Energy Policy 166 (2022) 112916

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

How the U.S. Renewable Fuel Standard could use garbage to pay for electric vehicles

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ARTICLE INFO

Keywords:
Renewable fuel standard
Bioelectricity
Waste-to-energy
Electric vehicles
Supply curve
Anaerobic digestion

ABSTRACT

The U.S. Renewable Fuel Standard (RFS) is a key federal program shifting the nation's transportation fuel mix towards lower-carbon alternatives. A 2014 update to the standard included certain types of renewable electricity as qualifying fuels, supporting vehicle electrification within the RFS for the first time. This study investigates the potential under existing regulatory authority to expand deployment of low-carbon waste-to-electricity pathways, yielding revenue that could be used to subsidize electric vehicle (EV) sales or to support other RFS-aligned climate and transport-sector goals. We find that by accounting for drivetrain efficiency in credit allocation and creating a centralized entity to accrue credits, the RFS could generate $8.7 to $24 billion in revenues annually that could be used to provide EV subsidies of $3600 to $9200 or to otherwise accelerate transport electrification. The economic potential for qualifying waste-derived bioelectricity production could meet EV fleet demand to at least 2029. Absent a federal Low Carbon Fuel Standard, or other technology-neutral fuel policy, the RFS could effectively support widespread vehicle electrification. Expansion of waste-derived electricity could mitigate *or* increase pollutant exposure for some populations, so policy design and implementation must pay close attention to environmental health, justice, and equity.

1. Introduction

Vehicles account for the largest share of greenhouse gas (GHG) emissions in the United States, producing over 28% of the total national carbon footprint in 2018 (U.S. Environmental Protection Agency, n.d.-e). This fraction is rising consistently as the electric power sector, which until 2017 was the largest contributor to U.S. GHG emissions, continues to make significant strides by developing low-carbon electricity sources. The Renewable Fuel Standard (RFS), created under the Energy Policy Act of 2005, is a key federal program aimed at reducing carbon intensity (CI) in the transport sector through the proliferation of renewable fuels. The RFS induces production of a fixed amount of biofuel. This contrasts with other policy designs such as Low Carbon Fuel Standards (LCFSs), which directly target a set reduction in fuel GHG emissions through a technology-neutral mechanism that enables direct support for vehicle electrification.

The unit of compliance with the RFS is the Renewable Identification Number (RIN), a tradable credit allocated to a gallon of qualifying renewable fuel. By the end of each compliance period, obligated parties, such as blenders and retailers of petroleum transportation fuel, must have acquired enough RINs to demonstrate compliance with the designated blend requirement. The RFS regulation distinguishes among qualifying biofuels, separating them into advanced biofuel, biomass-based diesel, cellulosic biofuel, and other renewable fuel, and creates targets for each. This produces distinct markets for RINs in each of these categories (distinguished by their D-codes) to specifically stimulate the development of lower-carbon transportation fuel alternatives. A 2014 rulemaking expanded the RFS to allocate cellulosic (D3) RINs to biogas derived from specified waste biomass resources—specifically landfills, municipal wastewater treatment plant digesters, agricultural waste (e.g., manure) digesters, and separated municipal solid waste digesters (U.S. Environmental Protection Agency, 2014; 2021a). Moreover, it also enabled so-called *eRINs* to be generated for bioelectricity derived from these qualifying biogas pathways. These eRIN pathways expanded the RFS to include vehicle electrification for the first time.

Production of cellulosic fuels eligible for D3 RINs has consistently

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https://doi.org/10.1016/j.enpol.2022.112916
Received 8 July 2021; Received in revised form 15 February 2022; Accepted 12 March 2022
Available online 10 May 2022
0301-4215/

fallen more than 90% short of the targets laid out in the statute owing to a lack of technology development and investment since the RFS was introduced (Bracmort, 2020). Furthermore, shortfalls of advanced and cellulosic biofuel production undermine the RFS's goals of reducing GHG emissions and growing the renewable fuels sector (Rusco, 2016). Expansion of eRIN pathways could aid in the goals of the RFS by filling this gap in program compliance while generating revenue that could be used to promote further uptake of electric vehicles (EVs). This study investigates the scale of the potential eRIN revenue stream and the magnitude of potential EV rebate that could be achieved via the RFS under several scenarios of bioelectricity pathway deployment and EV fleet expansion, and the associated policy design characteristics that are necessary for success.

2. Background

This study investigates the potential of the eRIN mechanism under the RFS to significantly expand deployment of carbon neutral and carbon negative energy (California Air Resources Board, 2021b; Franchetti, 2013; Lombardi et al., 2006; Tonini et al., 2016) from landfill gas, municipal wastewater treatment plants, manure, and separated municipal solid waste while delivering revenue that would be used to further support vehicle electrification. These outcomes depend on two key program characteristics to deliver the significant, stacked benefits of electrifying the vehicle fleet via waste-derived bioelectricity: adjusting eRIN crediting to account for the efficiency of the EV drivetrain and creation of a central entity vested with the responsibility of accruing and distributing eRIN revenue. The following subsections describe these policy characteristics and their justification in more detail.

2.1. eRIN equivalency

RINs are currently allocated to fuels based on energy content, with one RIN equating to one gallon of ethanol equivalent. The RIN equivalency for electricity is therefore set at 22.6 kWh/eRIN under the current RFS policy. This equivalency does not account for the fundamental difference between internal combustion engine (ICE) drivetrains and EV drivetrains, the latter of which power a vehicle *several times* more efficiently on an energetic basis.

EPA recognizes that calculating equivalency values solely on the basis of energy content "may unduly negatively affect the renewable electricity pathway" (U.S. Environmental Protection Agency, 2016) and has sought input as to whether a different approach might be warranted. There is precedent for crediting electricity differently from liquid fuels in transportation fuel policies. California's Low Carbon Fuel Standard, for example, applies an energy efficiency ratio to electricity, crediting each MJ of electricity used in EVs as 2.6–5 MJ of transportation fuel depending on the vehicle type (Low Carbon Fuel Standard Regulation, 2020, sec. 95486.1). The International Council on Clean Transportation has conducted an analysis of the RFS biogas pathway policy and proposed an equivalency value of 5.24 kWh/eRIN (The International Council on Clean Transportation, 2015). This value was also used by Xie et al. (2019) and Podkaminer et al. (2017) in their analyses of eRINs, and we use it here.

At the equivalency rate of 5.24 kWh/eRIN and eRIN price of $2.50, the total revenue for qualifying bioelectricity supplied to the RFS market would be $477/MWh.[1] This is a substantial potential subsidy, sufficient to drive significant buildout of qualifying waste-derived bioelectricity systems while leaving considerable surplus revenue that could be rebated to purchasers of new EVs.

2.2. The central eRIN accruer

In a 2016 rulemaking, the U.S. Environmental Protection Agency considered four pathways for eRIN allocation: Vehicle owners, charging station owners, electric utilities, and vehicle manufacturers (Podkaminer et al., 2017; U.S. Environmental Protection Agency, 2016; Xie et al., 2019). However, we propose a fifth option for consideration: a central accruer which would purchase the renewable attribute of qualifying bioelectricity, track qualifying miles driven (either through vehicle telemetry gathered by OEMs or through numerical models), and generate eRINs. We envision this entity as a chartered non-profit, although it could also be a government body. This would be a relatively novel structure, though EPA has already recognized the possible need for "a novel contract mechanism by the EPA or the involvement of a third-party aggregator in order to fulfill the requirements for RIN generation" (U.S. Environmental Protection Agency, 2016).

Creating a new non-profit entity vested with the responsibility of accruing and distributing eRIN revenue would enable the program to generate substantial income that could be allocated to EV rebates alongside other climate and transportation goals. Without the central accurer model, revenues of over $450/MWh would ultimately flow to bioelectricity producers while little would support EV rebates in certain scenarios. The central accruer can divert some of the (in some cases) extraordinary profit that would otherwise accrue to qualifying bioelectricity generators to support EV growth and the concomitant long-term growth of the eRIN market.

