (indicated in Table 1). For each of these four incentives, the relevant tax rate was varied across the full range observed across U.S. states (while holding all other location-specific parameters constant at median values) to assess the effect of tax rates on incentivized and nonincentivized MESPs. The three analyses were repeated for all three feedstocks.

Sensitivity and Uncertainty Analyses. BioSTEAM's built-in sensitivity and uncertainty analysis features were leveraged to evaluate the impacts of the full range of location-specific factors on biorefinery function under uncertain biorefinery operating parameters. A subset of biorefinery operating parameters (e.g., boiler-turbogenerator efficiency, fermentation efficiency; see Section S1.5 for a full description) were also varied to account for uncertainty inherent to biorefinery operations, regardless of the location. Latin hypercube sampling was used to generate samples for Monte Carlo simulation. For the state-specific analysis, 10,000 samples were generated per state. For the incentive structure analysis, 10,000 samples were generated per incentive. For the location-specific parameter impact analysis, 5,000 samples were generated per point across the range of each parameter.

RESULTS AND DISCUSSION

Relative Importance of Taxes and Incentivized Parameters to MESP. Both taxes paid and several incentivized parameters contribute significantly to biorefinery cash flows and the resulting MESP. Of the parameters incentivized, the TCI, which represents the entire amount of money invested to make the biorefinery operational, contributed the most to MESP: 25% [23−27%] (median [5th−95th percentiles]), 33% [30−36%], and 47% [42−53%] for the corn, corn stover, and sugarcane biorefineries, respectively. The FCI, which is the value of physical property purchased to make the biorefinery operational and constitutes the majority of the TCI, contributed 24% [22−26%] (corn), 31% [29−34%] (corn stover), and 45% [40−50%] (sugarcane) of the MESP. The cost of ethanol production equipment, which is a significant portion of FCI for the three biorefineries and is used here as a representative example of SEM, contributed 11% [10−12%] (corn), 18% [16−20%] (corn stover), and 27% [25−31%] (sugarcane) of the MESP. In the final year of biorefinery operation, which is representative of a typical operating year, income tax (chosen to represent ATA incentives) contributed less than 4% of the MESP for all three biorefineries. This small contribution is consistent with existing literature that suggested state income tax had little influence on MESP.[18] The number of jobs at the biorefinery contributed less than 7% of the MESP for all of the biorefineries when measured as the contribution of job wages to MESP. Thus, of the parameters incentivized, capital expenditures contribute the most to the MESP, while taxes and jobs contribute a smaller but nonnegligible portion. Moving forward, the remainder of the results and discussion focuses primarily on the corn stover biorefinery, which uses one of the most extensively studied cellulosic feedstocks and has the potential to reduce greenhouse gas emissions.

For the corn stover biorefinery, the median TCI was \$380 million [\$354−406 million] and the median FCI was \$362 million [\$337−387 million] (corn and sugarcane results can be found in Sections S2.2 and S2.3, respectively). Equipment used to produce ethanol incurred estimated costs of \$207 million [\$193−222 million]. The ethanol production rate was 230 million $L \cdot yr^{-1}$ [203−260 million $L \cdot yr^{-1}$]. Ethanol sales are the biorefinery's main source of income, leading to income tax expenses of \$12.0 million$\cdot yr^{-1}$ [\$10.6−13.4 million$\cdot yr^{-1}$] (at the median state income tax rate of 6.5%). Labor costs (\$3.3 million$\cdot yr^{-1}$) were consistent across all simulations because the number of jobs at the biorefinery was assumed to be 50 and was not varied.[39] The varied magnitude of these parameters gives some indication of how they may in turn affect the monetary value and corresponding efficacy of tax incentives.

