Could a bioenergy program stimulate electric vehicle market penetration? Potential impacts of biogas to electricity annual rebate program

Fei Xie | Zhenhong Lin | Kara Podkaminer

Abstract
The biogas-to-electricity pathway under the Renewable Fuel Standard (RFS) allows for Renewable Identification Number (RIN) credits to be generated when electricity produced from biogas is used in the transportation sector. Though approved as a general pathway, EPA has proposed multiple credit allocation methods to functionalize this pathway. This study describes and evaluates a potential credit allocation framework where vehicle manufacturers generate electricity RIN (E-RIN) credits and use these credits to increase the sales of plug-in electric vehicles (PEVs). Under this framework, manufacturers use part of the credit value to reimburse electricity generators, offsetting potential higher biogas electricity generation cost. The remaining credit value is passed on to consumers as an annual PEV rebate to stimulate PEV sales. An iterative simulation framework is developed to fulfill two tasks: (a) to estimate the annual rebate amounts and their upfront value to consumers based on various factors, such as vehicle mileage, E-RIN equivalence value, and biogas capacity, and (b) to evaluate potential impacts of the E-RIN program on electrification of the future light-duty vehicles (LDVs) and energy use. The annual rebate amount varies by vehicle technology and could be up to $870/year for battery electric vehicles (BEVs) and range between $230 and 825/year for plug-in hybrid electric vehicles (PHEVs) depending on the electric range. These per vehicle rebates decrease when demand for electricity exceeds biogas electricity availability. The effectiveness of the program as modeled here is subject to different factors, such as the E-RIN equivalence value, biogas electricity generation cost, biogas electricity generation capacity, and consumers’ valuation of the E-RIN rebate. Our modeling results indicate that an E-RIN program has the potential to produce nearly $12 billion in E-RIN credits annually and to significantly increase PEV annual sales by up to 2.3 million and the PEV population by about 19.7 million in 2030.
1 | INTRODUCTION

The transportation sector is the largest producer of greenhouse gas emissions (GHGs) in the United States and is almost entirely reliant on fossil energy to move people and goods (EIA, 2017). To improve the energy security and environmental quality, the Renewable Fuel Standard (RFS), authorized by the Energy Policy Act of 2005 and expanded under the Energy Independence and Security Act (EISA) of 2007, is a federal program that supports the deployment of low-carbon renewable fuels to reduce GHGs and displace petroleum in the transportation sector. Compliance with the RFS is tracked through Renewable Identification Numbers (RINs), which are serial numbers assigned to a batch of renewable fuels (e.g., biofuel; EPA, 2014). Under the RFS, there are four categories of renewable fuels, cellulosic biofuel, biomass-based diesel, advanced biofuel, and other renewable fuel. For each category, RINs are generated and attached to each gallon of the corresponding renewable fuel produced. At the end of each compliance year, obligated parties, such as refiners or importers of gasoline or diesel fuel, obtain sufficient RINs for each category to demonstrate compliance. Each RIN is tradable, and its value is determined by market forces; during 2016, the RIN market prices range from $0.84–2.70/RIN across all fuel categories with cellulosic RINs traded at the higher end of that range (PFL, 2016). An update by the Environmental Protection Agency (EPA, 2016) to the RFS regulations (EPA, 2014) allowed electricity produced from biogas and used as a transportation fuel to qualify for cellulosic RINs. For simplicity, the biogas electricity credit is here denoted as E-RIN. E-RINs have potential to stimulate plug-in electric vehicle (PEV) sales including both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), and thus help the entire transportation sector to contribute to energy security and emission reduction.

This study aims to assess an E-RIN allocation scheme and to investigate its potential impacts on the electrification of future light-duty vehicle (LDV) market as well as the displacement of petroleum use in the transportation sector. This analysis is an extension of the original concept in (Podkaminer, Xie, & Lin, 2017), which assumes that consumers receive the full E-RIN credits in the form of the PEV upfront purchase incentives and does not explicitly consider electricity generation cost. In this updated analysis, manufacturers still generate E-RINs credits, but the marginal cost of biogas electricity generation is explicitly modeled and the determination of biogas electricity usage in the transportation sector is updated. Compared to the scheme in Podkaminer et al. (2017), this new framework better captures technical and economic barriers of biogas electricity generation, namely the potential higher generation cost of biogas electricity. Also, instead of one-time purchase incentive (Podkaminer et al., 2017), here we consider annual rebates that are distributed throughout PEV lifetimes. This could reduce the program risk, because only earned credits are needed for distribution annually.