As a single purchaser of environmental attributes from qualifying bioelectricity facilities, this entity would be able to negotiate long-term offtake contracts with bioelectricity facilities at a rate consistent with their expected levelized cost of operation. This would offer a secure return on investment to facilitate new construction while allowing allocation of much of the eRIN revenue to achieve the established goals of the RFS rather than only spurring investment in bioelectricity, which occurs independent of the central accruer model.

Because the central accurer procures only environmental attributes – not the electricity itself – it would not be in competition with electricity buyers, and thus can be assumed to have access to all qualifying attributes. This structure is similar to California's LCFS in some ways: credits are tracked via a book and claim system (i.e., there is no end-to-end traceability of electricity), and electricity is treated as a transport fuel if it can be claimed in such a system. On the other hand, credits are bundled with electricity sales in the LCFS. Opinions differ on the unbundling of credits from electricity. For example, U.S. national policy allows unbundling of Renewable Energy Credits, while California policy does not. Moreover, such unbundling was considered in an eRIN allocation pathway considered by the EPA: accrual to vehicle manufacturers.

Creating a chartered not-for-profit central accruing entity represents a significant and novel expansion for the RFS program; however, such a role is not entirely novel. The responsibility could be analogous to the work of other entities already in existence at the federal and state levels. For example, the California Independent System Operator (CAISO) is a chartered non-profit, which operates the bulk electric power system and wholesale market in most of California. Moreover, in its role as the buyer of environmental attributes from qualifying producers, the central accruer is analogous to the administrator of the Medicare program (Centers for Medicare and Medicaid Services or CMMS). Notably, Medicare contracts with healthcare providers to provide care to patients, so CMMS sets contract prices and procures services on behalf of third parties in much the same way that the central accruer will engage in bioelectricity contracts and provide rebates to EV purchasers.

2.2.1. Economics of the central accruer

In the early stages of the program (Fig. 1a), low-cost RFS-qualifying

[1] For comparison, current wind projects are eligible for a federal tax credit of $25/MWh (DSIRE, 2021), while California's LCFS can lead to subsidies as high as $1900/MWh (California Air Resources Board, n.d.-b, 2021a; Low Carbon Fuel Standard Regulation, 2020, sec. 95486.1) (with a credit value of $185/MT and CI of −762 gCO_2e/MJ for some dairy digester projects).

bioelectricity (such as that from extant LFG systems) will exceed the quantity of RFS-qualifying electricity attributes demanded. This creates a shortfall in attribute quantity demanded that prevents the attribute market from reaching a market-clearing competitive equilibrium (P*, Q*). However, as more EVs enter the vehicle fleet (Fig. 1b), the quantity of low-cost qualifying bioelectricity supplied may not keep pace with the quantity of attributes demanded for vehicle fuel, pushing eRIN generation into higher-cost electricity systems, and eventually eclipsing the total technical capacity of qualifying bioelectricity. Especially later in the program, as supply of low-cost qualifying bioelectricity becomes constrained, most eRIN revenue would accrue as profit to bioelectricity producers, leaving little excess revenue to be allocated to EV deployment or other RFS goals. The central accruing entity, as illustrated by Fig. 1, can mitigate this issue.

Buyer surplus will be small because eRIN demand will be elastic and will have a correspondingly shallow slope if the quantity of eRINs remains small relative to the pool of D3 RINs. This is particularly likely early in the program and will continue to be the case if EPA continues to increase renewable volume obligations (RVOs). In contrast (as shown by the steeply sloped supply curves in Fig. 3) supply will become inelastic as Q grows. As a result, most of the surplus will be captured by electricity producers in later years, leading to tremendous profits.

As illustrated in the figure, a monopsony buyer can change the dynamics of the market by offering each potential supplier a negotiated rate (Blair and Durrance, 2014; Hussey and Anderson, 2003). As a single purchaser of environmental attributes from qualifying bioelectricity facilities, this entity would be able to enter long-term offtake contracts with bioelectricity facilities at a return on investment consistent with that facility's expected levelized cost of operation. This would mean that overall program revenue would not fall as a growing EV fleet pushes marginal eRIN generation into more expensive qualifying sources. Additionally, this structure would offer developers the reliable rate of return necessary to secure financing for construction, thereby facilitating significant build-out of qualifying bioelectricity while also directing surplus eRIN value to EV market growth and other RFS goals. In addition to offering a secure offtake, the new entity could act as a lender or loan guarantor for qualifying facilities to overcome the cost of capital that has been a major barrier to biogas build-out to date. As shown above, the central accruer may only be necessary during a part of the eRIN program life cycle. However, it will be beneficial to use the central accruer model for the entire program to provide stability to investors and to establish a robust market.

3. Methodology

To assess program revenue and vehicle subsidy, we modeled EV deployment and bioelectricity supply curves, treating EV deployment as an exogenous variable. The total program size in year *n* was calculated as the RIN value ($477/MWh) times the lesser of the total fleet demand (MWh) in year *n*-1 and the supply of bioelectricity available at a cost below the RIN value, while net program revenue was calculated by subtracting the cost of this bioelectricity from total program revenue and reducing the result by 20%, which was assumed to flow to other areas of the bioelectricity supply chain including the overhead cost of operating the central accruer. EV subsidy was calculated by dividing the revenue in year *n* by the number of vehicles sold in year *n*. Thus, the EV subsidy in year *n* depends on miles driven in year *n*-1.

3.1. EV deployment trajectory

We modeled uptake of EVs – both battery electric (BEV) and plug-in hybrid (PHEV) technologies – to 2040 with a focus on class 1 light-duty sedans and SUVs (as defined by the Federal Highway Administration, gross vehicle weight rating ≤6000 lbs.). We did not evaluate larger vehicles because those technologies are less mature, but the same opportunity will apply to them in principle. Other studies of eRIN potential (Podkaminer et al., 2017; Xie et al., 2019) have modeled vehicle sales trajectory as a function of rebate level. We took the opposite approach, investigating the scale of eRIN revenue and potential rebate levels as a function of varying EV sales trajectories, modeled exogenously. The market for electric vehicles is extremely dynamic at present, with a wide variety of unpredictable factors, including various incentives, vehicle make and model availability, range and charging infrastructure availability, and social factors including perceived vehicle quality and desirability. Therefore, rather than attempt to project a specific sales trajectory inclusive of the effect of the subsidy, we instead explored the range of possible trajectories and their impact on the eRIN market.

To estimate the potential amount of power consumed by the EV fleet, we computed three EV adoption trajectories based on differing fractions of EVs in class 1 light-duty vehicle sales in 2030. Table 1 illustrates this and other variations in EV uptake and electric vehicle miles traveled (eVMT) considered in our EV deployment model. Further details on the model and scenarios are provided in the Appendix.

The resulting annual EV sales and energy consumed for fleet charging are depicted in Fig. 2, split by EV sales trajectory, the parameter which drives the largest variation in estimates. Ribbons include variations across the parameters: Total Fleet Size, PHEV Fraction, and Model Year Eligibility for eRINs. Fleet charging consumption follows a similar trajectory to sales, with a similar 5× variation in magnitude across the different sales scenarios. In early years, Model Year Eligibility for eRINs is the second largest driver in energy consumption after EV Sales Trajectory, whereas PHEV Fraction becomes a significant driver

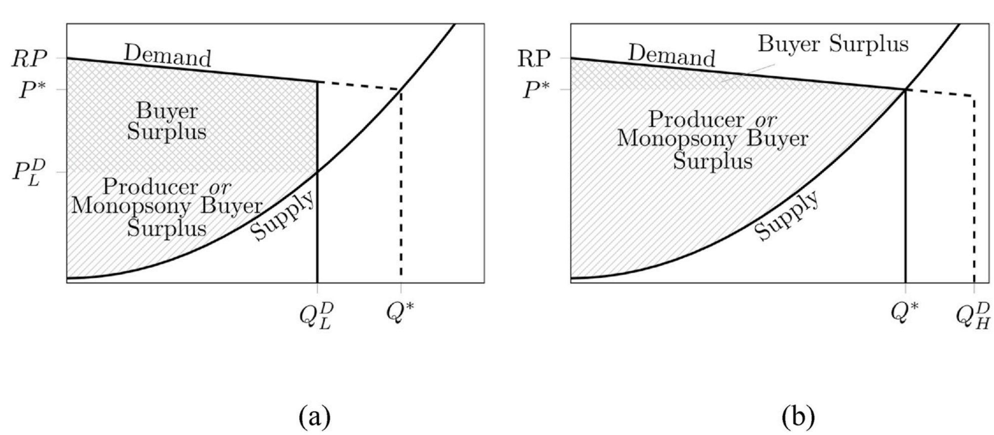

Fig. 1. Supply, demand, and market characteristics for eRIN environmental attributes with (a) and without (b) a demand shortfall (a). P* indicates the equilibrium price (for the renewable attribute of the electricity only), Q* the equilibrium quantity, Q^D the quantity demanded by EVs, P^D the market clearing price, and RP the RIN price with zero eRINs generated.