State-Specific Incentive Analysis. State-specific combinations of tax incentives and other economic parameters significantly influence the financial viability of the corn stover biorefinery (Figure 1). Nonincentivized MESPs ranged from 0.74 $\$\cdot L^{-1}$ [0.69−0.79 $\$\cdot L^{-1}$] (Oklahoma) to 1.02 $\$\cdot L^{-1}$ [0.95−1.09 $\$\cdot L^{-1}$] (New York), while the range of tax incentive-induced MESP reduction was negligible (Virginia)

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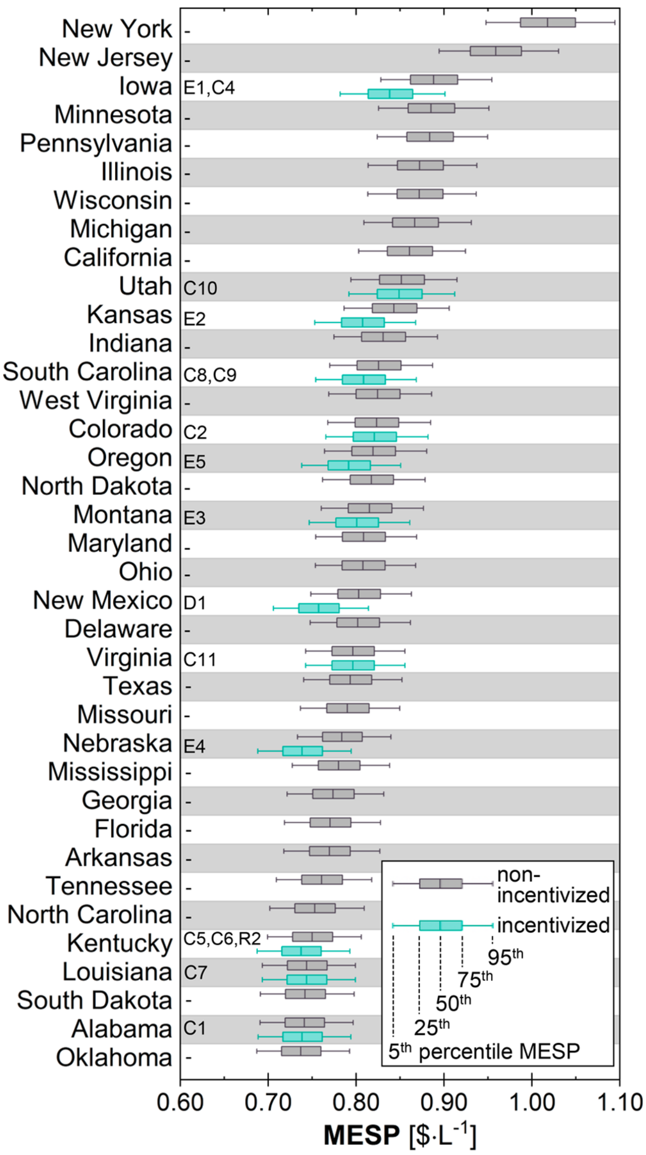

Figure 1. MESPs by state-specific scenarios for the corn stover biorefinery. Numbers along the left edge of the plot indicate the incentives considered in each scenario. Equivalent plots for corn and sugarcane biorefineries are in Figures S5 and S8, respectively.

to 5.77% [5.38–6.17%] (Iowa). State scenarios with high MESPs tended to have high property tax rates and LCCFs, both of which contribute to MESP via capital investment. Property tax assessments are determined by multiplying the value added to the property by the biorefinery (i.e., FCI) by the effective property tax rate, and the state-specific TCI is determined by multiplying the baseline TCI by the appropriate LCCF. Thus, since capital investment contributes to a large portion of the required MESP, higher property tax rates and LCCFs require a higher MESP to recover costs. Brown et al.[18] also found LCCF significantly affected a biorefinery's financial viability, though Li et al.[19] (who assessed a smaller range of locations and, thus, LCCFs) did not. Neither Brown et al. nor Li et al. explored the effect of varied property tax rates. Among state scenarios with the lowest MESPs, feedstock cost had a greater effect on MESP than tax rates and LCCF (e.g., although the Alabama scenario had slightly lower tax rates and LCCF than Oklahoma, Oklahoma had lower feedstock costs and MESP). The effect of alternative state income tax assessments (e.g., by gross receipts in Ohio and Texas and with federal income tax deducted in Alabama, Iowa, Louisiana, and Missouri) appears limited, largely because state income tax is not a significant contributor to MESP. All of these trends hold true for the corn and sugarcane biorefineries as well (see Sections S2.2 and S2.3).