To estimate the E-RIN annual rebate, we developed an iterative simulation procedure using a consumer choice model, the Market Acceptance of Advanced Automotive Technologies (MA3T) model (Lin, Dong, Liu, & Greene, 2012; Liu & Lin, 2016; McCollum et al., 2018; Xie & Lin, 2017) developed by the Oak Ridge National Laboratory (ORNL). This procedure can determine how the E-RIN annual rebates are allocated based on multiple factors, including vehicle mileage, E-RIN equivalence value, and biogas capacity. In addition, this assessment can also help both public and private sectors to understand impacts of the E-RIN annual rebate program on the future PEV market penetration and transportation energy. A set of scenarios are simulated, based on different policy assumptions, to understand potential impacts of the E-RIN program with a near-term scope from 2017 to 2030. Given the uncertainty of how these credits would be used in the market, this study highlights what is possible under the program using a series of assumptions on credit value, discount rates and duration and uptake of the program. We recognize the real-world complexity of implementation and the research need for it, but we exclude discussion of implementation in order to stay focused on the potential impact.

2 | MATERIALS AND METHODS

2.1 | Policy representation of E-RIN credits

Under current RFS regulation, there is a pathway for E-RIN generation from electricity when electricity derived from biogas is consumed in the transportation sector. Depending on the program structure, this policy has the potential to accelerate the electrification of the future LDV fleet. To further the goals of the RFS, the EPA sought input on approaches for the generation of E-RINs in the proposed Renewable Enhancement and Growth Support (REGS) rule (EPA, 2016), taking comments on various criteria on E-RIN generation and usage. In the rulemaking, EPA suggested several
potential entities that may be qualified to generate credits, including vehicle owners, public charging stations, electricity utilities, and vehicle manufacturers. Each of these entities has its own strengths and limitations in either production or usage verification processes along the biogas-to-electricity pathway, as described in the REGS rule (EPA, 2016).

This study assesses one potential allocation framework wherein all biogas electricity use by PEVs is recorded to maximize E-RIN generation, which in turn is used to reduce the ownership cost of PEVs. Within the structure, we assume that vehicle manufacturers would generate E-RIN credits and would be responsible to verify both biogas electricity production as well as its usage in the transportation sector. While EPA is considering other entities (e.g., charging stations) that could also generate the E-RIN credits, investigating the impacts of multiple allocation structures is beyond the scope of this study.

As stated in the REGS rule (EPA, 2016), vehicle manufacturers are less well-suited to verify the biogas electricity production (e.g., the production process should follow an approved pathway). Therefore, in the allocation framework, we assume that vehicle manufacturers would work with electricity generators to procure the expected amount of biogas electricity. Considering the potential economic and technical barriers of biogas electricity generation, this allocation framework assumes that manufacturers reimburse generators if biogas electricity generation cost is higher than the competing electricity generation method (e.g., natural gas-fired). While there are also other cost components (e.g., labor cost for program personnel) that may be reimbursed and take additional shares of the total credit value, for modeling simplicity, we only consider the electricity generation cost.

To verify electricity usage for E-RIN generation, vehicle manufacturers can check the state of charge (SOC) data of sold PEVs, data which many vehicle manufacturers that are already collecting (EPA, 2016). In our analysis demonstrating the potential impact to increase PEV sales, manufacturers pass on this credit value to PEV buyers. In this study, the framework assumes that these E-RIN credits will be in the form of annual rebates to reward PEV owners for their usage of biogas electricity in transportation.

In the rest of this section, we show the details on determining the reimbursement to generators and annual rebates to PEV owners, respectively. Also, as the annual rebates could potentially increase consumers’ acceptance of PEVs, we demonstrate the lifetime value of the annual rebate program to consumers.