Table 1
EV fleet variables considered in our model. All permutations were explored in our sensitivity analysis.

Variable	Scenarios
EV Sales Trajectory (as share of light-duty vehicle sales)	(a) S177 Adopted Nationwide[a]; (b) 30% by 2030; (c) 50% by 2030
Model Year (MY) Eligibility for eRINs	(a) All Model Years; (b) Only MY 2021 and later
PHEV Fraction	(a) Phase Out PHEVs; (b) Current mix of BEVs and PHEVs
Total Fleet Size (U.S. Energy Information Administration, 2020b)	(a) Low; (b) Reference; (c) High

[a] These are California plus twelve additional states (as of 2020) that have chosen to adopt California's Low Emission Vehicle (LEV) and Zero Emission Vehicle (ZEV) regulations as allowed under Section 177 of the Clean Air Act. Per CARB internal analysis roughly 30% of national vehicle sales occur in S177 states (California Air Resources Board, 2019).

later in program life.

Our baseline cases assume that all model years are eligible for eRINs, PHEVs phase out by 2030, and the total fleet size grows at the AEO reference rate. Our baseline includes three scenarios for fleet growth, which result in EV sales of 1.0 million, 2.3 million, and 3.8 million, in 2030, and 1.6, 5.2, and 8.6 million in 2040, as detailed in Table 2.

3.2. RIN price

eRIN revenue per unit of bioelectricity generated depends on two key factors: eRIN equivalency (kWh/eRIN), and RIN price ($/eRIN). We used a price of $2.50/RIN, which is $1/RIN higher than the value used by Xie et al. (2019), and is on the high end of historical averages, but is aligned with recent RIN values and is well below the maximum price of $3.50 (U.S. Environmental Protection Agency, n.d.-d). In our central EV fleet estimate, 6.3 billion eRINs are added to the market in 2030. This is well in excess of 590 million cellulosic RINs generated in 2020, which could apply a downward pressure to RIN price; however, the RFS statutory requirement for cellulosic RINs in 2020 was 10.5 billion gallons, a number that was revised downward, as it has been every year, to better align with production capacity (U.S. Environmental Protection Agency, 2021c). We therefore assume that this new supply of cellulosic RINs would be met with an increase in RVOs, better reflecting the statutory

Table 2
Model predictions for total fleet TWh consumed and new EVs sold in the year 2030. TWh calculation assumes inclusion of all model years on the road and that PHEVs are phased out by 2030. Both values assume the AEO Reference Scenario for total on-road fleet size.

Year	S177 Adopted Nationwide		30% by 2030		50% by 2030	
	TWh	EVs Sold	TWh	EVs Sold	TWh	EVs Sold
2025	13	612,000	18.9	1,220,000	25.9	1,930,000
2030	26.8	993,000	51.8	2,300,000	81.2	3,830,000
2035	45.2	1,280,000	107	3,660,000	175	6,110,000
2040	–	1,610,000	–	5,170,000	–	8,620,000

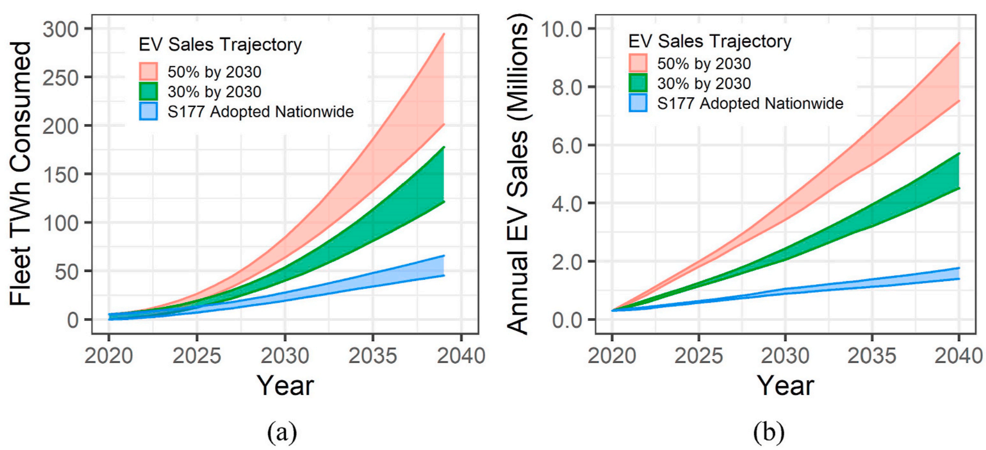

Fig. 2. (a) Range of forecasts of annual EV sales. (b) Range of forecasts of annual TWh consumed by the EV fleet.

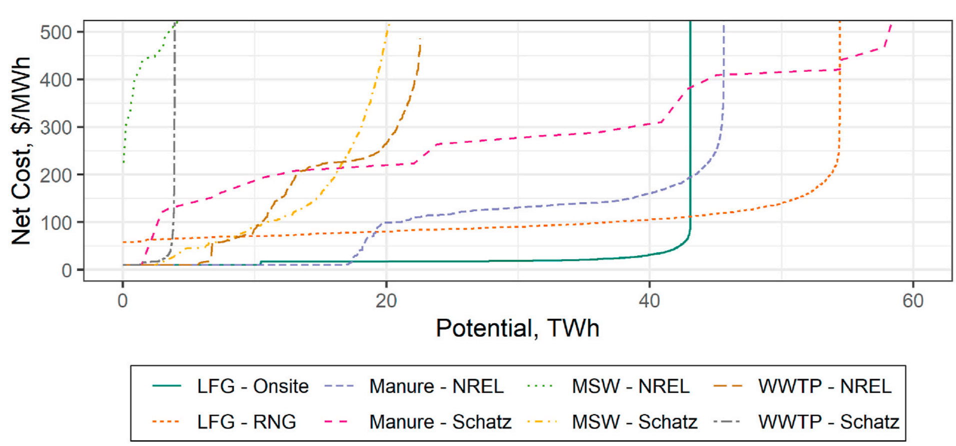

Fig. 3. Supply-cost curve for RFS-qualifying electricity. "NREL" indicates waste quantity and price were sourced from Badgett et al. (2019). "Schatz" indicates our estimates of waste quantity and price were used. All estimates use our waste-to-electricity model.

intent while maintaining current high D3 RIN prices. By 2040, higher eRIN production would necessitate increasing D3 RVOs.

3.3. Biolectricity supply

Following the RFS rule, we considered the following feedstocks: landfill gas (LFG), wastewater treatment plant (WWTP) sludge, manure, and separated municipal solid waste (MSW). We assumed that biogas is combusted onsite in combined heat and power generators, which also supply the process heat necessary for the anaerobic digestion (AD) process.

We did not consider other agricultural resides such as corn stover which cannot be processed via anaerobic digestion with current technology. Fats, oils, and greases (FOGs) are another resource with significant economic potential (Badgett et al., 2019; Milbrandt et al., 2018) that could increase bioelectricity supply via co-digestion. However, this technology is not yet mature (Salama et al., 2019), and since FOGs already have an RFS pathway via biodiesel (U.S. Environmental Protection Agency, 2021a), we omitted them from this analysis.