In addition to tax rates, the provisions of incentives themselves substantially affect the efficacy of tax incentives at reducing the MESP. Virginia, the scenario with the least effective incentive (Incentive C11), offers an income tax credit based on the number of jobs at the biorefinery meeting certain salary requirements. Because this incentive only provides 500 $\$\cdot\text{job}^{-1}$ per year for five years (thus, \$125,000 total for 50 jobs), it is a small fraction of the biorefinery's labor costs, it does not meaningfully offset income tax expenses, and it has no noticeable effect on MESP. In the Iowa scenario, there are two tax incentives available to the corn stover biorefinery: Incentives E1 and C4. Incentive E1 exempts the biorefinery from property tax assessment for 20 years while Incentive C4 provides an income tax credit of 5% of the TCI for 5 years. The Iowa scenario has the highest income tax rate and sixth highest property tax rate. Thus, given the high magnitude of capital investment, these incentives save the biorefinery a significant amount of money. The Nebraska and New Mexico scenarios had comparable MESP reductions due to tax incentives (5.77% [5.38–6.17%] and 5.67% [5.41–5.99%] reductions, respectively). Nebraska's Incentive E5 exempts the biorefinery from a 5% fuel producer tax on the wholesale value of its fuel, while New Mexico's Incentive D1 allows the biorefinery to deduct the value of biomass processing equipment and biomass itself from sales tax assessment (the sales tax rate is 5.125% in New Mexico). Given the importance of these material flows to the biorefinery (i.e., ethanol is the primary output while biomass is the primary input), the observed benefits of avoiding taxes associated with these flows are impactful.

There are two other states that offer more than one tax incentive for which corn stover biorefineries are eligible (South Carolina and Kentucky). However, providing more tax incentives did not necessarily result in a greater MESP reduction. South Carolina's two tax incentives (Incentives C8 and C9) reduced the MESP by 1.90% to 2.25%, whereas the three incentives (Incentives C5, C6, and R2) offered by Kentucky reduced the MESP by only 1.54% to 1.77%. Several other state scenarios (Kansas, Nebraska, New Mexico, and Oregon) achieved greater MESP reductions with only one tax incentive. Therefore, it is critical to further explore the importance of tax incentive structures and the interaction with tax rates.

Importance of Tax Incentive Type and Group. Of the four types of tax incentives, exemptions, deductions, and credits had appreciable effects for all three biorefineries (refunds were less impactful; Figure 2A). The value of all tax exemptions (5 incentives) and deductions (1 incentive) was determined by either the monetary value of specific equipment and materials (SEMs) at the biorefinery or the biorefinery's fixed capital investment (FCI), and 4 of these 6 incentives were applied to property tax. Property tax incentives may be the most straightforward way to offset a biorefinery's equipment (i.e., its physical property) costs, though other types of incentives are common. The tax exemptions and deductions evaluated here are highly beneficial because they preclude the