2.1.1 | Reimbursement to biogas electricity generator

In order to offset the potentially higher cost of biogas electricity production, part of the E-RIN credit value here is used to reimburse biogas electricity generators. We use the levelized cost of electricity (LCOE, unit: $/kWh) to determine the required reimbursement amount. The LCOE is a measure to compare average total costs between different electricity generation methods (EIA, 2017a). To determine the credit value that would be shared with the biogas electricity generator, we compare the difference in the LCOEs between biogas electricity and the electricity generated with the competing energy source and generation method. While the competing energy sources will vary by locations (e.g., natural gas or coal), for simplicity of the analyses at the national scale, we take the natural gas-fired electricity with conventional combined cycle (denoted as NG electricity) as the competing electricity generation for all regions. The NG electricity provides the largest share in the current electricity mix in United States (EIA, 2016a) and is often the marginal generator setting the electricity price (DOE, 2017). The unit reimbursement amount \( C_{\text{generator}} \) (unit: $/kWh) to biogas generator can be determined using Equation (1).

\[
C_{\text{generator}} = \max \{ \text{LCOE}^{\text{bio}} - \text{LCOE}^{\text{NG}}, 0 \} \tag{1}
\]

Following Equation (1), if biogas electricity’s LCOE \( (\text{LCOE}^{\text{bio}}) \) is higher than NG electricity’s \( (\text{LCOE}^{\text{NG}}) \), then we assume the difference \( (\text{LCOE}^{\text{bio}} - \text{LCOE}^{\text{NG}}) \) is the reimbursement to generators; otherwise, no reimbursement is allocated to generators as producing biogas electricity is cost competitive and does not incur additional cost compared to the competing generation method.

As noted above, the LCOEs of biogas and NG electricity are site- and scale-specific. To capture the range of potential costs, in this analysis, we considered two biogas electricity generation cost scenarios in determining \( C_{\text{generator}} \): (a) low cost scenario—low-cost estimate of LCOE\(^{\text{bio}}\) and high-cost estimate of LCOE\(^{\text{NG}}\), and (b) high-cost scenario—high-cost estimate of LCOE\(^{\text{bio}}\) and low-cost estimate of LCOE\(^{\text{NG}}\). The two scenarios together show bounds of potential impacts. In this study, all dollars in the literature are converted to 2005 dollars. With the assumption of long-run adoption of biogas electricity technologies, we consider LCOE\(^{\text{bio}}\) ranging between $0.065 and 0.10/kWh (IRENA, 2012; NREL, 2012) and LCOE\(^{\text{NG}}\) ranging between $0.04 and 0.07/kWh (EIA, 2017a). For the low-cost scenario, \( C_{\text{generator}} \) is calculated as $0/kWh, indicating no additional reimbursement is needed to produce biogas electricity. Contrarily, \( C_{\text{generator}} \) for the high-cost scenario is high at $0.06/kWh (=0.10 − 0.04), indicating that manufacturers would need to share the E-RIN credit to cover the higher cost to generate biogas electricity. Note that it is possible that some biogas facilities would likely have even higher generation cost. However, this study does not consider that for the national level analysis.
2.1.2 | Determination of E-RIN annual rebates

After subtracting the biogas marginal costs, the remaining credit value is allocated to PEV users in the form of annual rebates. We consider one simple framework for estimating annual rebates. Let \( i \) index PEV technologies (i.e., PHEV10/20/40 and BEV100/200/300; numerical values indicate electric range in miles), \( j \) index the model year (MY; e.g., \( j = 2017 \) for MY 2017), and \( t \) index the age of the PEV. The annual rebate—\( A_{ijt} \) (\$) by technology \( i \) with MY \( j \) and age \( t \) is calculated using Equation (2).

\[
A_{ijt} = C_{\text{consumer}} \times E_{it} \times \beta_{j+t-1} \tag{2}
\]

where

\[
C_{\text{consumer}} = \max \left\{ \frac{\text{price}_{\text{RIN}}}{\text{equivalence}_{\text{RIN}}} - C_{\text{generator}}, 0 \right\} \tag{2a}
\]

\[
E_{it} = \gamma \times \alpha_i \times eVMT_i \tag{2b}
\]

The annual rebate \( A_{ijt} \) is the product of three factors: credits to consumers \( C_{\text{consumer}} \) (\$/kWh), annual fuel consumption \( E_{it} \) (kWh), and E-RIN credit reduction factor \( \beta_{j+t-1} \) (%).