The only studies of eRINs identified by the authors, (Podkaminer et al., 2017; Xie et al., 2019), rely on a relatively low estimate of the available quantity of qualifying electricity, 41.2 TWh/year (from 0.37 EJ/year of primary energy, see U.S. Department of Agriculture (2014)), to determine the possibility for "nearly $12 billion in eRIN credits annually" (Xie et al., 2019, p. 623), or $230 to $870 per vehicle depending on economic assumptions and vehicle type. A more recent study of a subset of waste-to-energy resources in the U.S. estimates the annual primary energy potential at 1 EJ (Milbrandt et al., 2018). Feedstock considerations and energy estimates in these two studies are juxtaposed in Table 3. Milbrandt et al. consider more feedstocks, and where the two studies overlap, estimate potentials 2.5 to 4 times higher than the U.S. Department of Agriculture's (USDA's) study. This is because the USDA study only includes resources which are presently economically viable, whereas Milbrandt et al. consider a wider range of facility sizes. Because the application of eRINs creates a significant shift in project economics, our study uses the results of Milbrandt et al.'s study alongside our own estimates of resource potential.

We assume that all resources other than LFG are converted to biogas via an AD process with onsite electricity generation. For each other resource, we generated two estimates to assess model sensitivity, one using estimates of waste availability and cost developed by the National Renewable Energy Laboratory (NREL) (Badgett et al. (2019), which uses potential estimates from Milbrandt et al. (2018)), and the other utilizing our own bottom-up estimates described below.

For all of these facilities, the net cost of eRIN generation is the sum of biogas production and electricity production costs (including operating costs and capital costs as applicable), minus the average wholesale market price of bioelectricity, $61.24/MWh (U.S. Energy Information Administration, 2020a). We apply a $10/MWh net cost floor to all bioelectricity pathway estimates to cover transaction costs, assuming that producers with a negative net cost of production will retain this portion of profit. We account for existing supply, which includes 1.41 TWh/year of manure-based bioelectricity (U.S. Environmental Protection Agency, 2021b), 1.3 TWh/year from WWTPs, 10.4 TWh/year from LFG, and no source-separated MSW-derived electricity[2] (U.S. Energy Information Administration, 2020a), by setting the price of these credits to $10/MWh to account for any overhead associated with transitioning low-cost supply streams to support the RFS. Further details on each pathway, and on the biogas production models are provided in the Appendix.

Table 3
Comparison of primary energy estimates in recent studies.

Resource	Primary energy potential, petajoules/year	
	U.S. Department of Agriculture (2014)	Milbrandt et al. (2018).
Livestock manure	150	570
Landfill gas	150	–
Wastewater facilities	71	188
Food waste	–	81
Fats, oils, & greases	–	212

To investigate the impact of modeling assumptions on program revenue and subsidy size, we modeled supply curves for qualifying bioelectricity for a range of scenarios across the parameters described in Table 4. Further details on these scenarios are provided in the Appendix.

4. Results and discussion

This section begins with a summary of supply curves from qualifying biogas sources (Section 4.1). After introducing these results, we evaluate the total program size and the program net revenue (after qualifying electricity costs) (Section 4.2). Penultimately, we describe our midpoint estimates of vehicle subsidy enabled (Section 4.3) before finally exploring sensitivity to variables (Section 4.4).

4.1. Supply curves for qualifying bioelectricity pathways

Our estimates of electricity generation potential by source are summarized in Table 5 and Table 6 based on our bottom-up supply curves and Badgett et al.'s (2019) bottom-up supply curves, respectively. Existing supply is currently dominated by LFG – with small contributions from WWTPs and manure—and is small compared to the projected fleet demand depicted in Table 2. On the other hand, the economic potential (i.e., under $500/MWh) from sources such as LFG and manure are quite large—individually on the scale of the 2035 demand for the two slower EV sales trajectories.

Our bottom-up estimates (labeled 'Schatz' in Fig. 3) are notably different from and Badgett et al.'s (2019) (labeled 'NREL') across the board. Our estimate for MSW potential is similar, though ours is 50% larger because we include yard trimmings. On the other hand, their estimate of price is far higher, largely because they include the significant cost of source separation. NREL's estimate of electricity potential from WWTPs is much larger because our estimate is derived from a dataset of plants with AD already in place, whereas they include all publicly owned treatment plants with available data. Badgett et al. (2019) estimate that a significant quantity of cheaper waste is available because of negative-cost assumptions compared to our zero-cost assumption; however, this is mitigated by the lower limit of $10/MWh which we applied to all estimates. Finally, while our estimate of manure-based electricity potential is about three times the size of

Table 4
Bioelectricity generation variables considered in our modeling. All permutations were explored in our sensitivity analysis.

Variable	Scenarios
Biogas Upgrading to RNG	(a) None; (b) 100% of LFG supply
WWTP/Manure/MSW supply	(a) Our estimate; (b) NREL's estimate (Badgett et al., 2019) (8 permutations)
Bioelectricity Buildout	(a) 100%; (b) 75% of cheapest, 50% of most expensive (linear)
Bioelectricity Cost per MWh	(a) As calculated & $\geq$$10; (b) +25% & $\geq$$20; (c) +50% & $\geq$$40

[2] The EPA database indicates that all biogenic electricity from MSW is provided at a fixed ratio to non-biogenic electricity from MSW (U.S. Energy Information Administration, 2020a), indicating that none is source separated.

Table 5
Existing and potential electricity supply based on our bottom-up models.

Feedstock	Process	Existing Supply (TWh)	Additional Potential Under $500/MWh (TWh)	Total Additional Potential (TWh)
LFG[a]	Biogas	10.4	32.6	32.6
LFG[a]	via RNG	–	54.4	54.4
Manure	Biogas	1.4	56.4	102
MSW	Biogas	–	20.1	23.0
WWTP	Biogas	1.3	2.6	2.6

[a] these pathways are mutually exclusive (i.e., they use the same feedstock).

Table 6
Existing and potential electricity supply drawn from Badgett et al.'s model of biomass resources (Badgett et al., 2019).

Feedstock	Process	Existing Supply (TWh)	Additional Potential Under $500/MWh (TWh)	Total Additional Potential (TWh)
Manure	Biogas	N/A	45.6	46
MSW	Biogas	N/A	2.6	15.4
WWTP	Biogas	N/A	22.6	22.6

The supply curves in Fig. 3 compare results across feedstocks, processes (for LFG) and data sources (for other resources). LFG and manure provide the greatest potentials, particularly at low cost, regardless of data source and processing method.

Badgett et al.'s, this largely results from our inclusion of smaller farms, which we implicitly exclude by economic constraints. As with WWTPs, Badgett et al. predict lower costs for manure-based electricity due to assumption of some negative-cost manure compared to our assumption of zero-cost.

4.2. Total program size and net revenue

After generating the supply curves, we calculated the total program size[3] and net program revenue.[4] These results are shown in Table 7 for selected years. Program size and net revenue grow through 2040 in all cases except the '50% by 2030' vehicle rollout case, in which qualifying bioelectricity supply would be fully utilized by 2035. Program size and net revenue in the '30% by 2030' sales scenario are 1.3–2.3 times their respective values in the 'S177 adopted nationwide' scenario, while program size and net revenue are 1.7–3.1 times as large in the '50% by 2030' scenario compared to the 'S177 adopted nationwide' scenario. At $2.50 per RIN, we estimate creation of between 2.1 and 3.7 billion eRINs in 2025, 4.5 to 12.8 billion RINs in 2030 (6.3 billion in the median case), and between 11.8 and 24 billion eRINs in 2040.

Table 7
Average program size and net revenue (both in billions of USD) after electricity procurement cost across supply scenarios with 100% supply buildout, as-calculated cost, reference total fleet size, phase out of PHEVs, and all model years eligible for eRINs.