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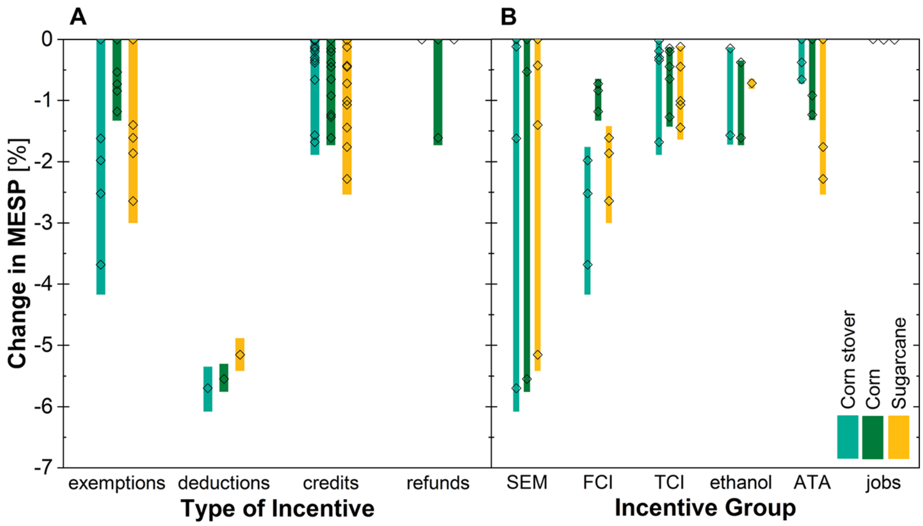

Figure 2. Effect of tax incentives on MESP (A) by incentive type and (B) by incentivized parameter group with location-specific economic parameters at median values observed across states. Colored bars indicate the range of change in MESP due to the most and least effective incentives in each group. Diamond-shaped points indicate a median change in MESP due to individual tax incentives in each group.

entire monetary value of certain property from tax assessment, so the biorefinery will avoid tens of millions of dollars in tax assessments. They may also be simpler to implement because government tax revenue is not returned to the biorefinery (as with tax credits and refunds); rather, the tax is never collected. Government entities may prefer tax credits, which represented 11 of the 20 incentives evaluated in this study, because it allows them to collect tax revenue and return only a portion of it to the biorefinery in a form over which they still have some control; for instance, tax credits may be applied to future tax assessments but not "cashed out".

One of the major features of all tax incentives is the parameter they incentivize, that is, the biorefinery parameter used to determine the monetary value of the incentive (e.g., TCI, volume of ethanol produced). For all three biorefineries, Incentive D1 (a SEM incentive) was the most effective at reducing the biorefinery's MESP (Figure 2B). This incentive allows the biorefinery to deduct the value of biomass processing equipment and biomass itself from sales tax assessment (so the biorefinery avoids paying tax on these items). The three other SEM incentives were less effective than FCI incentives at lowering the MESP. SEM and FCI incentives likely had the largest effect because of the large magnitude of these parameters (for the corn stover biorefinery, FCI is \$362 million and the value of ethanol producing equipment is \$207 million). TCI, ethanol, and ATA incentives tended to have less effect on the MESP (though the efficacy depends on the specific incentive) due to the smaller magnitude of these parameters. The single incentive based on the number of jobs created by the biorefinery did not noticeably affect the MESP. Since the magnitude of the incentivized parameter has a strong influence on the monetary value of a tax incentive, incentives based on parameters with greater magnitudes (such as FCI) could be prioritized to provide more financial support to biorefineries.

The type of biorefinery (corn stover, corn, or sugarcane) also influenced the monetary value of tax incentives, especially for FCI and ATA incentives. Due to the need for additional processing to convert cellulose to ethanol, the capital investment for cellulosic biorefineries (such as those processing corn stover) is significantly higher than for conventional biorefineries processing corn and sugarcane (corn stover FCI: \$362 million; corn: \$62.7 million; sugarcane: \$171 million). Thus, the financial benefits of these incentives are more pronounced for the corn stover biorefinery, leading to a greater MESP reduction. Tax contributes a higher fraction of MESP for the sugarcane biorefinery, allowing ATA incentives to be more effective. The relevance of the incentivized parameter to a biorefinery's overall economics must be considered to understand how future tax incentives can provide the greatest benefit to the biorefinery of interest.

Impact of Incentive Duration and Maximum Value. In addition to the type of incentive and its respective incentivized parameters, other unique specifications of the incentive also influence its impact (Figure 3). For example, though SEM incentives were effective at reducing the MESP overall, some were more effective than others (e.g., Incentive D1 vs R2). The difference in the effects of individual tax incentives focused on the same incentivized parameter comes down to differences in four key specifications of the incentives: the portion of the parameter incentivized, the maximum monetary value of the incentive (if any), the duration of the incentive, and the type of tax to which the incentive is applied.