The first factor \( C_{\text{consumer}} \) in Equation (2) measures the estimated unit monetary value of the E-RIN credits passed to PEV owners and is calculated using Equation (2a). In (2a), price\(_{\text{RIN}}\) (\$/RIN) is the unit price of E-RIN credits, and equivalence\(_{\text{RIN}}\) (kWh/RIN) is the equivalence value, a conversion factor that determines the basis for how many kWh of biogas electricity should be used to generate 1 RIN credit. Therefore, price\(_{\text{RIN}}/\text{equivalence}_{\text{RIN}}\) yields the maximum monetary value of the E-RIN credits for each kWh of biogas electricity. Subtracting \( C_{\text{generator}} \), the remainder is the annual monetary value to PEV owners for E-RIN credits. A lower bound of zero value is enforced to prevent negative values. As mentioned above, \( C_{\text{generator}} \) can be determined using Equation (1). For price\(_{\text{RIN}}\), a constant cellulosic RIN price of $1.50/RIN is assumed in this analysis. This estimate is at the lower bound of today’s cellulosic RIN prices (PFL, 2016). For equivalence\(_{\text{RIN}}\), existing regulations set the equivalence value to 22.6 kWh/RIN (EPA, 2016), based on the energy content compared to ethanol. The International Council on Clean Transportation (ICCT, 2015) suggested that the equivalence value should reflect petroleum displacement. Since a new PEV can displace 4.3 ethanol equivalent gallons of gasoline, due to the higher fuel efficiency of PEVs (DOE, 2015), ICCT suggested an equivalence value of 5.24 kWh/RIN (5.24 = 22.6/4.3) for E-RINs. To understand the impact of the equivalence value, both values are considered in this study.

The second factor \( E_{it} \) in Equation (2) measures the biogas electricity consumption for technology \( i \) in age \( t \) and is determined using Equation (2b). This factor reflects the principle that the annual rebate should be proportional to the biogas electricity consumption. In (2b), \( \gamma \) is the electricity fuel consumption rate of PEVs and the value of 0.32 kWh/mile is adopted from the memorandum by ICCT (2015). eVMT, is first-year electric vehicle miles traveled (eVMT), and it varies between vehicle technologies related to vehicle range. In this study, the eVMT is defined as PHEV10—2,500 miles/year, PHEV20—4,000 miles/year, PHEV40—9,000 miles/year, and BEV100/200/300—9,500 miles/year (Carlson, 2015). We also recognize the gradual decline in the eVMT as the vehicle ages. \( \alpha_i \) (%) is discounted driving distance by vehicle age \( t \) and is adopted from the Transportation Energy Data Book (Davis, Williams, & Boundy, 2016).

The third factor \( \beta_{j+t-1} \) in Equation (2) is the E-RIN credit reduction factor. The E-RIN credit generation is subject to the generation capacity of biogas electricity (CAP) used in the transportation sector. After the CAP is exceeded, any further transportation electricity demand cannot be credited. In the United States, the current generation capacity of biogas electricity is 15.6 TWh/year (DOE, 2016; EIA, 2016b), and an expanded biogas supply can support 41.2 TWh/year (USDA, 2014) or even higher (Saur & Milbrandt, 2014). This reduction factor accounts for the share of biogas electricity in the total transportation electricity consumption. For example, if the available biogas electricity can only meet 75% of the PEV demand in year 2030, then a BEV in MY 2017 (\( j = 2017 \)) at its 14 years age (\( t = 14 \)) will only receive 75% of the electricity credit value for each kWh of electricity consumed (i.e., \( \beta_{2017+14-1} = \beta_{2030} = 75\% \)).

2.1.3 | Value of E-RIN annual rebates to consumers

To evaluate how the E-RIN annual rebate affects consumers’ acceptance of PEVs, we are also interested in determining the perceived upfront monetary value of all annual rebates to consumers at the point of purchase.

\[
V_{ij} = \min \left\{ T_i, T_j \right\} \times PV(t,7\%) \times A_{ijt} \tag{3}
\]

The perceived upfront value is determined using Equation (3). The upfront value is the summation of discounted annual rebates over a certain number of years, and \( PV(t,7\%) \) is the discount factor to covert the annual rebate \( A_{ijt} \) in age \( t \) to the present value. This study considers 7% discount rate, which is normally used in evaluating federal programs (OMB, 1992). The length of the period for
determining the upfront value is the minimum of two factors, the eligible program time $T_1$ (years) and the perceived program time $T_2$ (years). $T_1$ is the eligible time after the initial purchase when PEVs can receive E-RIN credits, and we assume it equals the average vehicle lifetime of 15 years (Davis et al., 2016). $T_2$ measures consumers’ perceived time period when annual rebates could be received. In this study, we initially assume that $T_2$ equals $T_1$. However, $T_2$ may also be smaller than $T_1$, reflecting the condition when consumers undervalue the E-RIN annual rebate program. We also include analysis on the possible undervaluation impacts in the result section.