Year	S177 Adopted Nationwide		30% by 2030		50% by 2030	
	Program Size	Net Revenue	Program Size	Net Revenue	Program Size	Net Revenue
2025	$5.25	$4.1	$7.05	$5.49	$9.15	$7.1
2030	$11.2	$8.65	$20.7	$15.8	$31.9	$23.6
2035	$19.7	$15.0	$44.9	$31.4	$60.1	$37.4
2040	$29.4	$21.9	$60.1	$37.4	$60.1	$37.4

[3] eRIN revenue times the lesser of fleet TWh demanded and economic supply size. The fleet demand used is the total TWh from the previous year, e.g., the revenue available to subsidize new vehicle sales in 2030 is derived from electric vehicle miles traveled in 2029.

[4] By subtracting electricity cost plus 20% of the remainder, assumed to flow to administrative costs and profit along the supply chain.

Fig. 4 depicts these data in all years along with their possible ranges across other program variables. Under all sets of modeling assumptions, the program size and net revenue (after the cost of bioelectricity) start small but grow significantly to 2035. Values continue to grow in many cases, including our baseline case (the black lines), all the way to 2040. In 2040, program size could be 22 to 74 billion USD, while net program revenue could be between 13 and 45 billion USD.

4.3. Electric vehicle subsidy enabled

If net program revenue were used entirely to subsidize new EV sales, the result would be that depicted in Fig. 5. EV sales trajectory has a significant impact on the subsidy, particularly in later years. The more vehicles sold, the smaller the potential subsidy for each new vehicle because the supply of qualifying bioelectricity gets increasingly expensive and may be eventually exhausted (as indicated by the apex in the right two subfigures). Generating eRINS from all model years (MYs) increases the early-program subsidy significantly, but the effect tapers off as the fraction of total eVMT driven by post-2021 MY cars increases.

Table 8 breaks down the average EV subsidy at intervals over the program life, following the solid line in Fig. 5, with 100% supply buildout, as-calculated cost, reference total fleet size, phase out of PHEVs, and all MYs generating eRINs, with the range across variables shown parenthetically. The faster the adoption rate the lower the subsidy and the sooner the subsidy begins to taper off.

Although varying assumptions and timeframes make a significant difference to the size of the program, we find the potential per-vehicle subsidy to be quite substantial across the board. We next show the results of a sensitivity analysis which explores the source of variability in potential EV subsidy.

4.4. Sensitivity analysis

Table 9 shows the relative share of total variation attributable to each model variable. EV sales trajectory dominates for each year after 2025, accounting for 39–58% of variation in potential subsidies across the study period. This indicates that the growth rate of EV sales is the key assumption in our analysis. Xie et al. (2019) find that an EV credit of $2500 could increase year 2030 sales by about 1.6 million vehicles. Our model shows the possibility of larger credits (due to our calculated larger supply, as discussed), and EV sales trajectory will certainly depend on a wide variety of unpredictable factors, such as other incentives, perceived vehicle quality and desirability (including social factors). Therefore, we can only say that this program could likely increase EV sales significantly—quite possibly from a baseline of 15% to above 50%.

Among the remaining variables, model year eligibility for eRINs is the most important, especially early in the program, but this can be controlled by program structure. MY eligibility is followed in significance by bioelectricity supply (including data source for biomass supply and cost, and whether LFG is upgraded to RNG). Remaining variables are each meaningful, accounting for at least 9% of variation in at least one period.

The importance of EV deployment trajectory is partly an artifact of our modeling and is not likely to be as large in practice. We modeled EV sales exogenously rather than making it a function of rebate size, but in reality, the framework would be self-correcting in response to its market necessity. Since rebate inversely correlates to sales growth rate, if EV sales are lower than anticipated the subsidy would rise, increasing the market appeal of those EVs. Conversely, if EV sales rise rapidly in the coming years the subsidy amount would fall in response, stabilizing the growth rate. This finding confirms and quantifies an appealing characteristic of this policy design.

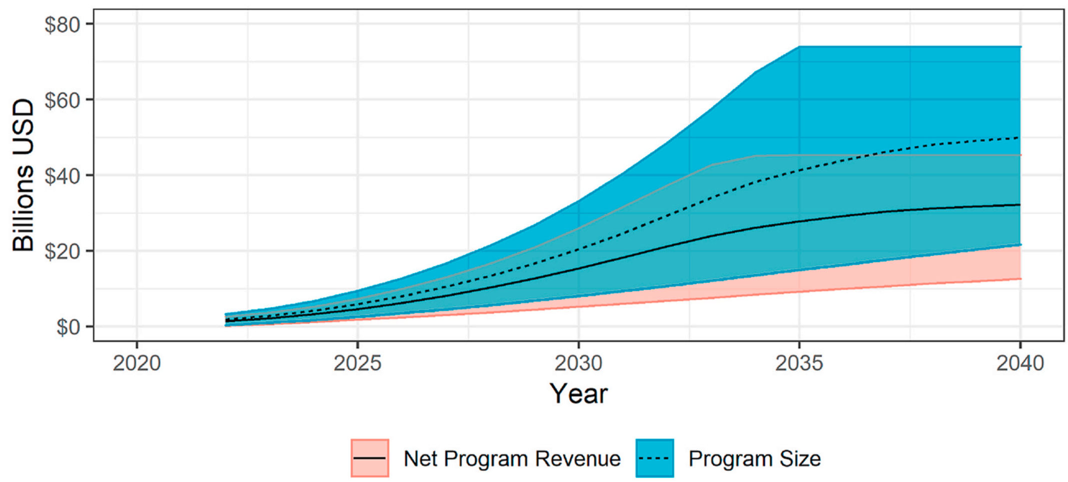

Fig. 4. Projected program size and net program revenue. The lines indicate the average value obtained with 100% supply buildout, as-calculated cost, reference total fleet size, and phase out of PHEVs.

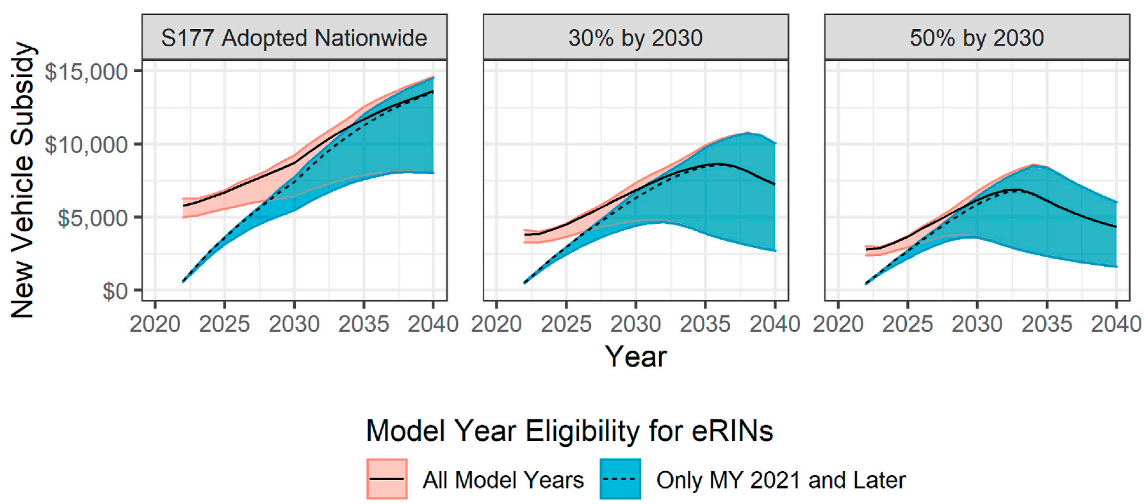

Fig. 5. Projected EV subsidy. The line indicates the average value obtained with reference supply buildout and cost, reference total fleet size, and phase out of PHEVs.

5. Additional considerations

Our analysis indicates that there is significant potential for EPA to leverage the existing RFS policy to achieve a suite of objectives, including: broad-scale uptake of electric vehicles; promoting a circular economy and facilitating the large-scale productive use of waste streams that are otherwise an environmental and economic liability; preventing emissions from what are otherwise major sources of uncontrolled methane by diverting these wastes to power production[5]; and addressing a long-standing problem in the RFS program[6] by enabling cellulosic biofuel production under the RFS to increase significantly.