For some parameters (often TCI), only a portion of the parameter is incentivized. As expected, incentivizing a greater portion of the parameter for a longer duration increases the effect of the incentive (Figure S3). Of Incentives C4, C1, and C8, Incentive C8 decreases the MESP by the most, even though they are offered for comparable durations (5, 10, and 7 years, respectively). Incentive C8 incentivizes the greatest amount of the biorefinery's TCI (25% vs 5% for C4 and 1.5% for C1), allowing it to have the greatest effect.

Some tax incentives (7 of 20 evaluated in this study) specify the maximum yearly amount that may be paid to biorefineries. These maximum amounts tend to be comparatively low (e.g., 4 of these 7 incentives are capped at \$1 million·yr^{-1} or less), which limits the ability of these tax incentives to have a significant effect on the biorefinery's operating costs. For instance, Incentive C7 credits 18% of a biorefinery's TCI but is capped at \$1 million·yr^{-1} (0.26% of TCI) and offered for two years and was the least effective of all incentives based on TCI. Incentive C2 credits 3% of TCI for 22 years but is capped at

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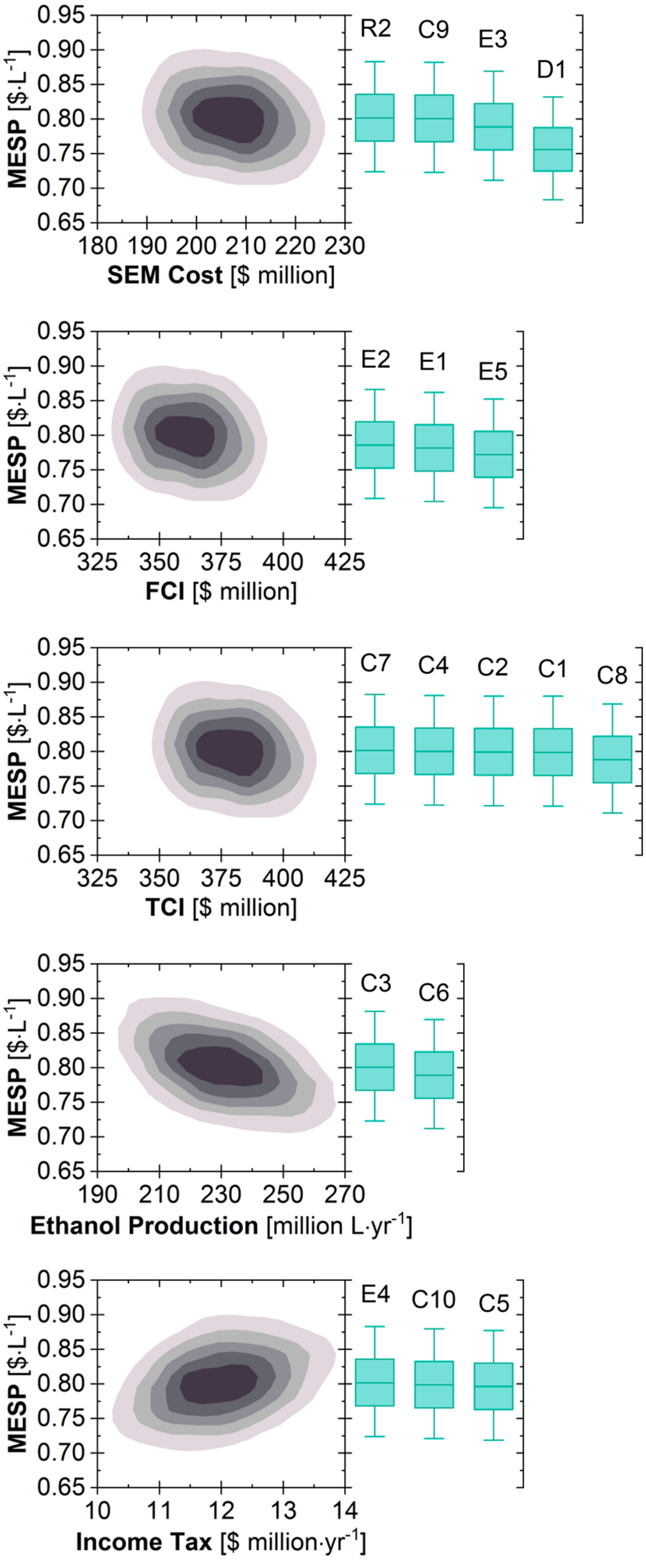