### 2.2 Simulating impacts of E-RIN PEV annual rebates

The perceived upfront value of the annual rebates determined with Equation (3) has the potential to increase consumers’ adoption of PEVs. We use an existing vehicle choice model, the MA3T model developed by ORNL, to simulate the impacts of the annual rebate program on future PEV sales and energy use in the LDV sector. The core of the MA3T model is a nested multinomial logit discrete choice model that estimates market shares of various LDV technologies based on a wide range of inputs regarding vehicle technology, consumer behaviors, policy, and infrastructure scenarios. To simulate impacts of the E-RIN rebate program on the relative competitiveness of PEVs, we consider multiple fuel powertrain technologies, including gasoline, diesel, hybrid electric vehicles (HEVs), and PEVs. For simplicity, other alternative fuel technologies, such as fuel cell electric vehicles (FCEVs), are not considered in this study. For detailed information on the MA3T model structure and data assumption, interested readers are referred to studies (Lin et al., 2012; Liu & Lin, 2016; McCollum et al., 2018; Xie & Lin, 2017).

One challenge in the simulation work is that the E-RIN PEV annual rebate depends on the actual sales of PEVs. In particular, $\beta_{j+t-1}$ in Equation (2) is dependent on the total estimated biogas electricity demand which is correlated with the PEV market share. This interdependency between inputs (i.e., rebate amount) and outputs (i.e., market share of PEVs) cannot be directly modeled by the MA3T model. Thus, an iterative simulation process is developed using the MA3T model to foresee the future PEV deployment and to estimate $\beta_{j+t-1}$.

For simplicity, the E-RIN credit reduction factor $\beta_{j+t-1}$ can be denoted by $\beta_k$ where $k = j + t - 1$. Note that $k$ here indexes years in the time scope. Although we limit the time scope of the impact analysis up to 2030, $\beta_k$ for later years (2031 $\leq k \leq 2044$) also need to be determined, as they affect the upfront perceived value of annual rebates for PEVs that still earn E-RIN credits after 2030. As we assume the E-RIN program starts in 2017, the developed iterative algorithm takes a bisection-based approach to estimate $\beta_k$ for each year $k$ ($2017 \leq k \leq 2044$). Prior to the iteration, we set two initial bounds for each $\beta_k$, namely, a lower bound value $\beta_L = 0\%$, and an upper bound value $\beta_U = 100\%$. The iteration mainly updates the two bounds which converge over time. The detailed iterative process is shown in Figure 1.

One important input that affects outcomes of the iterative process in Figure 1 is the biogas electricity capacity $CAP$. As mentioned above, this study considers two scenarios: 15.6 TWh/year (EIA, 2016b; DOE, 2016; current generation capacity) and 41.2 TWh/year (USDA, EPA, & DOE, 2014; expanded biogas capacity).

### 2.3 Discussion on E-RIN annual rebate program assumptions

To model the system, a number of assumptions and simplifications are made, as discussed below.

#### 2.3.1 Average eVMT and electricity consumption rates

For simplicity, the eVMT and electricity consumption rates modeled here are invariant to consumer groups and actual vehicle models, respectively. However, in real-world operations, these parameters could vary and contribute to different biogas electricity consumptions, and in theory, annual rebate could be adjusted accordingly. For example, frequent drivers with higher eVMT are expected to receive larger rebate, and similarly, larger vehicles (e.g., pickup) that use more electricity would also receive a larger credit value. However, it may be challenging to verify the driving intensity and actual energy consumption of each vehicle, and using the average eVMT to represent all consumers can prevent certain consumers from intentionally increasing mileage to earn additional credits. Similarly, using the average electricity consumption rate to determine credit value could prevent inappropriately rewarding less fuel-efficient vehicles.