Beyond the uniform light-duty EV purchase rebates evaluated in this work and consistent with EPA's stated goals for the program – including reducing air pollution and GHG emissions, generating renewable electricity, deploying charging infrastructure, and growing EV ownership (U.S. Environmental Protection Agency, 2016)—the EPA might consider devoting some eRIN revenues to other investments that would promote broader penetration of electricity into the transportation sector, and a more equitable distribution of the benefits of this transition. Such investments could include:

- Installation of public charging infrastructure, especially in underserved communities where market drivers may not deliver this service (Hsu and Fingerman, 2021).
- Electrification of municipal fleets, buses, garbage collection, and other vehicle classes where electrification is slow to emerge but offers climate and health benefits.
- A progressive and/or partially means-tested EV subsidy. This is particularly important because the RFS taxes gasoline to support deployment of EVs, a structure which imposes a proportionally higher burden on lower-income people (Wier et al., 2005).

[5] Reduction in methane emissions plays a critical role in near-term climate change mitigation. In California, for example, livestock, landfills, and wastewater accounted for 80% of total methane emissions in 2018 (California Air Resources Board, n.d.-a).

[6] To date, this fuel class has consistently fallen more than 90% short of the targets laid out in the statute owing to a lack of technology development and investment since the policy was introduced (Bracmort, 2020).

Table 8
Average vehicle subsidy made possible across all supply scenarios with 100% supply buildout, as-calculated cost, reference total fleet size, phase out of PHEVs, and all model years eligible for eRINs. The range across the remaining variables is shown parenthetically.

Year	S177 Adopted Nationwide	30% by 2030	50% by 2030
2025	$6700 ($3100-$6900)	$4500 ($2500-$4600)	$3700 ($2200-$3700)
2030	$8700 ($5500-$9200)	$6900 ($4400-$7400)	$6200 ($3600-$6800)
2035	$12,000 ($7600-$13,000)	$8600 ($3900-$9900)	$6100 ($2300-$8400)
2040	$14,000 ($8000-$15,000)	$7200 ($2700-$10,000)	$4300 ($1600-$6000)

Table 9
Share of total variation in subsidy attributable to each input assumption. Bioelectricity Supply includes the aggregate effects of biogas upgrading to RNG and WWTP/Manure/MSW supply models.

Parameter	Share of Total Variation			
	2025	2030	2035	2040
Bioelectricity Supply	6%	18%	18%	15%
Bioelectricity Buildout	0%	3%	10%	10%
Bioelectricity Cost	6%	9%	8%	6%
EV Sales Trajectory	43%	39%	50%	58%
Model Year Eligibility for eRIN	41%	12%	1%	0%
PHEV Fraction	3%	10%	6%	4%
Total Fleet Size	1%	9%	8%	7%

- Incentivizing EVs in medium and heavy-duty vehicle fleets to move these markets towards maturity. People of color are disproportionately exposed to PM2.5 from heavy-duty diesel vehicles (Tessum et al., 2021) (as with light-duty gas vehicles), so transitioning these fleets to electric propulsion can further environmental justice goals.

Some of the above investments may be seen as stretching EPA's statutory authority; however, they are entirely aligned with the stated goals of the RFS including reducing greenhouse gas emissions and increasing the use of renewable fuels (Rusco, 2016; U.S. Environmental Protection Agency, n.d.-a). Moreover, EPA has recognized the ability of the RFS to further goals of the Clean Air Act by leading to "greater availability of public charging infrastructure, increased ownership of EVs" (U.S. Environmental Protection Agency, 2016). As such, increasing access to electric vehicles among population sectors who would not otherwise be able to afford them and industry sectors among which EVs are struggling to gain a foothold, and increasing access to EV chargers fall squarely within the goals of the RFS and other EPA endeavors.

Finally, the amount of money that will be harnessed towards these goals will depend upon the eRIN equivalency and stability of the RIN price as discussed in Sections 2.1 and 3.2, respectively. Distribution of funds among the EPA's stated goals will depend upon program priorities and the central accruer—without which most program revenue will flow to bioelectricity supply.

5.1. Environmental justice concerns

Waste-to-energy (WtE) processes, confined animal feeding operations (CAFOs), and other facilities which handle waste have a history of pollution and unequal impacts from siting (Bullard et al., 2008; Faber Daniel R & Krieg Eric J, 2002; Katami et al., 2004; van Veizen et al., 2002; Wendee, 2013). While the technology to clean up WtE facilities has significantly reduced pollutant emissions, (Liu et al., 2012; Mukherjee et al., 2016; van Veizen et al., 2002), socioeconomic and racial disparities in siting of undesirable facilities and exposure to emissions in general are still a major cause for concern (Bullard et al., 2008; Tessum et al., 2021). Future developments must recognize this reality and the associated community perceptions of injustice and risk.

The RFS (and this study) focuses on anaerobic digestion of separated municipal solid waste streams and other resources, which alleviates (but does not eliminate) some of the concerns that have been associated with incineration-based WtE systems. These developments could potentially lead to improvements in impacted communities by reducing odors and emissions from landfills and CAFOS (Wilkie, 2005). If done properly, "WtE can prevent potential harm of 'waste' by transferring it in[to] a valuable renewable source of energy… contributing to the environment… and human health." (Malinauskaite and Jouhara, 2019, p. 643). Expansion of WtE could mitigate *or* increase exposure levels for racially, economically, or otherwise marginalized groups. Policy design and implementation must, therefore, pay close attention to environmental health, justice, and equity.

5.2. Operational challenges

While the scaling up of eRIN generation and revenue suggested by our model presents many benefits, there are also some challenges to program design and implementation that warrant attention:

1. *The biogas system buildout necessary to support eRIN generation to 2030 and beyond is very ambitious.* However, we find that with a reduced bioelectricity supply, vehicle subsidy is reduced by only 2.8% in 2030 and 16% in 2035. As discussed above, particular care would be necessary to ensure that these developments serve to ameliorate rather than exacerbate existing environmental health burdens and injustices.
2. *EVs may travel less distance than other vehicles—especially in the short term.* This analysis assumes that EVs are a direct replacement for conventional vehicles and that therefore the vehicles travel, on average, the same distance as conventional vehicles do today. This implies that the shift to EVs does not occur disproportionately at one end of the vehicle use spectrum. However, recent studies show that EVs may in some cases be traveling as little as half of the national average (Burlig et al., n.d.). Burlig et al.'s research is preliminary, and moreover is likely to reflect a trend in early model EVs – which were more range-limited – that may not extend to EVs sold today and into the future. However, if this trend extends broadly, it could reduce the number of eRINs generated per vehicle, especially in the short term.
3. *eRIN value may not remain at the level modeled here for as long as intended.* Our modeling assumes that D3 (cellulosic) RINs will remain at their recent price of $2.50. The new supply of 2.1–24 billion eRINs per year between 2025 and 2040 would take some pressure away from the cellulosic fuel mandate in the RFS, leading D3 RIN and/or cellulosic waiver credit prices to fall. Furthermore, our levelized cost modeling for biogas systems assumes a 15-year period. To stimulate the necessary buildout, EPA may need to act to ensure eRIN revenue remains sufficient at least to offset the levelized cost of qualifying bioelectricity generation.

4. *Deployment of electric vehicles at the scale modeled here will raise other concerns that must be managed.* Public EV charging infrastructure will need to be constructed to support the rapidly growing EV fleet. We estimate that this will cost $1600 to $1800 per vehicle, which is less than half of the available eRIN revenue in any study case and less than one third of that of our baseline[7] 2030 case.[8] As mentioned previously, some of this funding could come from eRIN program revenues if market conditions allow, while some would likely come from other public programs such as The Bipartisan Infrastructure Deal (White House Briefing Room, 2021). In addition, it will be particularly important to design rebate allocation and infrastructure investment to facilitate equity in access to the benefits of vehicle electrification (Hsu and Fingerman, 2021). Finally, the substantial new electric load represented by this growing vehicle population could exacerbate existing grid strain surrounding integration of intermittent renewables and uncontrolled loads. Vehicle-grid-integration, R&D, and utility planning are critical for supporting mass EV adoption. These concerns are not specific to the eRINs structure within RFS (in fact, the stimulated investment in bioelectricity will help serve the load from electric vehicles) but warrant attention here as this policy could spur rapid scale-up of the EV fleet in the U.S.