Figure 3. Effect of specific tax incentives grouped by incentivized parameters for the corn stover biorefinery. Kernel density plots show the response of the nonincentivized MESP to changes in the magnitude of the incentivized parameter. Boxplots indicate MESP when a given incentive (denoted by the number above the boxplot) is included in TEA. Equivalent plots for corn and sugarcane biorefineries are in Figures S6 and S9, respectively.

750,000 $·yr^{-1} (0.20% of TCI). Though it led to a greater reduction in MESP than Incentive C2 (which does not have a maximum value) due to a longer duration, the overall effect was nonetheless limited. Of the incentives available to corn stover biorefineries with specified maximum values, only Incentive C6 (which offers a 1.00 $·gal^{-1} income tax credit, capped at $5 million·yr^{-1} for the biorefinery's lifetime) reduced the biorefinery's MESP by more than 1%. All but one of the incentives with specified maximum yearly amounts are income tax credits, suggesting government entities may be interested in limiting the amount of money they give back to biorefineries after taxes have been collected. While capping the value of tax incentives limits their usefulness to biorefineries, it allows the government and biorefinery to benefit simultaneously.

Many tax incentives also specify the number of years a biorefinery can receive the incentive (10 of 20 incentives specify a duration of 10 years or less; only 5 do not specify a duration). Offering a tax incentive for a longer duration allows the biorefinery to pay less tax and achieve a greater reduction in MESP (Figure S4). Notably, though increasing the duration of the incentive increases the effect on MESP, the efficacy is most significant for the first few years of biorefinery operation due to the time value of money (i.e., incentives provided in the future are not as effective as those provided today). Though Incentive E5 had the greatest effect on MESP (3.68% [3.27–4.17%] reduction) among FCI incentives, Incentive E1 also had a nonnegligible effect (2.52% [2.23–2.87%] reduction), suggesting it is not necessary to offer an incentive for the entire lifetime of the biorefinery for the biorefinery to benefit. Incentives R2, E3, and D1 show a similar trend. This possibility is important to note since government entities may be more willing to commit to offering incentives with a shorter duration, so they can be certain of their budget.

Finally, there is also evidence of interplay between the specifications within tax incentives. Though Incentives C3 and C6 are capped at similar values, because Incentive C6 credits five times as much as Incentive C3 per gallon of ethanol and is offered for the biorefinery's entire lifetime, it has a greater effect on the MESP. Though Incentive C1 credits a smaller portion of TCI than Incentive C4, it reduces the MESP more because it is offered for double the duration. Though Incentive C8 is only offered for seven years, it has the greatest effect on MESP of all incentives based on TCI because it credits the greatest portion of TCI and it is applied to property tax, which is of a larger magnitude than income tax. Altogether, balancing the unique specifications of a tax incentive is critical to achieve desired benefits.