6. Conclusions and policy implications

With the right policy changes, the Renewable Fuel Standard (RFS) can enable significant investment in waste-to-energy systems, EVs, and other desirable infrastructure, on the scale of tens of billions of dollars per year. These changes are: Increasing the number of credits accruing to electric vehicle miles traveled to account for the higher drivetrain efficiency and accruing credits to a new non-profit entity vested with the responsibility of distributing revenue to EV rebates alongside other RFS climate and transportation goals.

We predict that, in 2030, $8.65 to $23.6 billion could flow to EV buyers, supporting subsidies between $6200 and $8700 per vehicle in our baseline cases, and subsidies between $3600 and $9200 across all variation in our model. While the range of these projections is significant, revenues and vehicle subsidies remain meaningful across scenarios. Additionally, between $2.55 and $8.3 billion could be harnessed to support waste-diversion in 2030.

In the early years of the program, existing qualifying bioelectricity – 13.1 TWh/year, mostly from landfill gas – will be sufficient to support electricity demand from class 1 light-duty EVs through 2025, 2023, and 2022 in our three increasing demand scenarios, enabling vehicle subsidies through 2026, 2024, and 2023, respectively. Additional buildout will be necessary to support sizeable subsidies towards 2030 and beyond.

However, by the middle of the decade, we anticipate that one or both of the following will have occurred, changing the landscape for this policy: The EV market may have matured to the point of cost-competitiveness with ICE vehicles, at which point any barriers to further penetration of EVs will not be addressed with a purchase rebate; successor legislation to the RFS, such as a national Low Carbon Fuel Standard or other technology-neutral or EV-specific mechanism will act to promote EV deployment without explicit reliance on bioelectricity. Therefore, we find that the current pathways can lead to an effective program without the process and stakeholder hurdles of major changes to the approved pathways.

The bioelectricity harnessed under this policy could decarbonize the grid by replacing higher carbon sources of electricity while simultaneously reducing methane emissions by diverting waste to anaerobic digestion. Some program revenue could support environmental health, justice, and equity, including installation of charging infrastructure in underserved communities or electrification of heavy-duty diesel vehicles. Yet many challenges still exist, including the necessary speed of bioelectricity deployment, EV miles traveled and their resulting electrical grid stress, equitable access to EVs and EV charging, and long-term stabilization of the RFS credit market.

[7] With 100% supply buildout, as-calculated cost, reference total fleet size, phase out of PHEVs, and all model years eligible for eRINs.

[8] At a rate of 1,056,000 to 1,198,000 Level 2 chargers and 30,000 to 31,000 DC Fast Chargers per 8-million vehicles (Alexander et al., 2021), at a cost of $9400 per Level 2 charger and $105,000 per DC Fast Charger (California Energy Commission, 2021).

Data availability

The underlying data used in this article are generally available online at the URLs provided in the References; however, the raw data in Badgett et al. (2019) are not publicly available and were made available to the authors by special request.

Analysis software is available at: http://doi.org/10.5281/zenodo.5062304 (Younes et al., 2021a).

Fully processed data are available at: http://doi.org/10.5281/zenodo.5062316 (Younes et al., 2021b).

CRediT authorship contribution statement

Amin Younes: Conceptualization, Methodology, Software, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Kevin R. Fingerman:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Cassidy Barrientos:** Conceptualization, Methodology, Software, Writing – original draft. **Jerome Carman:** Conceptualization, Methodology, Software, Validation, Data curation, Writing – original draft, Visualization, Project administration. **Karly Johnson:** Data curation, Writing – original draft. **Eli S. Wallach:** Conceptualization, Methodology, Software, Validation, Data curation, Writing – original draft, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The William and Flora Hewlett Foundation for funding this study.

Juliette Bohn, Kristen Brainerd, Steven Hackett, Peter Hansel, Arne Jacobson, Tatiana Kornienko, Jeremy Martin, and Neelesh Nerurkar for valuable insights, guidance, and feedback.

The National Renewable Energy Laboratory for providing supply and cost data for waste products used in this analysis.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2022.112916.

References

Alexander, M., Crisostomo, N., Krell, W., Lu, J., Ramesh, R., 2021. Assembly Bill 2127 Electric Vehicle Charging Infrastructure Assessment Analyzing Charging Needs to Support ZEVs in 2030 – Commission Report. (CEC-600-2021-001-CMR.). California Energy Commission. https://efiling.energy.ca.gov/getdocument.aspx?tn=238853.

California Air Resources Board. (n.d.-a). Current California GHG Emission Inventory Data | California Air Resources Board. Retrieved February 16, 2021, from https://ww2.arb.ca.gov/ghg-inventory-data.

California Air Resources Board. (n.d.-b). Weekly LCFS Credit Trading Activity Reports. Retrieved May 25, 2021, from https://www.arb.ca.gov/fuels/lcfs/credit/lrtweeklycreditreports.htm.