Impact of Location-Specific Parameters on Tax Incentive Efficacy. The type of the tax to which the incentive is applied also affects the monetary value and its resulting effect on the biorefinery's MESP. For any tax incentive, the biorefinery cannot receive more money than it would have paid (in the case of tax exemptions and deductions) or did pay (in the case of tax credits and refunds) in taxes. Thus, the relevant tax rate (i.e., the type of tax to which the incentive is applied), combined with the magnitude of the incentivized parameter, determines the absolute maximum monetary value of the tax incentive. For a given biorefinery, this absolute maximum value increases with the tax rate. As a consequence, the greatest benefit (in terms of MESP reduction) will occur at the highest tax rates (Figure 4). Of all the taxes considered in this study, the range of property tax rates had the greatest effect on MESP. The MESP at the highest property tax rate was 10% [9.6–11%] higher than at the lowest rate. Ranges of fuel producer tax, sales tax, and state

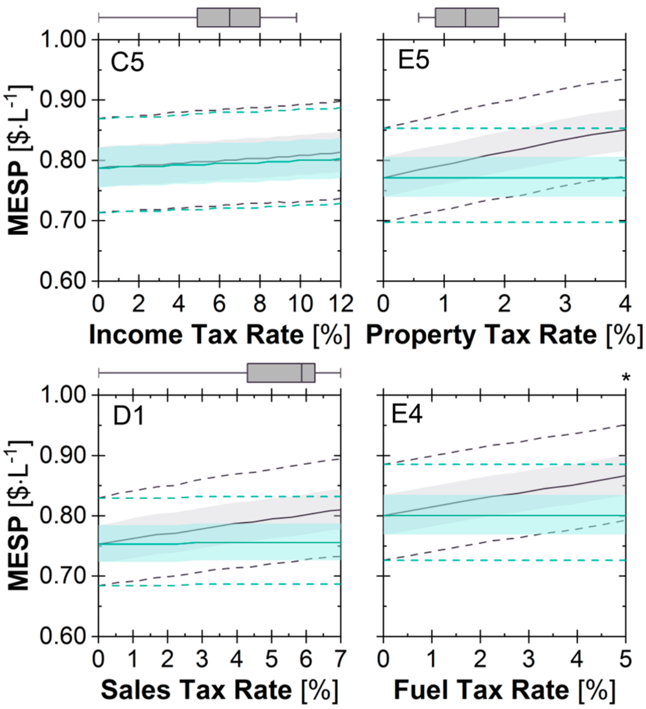

Figure 4. Nonincentivized (gray curves) and incentivized (teal green curves) MESPs as a function of relevant tax rates for the corn stover biorefinery (for 4 representative tax incentives indicated in the top left corner of each subplot). For each plot, the solid line indicates the 50th percentile of the MESPs; shaded area indicates 25th to 75th percentiles, and dashed lines indicate 5th to 95th percentiles. Gray boxplots on top of each subplot indicate ranges of tax rates (50th, 25th to 75th, and 5th to 95th percentiles) observed or estimated for the states considered in this study. "*" indicates only one state (Nebraska) was identified to assess a fuel producer tax at 5%. Equivalent plots for corn and sugarcane biorefineries are in Figures S7 and S10, respectively.

income tax increased the MESP by 8.3% [7.5–9.1%], 7.7% [7.3–8.0%], and 3.4% [3.3–3.4%], respectively.

Considering this relationship, some states have well-matched tax incentives and tax rates. Iowa, the state scenario with the greatest incentive-induced MESP reduction, offers a property tax exemption and has a high property tax rate (2.9%). Nebraska was the only state identified to charge a fuel producer tax but also exempts biorefineries from this tax via an incentive. This incentive would allow a biorefinery operating in Nebraska to achieve MESPs comparable to those of a biorefinery operating in Alabama and Oklahoma, the scenarios where the lowest MESPs were achieved.

Some states, however, have chosen to apply incentives to inconsequential taxes (i.e., state income tax) or to have matched tax incentives to their local tax rates less well. Colorado, Kentucky, and Utah, for example, offer income tax credits (Incentive C2 in CO, Incentives C5 and C6 in KY, and Incentive C10 in UT), but the income tax rates in these states are not particularly high (4.63%, 5%, and 4.95%, respectively). Montana offers a property tax exemption (Incentive E3) but also has a moderate property tax rate (1.15%). Though the specifications of the individual incentives undoubtedly came into play, the relatively low tax rates in the locations where these incentives exist contribute to the small MESP change due to these incentives (0.28–0.34% in CO, 1.54–1.77% in KY, 0.27–0.32% in UT, 1.63–1.92% in MT).

Implications for Future Bioenergy Policy Incentives. The overarching goals of bioenergy policies are often founded in the desire to reduce life cycle greenhouse gas emissions (e.g., RFS,[44] Renewable Energy Directive,[45] Low Carbon Fuel Standard[46]). For instance, the RFS defines cellulosic biofuels as reducing greenhouse gas intensity of fuels by 60% (relative to baseline of gasoline or diesel).[44] Nonetheless, the economics remain challenging. State-level tax incentives have the potential to enhance the financial viability of biorefineries. Through the quantitative evaluation of the monetary value of incentives in state-specific and state-agnostic scenarios and across ranges of relevant parameters, results from this study support the role of tax incentives in promoting the bioindustry. The efficacy of tax incentives depends on the specifications of the incentive itself and the interaction of these specifications with biorefinery operating parameters and location-specific contextual parameters. In general, incentives applied to biorefinery parameters with large magnitudes, such as capital investment, tend to allow for the greatest benefit to a biorefinery (e.g., Incentives E5 and C8). However, the portion of the parameter incentivized, the maximum monetary value of the tax incentive, and the duration for which the incentive is provided also determine an incentive's effect. The type of tax to which an incentive is applied also affects the monetary value of a tax incentive (e.g., income tax vs property tax incentives), and the efficacy of the incentive is closely related to the specific tax rates (e.g., Incentive E4). Moreover, biorefineries processing different feedstocks are affected differently by tax incentives.

The magnitude of incentive-induced reductions in production cost (e.g., around 6% for the most effective incentives evaluated in this study) are somewhat more optimistic than the results of previous studies of federal biofuel tax incentives. For example, Brown[17] found the Second Generation Biofuel Producer Tax Credit and Volumetric Ethanol Excise Tax Credit, which provided federal income tax credits of up to \$0.27 and \$0.12 per liter of qualified biofuel production, respectively, had little effect on improving the financial viability of cellulosic biorefineries due to a lack of federal income tax liability. However, Sanchez et al.[14] found combining cellulosic biofuel production with carbon capture and federal tax credits over \$30 per ton of carbon dioxide (similar to the credit provided by 26 U.S. Code Section 45Q[47]) could incentivize significant carbon sequestration while improving profitability for ethanol producers. Overall, these mixed results suggest improved and complementary policy interventions are necessary to achieve cost reductions that will make cellulosic biofuels financially viable and achieve their desired environmental benefits.[6,14]

When implementing policy incentives, the goal of incentivization is important. While biofuel consumption mandates such as the RFS establish requirements for biofuel production, they offer limited assistance in derisking novel technologies by providing guaranteed financial support. Therefore, policy incentives should be designed to reflect their specific goals. For example, if the goal is to increase the production of environmentally beneficial biofuels, incentivizing the volume of fuel produced by a biorefinery with a verified reduction in life cycle greenhouse gas emissions will likely be most effective to achieve this goal. However, if a state is interested in increasing the number of operating biorefineries (and consequently the volume of biofuels produced), a property tax exemption based on TCI may be more beneficial as it would reduce the operating costs of the biorefinery regardless of the amount of

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fuel produced. Policy approaches must also consider potential effects on the broader biofuel economy, for example, how the policy may influence the capacity and corresponding economies of scale of biorefineries constructed in response. Altogether, this study illustrates the significance of considering biorefinery constraints and location-specific contextual parameters in designing a tax incentive and provides practical guidance for policymakers to achieve desired targets to advance the development and deployment of more environmentally sustainable fuels.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.2c07936.

> Detailed methodology used to collect tax incentive information from databases; detailed descriptions of individual tax incentives and incentive groups; detailed methodology for location-specific parameter data collection; explanation and visualization of BioSTEAM-BLocS connection; description of input parameter distributions and sensitivity analysis results; expanded TEA results for corn, corn stover, and sugarcane biorefineries (PDF)

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