Badgett, A., Newes, E., Milbrandt, A., 2019. Economic analysis of wet waste-to-energy resources in the United States. Energy 176, 224–234. https://doi.org/10.1016/j.energy.2019.03.188.
Blair, R., Durrance, C., 2014. Group purchasing organizations, monopsony, and antitrust policy. Manag. Decis. Econ. 35 https://doi.org/10.1002/mde.2633.
Bracmort, K., 2020. The Renewable Fuel Standard (RFS): an Overview (No. R43325; P. 17). Congressional Research Service. https://fas.org/sgp/crs/misc/R43325.pdf.
Bullard, R.D., Mohai, P., Saha, R., Wright, B., 2008. Toxic wastes and race at twenty: why race still matters after all of these years. Environ. Law 38 (2), 371–411. http://www.jstor.org/stable/43267204.
Burlig, F., Bushnell, J., Rapson, D., & Wolfram, C. (n.d.). Low Energy: Estimating Electric Vehicle Electricity Use. vol. 16.
California Air Resources Board, 2019, August 19. States that Have Adopted California's Vehicle Standards under Section 177 of the Federal Clean Air Act. https://ww2.arb.ca.gov/sites/default/files/2019-03/177-states.pdf.
California Air Resources Board, 2021a. Current Pathways. https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/fuelpathways/current-pathways_all.xlsx.
California Air Resources Board, 2021b. Current Pathways. https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/fuelpathways/current-pathways_all.xlsx.
California Energy Commission, 2021, October 31. California Electric Vehicle Infrastructure Project (CALeVIP) Cost Data. https://web.archive.org/web/20211031172540/https://www.energy.ca.gov/programs-and-topics/programs/clean-transportation-program/california-electric-vehicle.
DSIRE USA, 2021, January 27. Renewable Electricity Production Tax Credit (PTC). https://web.archive.org/web/20201101050624/https://programs.dsireusa.org/system/program/detail/734.
Faber Daniel, R., Krieg Eric, J., 2002. Unequal exposure to ecological hazards: environmental injustices in the Commonwealth of Massachusetts. Environ. Health Perspect. 110 (Suppl. 2), 277–288. https://doi.org/10.1289/ehp.02110s2277.
Franchetti, M., 2013. Economic and environmental analysis of four different configurations of anaerobic digestion for food waste to energy conversion using LCA for: a food service provider case study. J. Environ. Manag. 123, 42–48. https://doi.org/10.1016/j.jenvman.2013.03.003.
Hsu, C.-W., Fingerman, K., 2021. Public electric vehicle charger access disparities across race and income in California. Transport Pol. 100, 59–67. https://doi.org/10.1016/j.tranpol.2020.10.003.
Hussey, P., Anderson, G.F., 2003. A comparison of single- and multi-payer health insurance systems and options for reform. Health Pol. 66 (3), 215–228. https://doi.org/10.1016/s0168-8510(03)00050-2.
Katami, T., Yasuhara, A., Shibamoto, T., 2004. Formation of dioxins from incineration of foods found in domestic garbage. Environ. Sci. Technol. 38 (4), 1062–1065. https://doi.org/10.1021/es030606y.
Liu, H., Kong, S., Liu, Y., Zeng, H., 2012. Pollution control technologies of dioxins in municipal solid waste incinerator. Procedia Environ. Sci. 16, 661–668. https://doi.org/10.1016/j.proenv.2012.10.091.
Lombardi, L., Carnevale, E., Corti, A., 2006. Greenhouse effect reduction and energy recovery from waste landfill. Energy 31 (15), 3208–3219. https://doi.org/10.1016/j.energy.2006.03.034.
Low Carbon Fuel Standard Regulation, 2020. https://govt.westlaw.com/calregs/Browse/Home/California/CaliforniaCodeofRegulations?guid=I06FA57F08B1811DF8121F57FB716B6E8&originationContext=documenttoc&transitionType=Default&contextData=(sc.Default.
Malinauskaite, J., Jouhara, H., 2019. The trilemma of waste-to-energy: a multi-purpose solution. Energy Pol. 129, 636–645. https://doi.org/10.1016/j.enpol.2019.02.029.
Milbrandt, A., Seiple, T., Heimiller, D., Skaggs, R., Coleman, A., 2018. Wet waste-to-energy resources in the United States. Resour. Conserv. Recycl. 137 (C) https://doi.org/10.1016/j.resconrec.2018.05.023. Article NREL/JA-6A20-71769.
Mukherjee, A., Debnath, B., Ghosh, S.K., 2016. A review on technologies of removal of dioxins and furans from incinerator flue gas. Procedia Environmental Sciences 35, 528–540. https://doi.org/10.1016/j.proenv.2016.07.037.
Podkaminer, K., Xie, F., Lin, Z., 2017. *Analyzing the Impacts of a Biogas-To-Electricity Purchase Incentive on Electric Vehicle Deployment with the MA^{3}T Vehicle Choice Model*. https://doi.org/10.2172/1362153. ORNL/TM–2017/14, 1362153; p. ORNL/TM–2017/14, 1362153).
Rusco, F., 2016. Report to the Chairman, Subcommittee on Regulatory Affairs and Federal Management, Committee on Homeland Security and Governmental Affairs. U.S. Government Accountability Office. *U.S. Senate* (GAO-17-94). https://www.gao.gov/assets/690/681252.pdf.
Salama, E.-S., Saha, S., Kurade, M.B., Dev, S., Chang, S.W., Jeon, B.-H., 2019. Recent trends in anaerobic co-digestion: fat, oil, and grease (FOG) for enhanced biomethanation. Prog. Energy Combust. Sci. 70, 22–42. https://doi.org/10.1016/j.pecs.2018.08.002.
Tessum, C.W., Paolella, D.A., Chambliss, S.E., Apte, J.S., Hill, J.D., Marshall, J.D., 2021. PM2.5 polluters disproportionately and systemically affect people of color in the United States. Sci. Adv. 7 (18), eabf4491 https://doi.org/10.1126/sciadv.abf4491.
The International Council on Clean Transportation, 2015. Memorandum on the Equivalence Value of Electricity in the Renewable Fuel Standard. https://www.reginfo.gov/public/do/eoDownloadDocument?pubId=&eodoc=true&documentID=1719.
Tonini, D., Hamelin, L., Alvarado-Morales, M., Astrup, T.F., 2016. GHG emission factors for bioelectricity, biomethane, and bioethanol quantified for 24 biomass substrates with consequential life-cycle assessment. Bioresour. Technol. 208, 123–133. https://doi.org/10.1016/j.biortech.2016.02.052.
U.S. Environmental Protection Agency. (n.d.-c). Renewable Fuel Standard Program [Overviews and Factsheets]. Retrieved January 22, 2022, from https://www.epa.gov/renewable-fuel-standard-program.
U.S. Environmental Protection Agency. (n.d.-d). RIN Trades and Price Information [Other Policies and Guidance]. U.S. Environmental Protection Agency. Retrieved July 1, 2021, from https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rin-trades-and-price-information.
U.S. Environmental Protection Agency. (n.d.-e). Sources of Greenhouse Gas Emissions [Overviews and Factsheets]. US EPA. Retrieved February 23, 2021, from https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.
U.S. Department of Agriculture, 2014. Biogas Opportunities Roadmap. https://www.energy.gov/sites/default/files/2014/08/f18/Biogas%20Opportunities%20Roadmap%208-1-14_0.pdf.
U.S. Energy Information Administration, 2020a. Form EIA-923 Detailed Data with Previous Form Data (EIA-906/920). https://www.eia.gov/electricity/data/eia923/.
U.S. Energy Information Administration, 2020b. Annual Energy Outlook 2020. https://web.archive.org/web/20201208201625/https://www.eia.gov/outlooks/aeo/.
U.S. Environmental Protection Agency, 2014. Federal Register, vol. 79, 138. https://www.govinfo.gov/content/pkg/FR-2014-07-18/pdf/2014-16413.pdf.
U.S. Environmental Protection Agency, 2016. Federal Register, vol. 81, 221. https://www.govinfo.gov/content/pkg/FR-2016-11-16/pdf/2016-25292.pdf.
U.S. Environmental Protection Agency, 2021a. *Approved Pathways for Renewable Fuel* [Other Policies and Guidance]. U.S. Environmental Protection Agency. https://web.archive.org/web/20210312214239/https://www.epa.gov/renewable-fuel-standard-program/approved-pathways-renewable-fuel.
U.S. Environmental Protection Agency, 2021b. *AgSTAR Data and Trends* [Data and Tools]. US EPA. http://web.archive.org/web/20210405210847/https://www.epa.gov/agstar/agstar-data-and-trends.
U.S. Environmental Protection Agency, 2021c. Final Renewable Fuel Standards for 2020, and the Biomass-Based Diesel Volume for 2021. US EPA. https://web.archive.org/web/20210704115058/https://www.epa.gov/renewable-fuel-standard-program/final-renewable-fuel-standards-2020-and-biomass-based-diesel-volume.
van Veizen, D., Langenkamp, H., Herb, G., 2002. Review: mercury in waste incineration. Waste Manag. Res. 20, 556–568. https://doi.org/10.1177/0734242X0202000610.
Wendee, N., 2013. CAFOs and environmental justice: the case of North Carolina. Environ. Health Perspect. 121 (6), a182–a189. https://doi.org/10.1289/ehp.121-a182.
White House Briefing Room, 2021, December 4. Fact Sheet: the Bipartisan Infrastructure Deal. https://web.archive.org/web/20211204094020/https://www.whitehouse.gov/briefing-room/statements-releases/2021/11/06/fact-sheet-the-bipartisan-infrastructure-deal/.
Wier, M., Birr-Pedersen, K., Jacobsen, H.K., Klok, J., 2005. Are CO2 taxes regressive? Evidence from the Danish experience. Ecol. Econ. 52 (2), 239–251. https://doi.org/10.1016/j.ecolecon.2004.08.005.
Wilkie, A.C., 2005. Anaerobic Digestion: Biology and Benefits. Undefined./paper/Anaerobic-Digestion%3A-Biology-and-Benefits-Wilkie/6bcc933608cb6dd9e096e807cec4cb15443f904d.
Xie, F., Lin, Z., Podkaminer, K., 2019. Could a bioenergy program stimulate electric vehicle market penetration? Potential impacts of biogas to electricity annual rebate program. GCB Bioenergy 11 (4), 623–634. https://doi.org/10.1111/gcbb.12581.
Younes, Amin, Fingerman, Kevin, Barrientos, Cassidy, Carman, Jerome, Johnson, Karly, Wallach, Eli, 2021a. Trash to Treasure: How the Renewable Fuel Standard can use garbage to pay for electric vehicles - analysis software (v1.1). Zenodo. https://doi.org/10.5281/zenodo.5062304.
Younes, Amin, Fingerman, Kevin, Barrientos, Cassidy, Carman, Jerome, Johnson, Karly, Wallach, Eli, 2021b. Trash to Treasure: How the Renewable Fuel Standard can use garbage to pay for electric vehicles - summary results (1.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.5062316.