#### 2.3.2 Economic and Technical Inputs at the National Scale

Since this study focuses on the impact analysis on the national scale, we simplify model inputs by taking national average values for policy-related parameters, such as E-RIN price, competing electricity energy source, and biogas capacity. However, these parameters may be different over multiple regions and years and can affect the real-world impact of this policy. Note that the purpose of this study was not to project the actual impact of the program, but was to demonstrate...
boundaries of potential impacts and influences of given parameters for considerations by policy makers, manufacturers, and other interested stakeholders. Therefore, considering national average values is appropriate for this study.

2.3.3 Variations in vehicle lifetime

In this study, the eligible program time \((T_1)\) is assumed to equal average vehicle lifetime of 15 years (Davis et al., 2016). The actual life expectancy could vary between vehicles, but is not considered because that is difficult to estimate at the point of purchase.

2.3.4 Interactions with other incentive programs

Other national or state level incentive programs may also exist in addition to the E-RIN annual rebate program. These programs could collaboratively stimulate the PEV market penetration. Since the E-RIN annual rebate allocation is dependent on the estimation of the PEV market penetration, potential impacts by other incentive programs should also be considered when estimating future rebate values. This study incorporates the federal American Recovery and Reinvestment Act (ARRA) credit incentive and existing state credit programs into the baseline as part of the policy inputs in the MA3T model.

2.3.5 Uncertainties in E-RIN annual rebate program

Due to the volatile vehicle and energy market, uncertainties are inevitable in estimating future allocation of the E-RIN annual rebates. Given the intent of this analysis to understand the potential impact of this program, a conservative E-RIN price of $1.5/RIN was used to represent this uncertainty. Further analysis on E-RIN price uncertainty is out of scope in this study.
3 | RESULTS

3.1 | Estimation of annual rebate schedules

With the modeling framework and the iterative process described above, we estimate how annual rebates are allocated in each year. Figure 2 shows the example schedule for the scenario with low biogas electricity generation cost, 5.24 kWh/RIN equivalence value, and 41.2 TWh/year biogas capacity.

In Figure 2, the four solid lines show the annual rebates by technology by year, and the dotted line shows the expected national total annual rebate allocation for each year. As this scenario assumes a biogas capacity of 41.2 TWh/year, the maximum national total annual rebate per year is $11.8 billion (= 41.2 × 1.5/5.24) with all credits allocated to consumers in the low generation cost scenario. The maximum national total value is not reached until 2027, when the estimated electricity consumption by sold PEVs reaches the national biogas capacity. As a result, before 2027, all vehicle technologies receive the full annual rebates during their eligible program period ($T_1 = 15$ years). After 2027, the annual rebates per vehicle gradually decline as more PEVs share the total annual rebate. Since BEVs are expected to have the largest eVMT, they have the largest annual rebate. The rebate for PHEVs is generally less, with PHEV10 receiving the lowest value based on a lower assumed eVMT (Carlson, 2015).

3.2 | Consumer valuation of E-RIN annual rebate

To analyze the impacts of an E-RIN program, we consider eight scenarios with combinations of different assumptions.

**FIGURE 2** Annual rebate schedule by vehicle type (left) and national total rebate (right) for the scenario: Low biogas electricity generation cost, 5.24 kWh/RIN equivalence value, and 41.2 TWh/year biogas capacity

**FIGURE 3** Perceived upfront value of annual rebates for purchasing BEVs in 2017 and 2030
on biogas electricity generation cost (high or low cost), RIN equivalence value (22.6 or 5.24 kWh/RIN), and biogas capacity (15.6 or 41.2 TWh/year) to determine the impact of these factors.

Figure 3 shows the perceived upfront value of annual rebates (discounted 7% annually) for purchasing BEVs in 2017 and 2030 for the eight scenarios. The perceived upfront value in 2030 is much lower than the one in 2017. As the electricity usage exceeds biogas capacity in later years with a larger accumulated PEV fleet, the credits are spread among all vehicles, resulting in each PEV generating a smaller annual rebate in later years. The upfront value of the annual rebates also differs significantly between scenarios and can range between $118 (scenario “High cost + 22.6 kWh/RIN” with 15.6 TWh/year biogas capacity in Figure 3) and $6,050 (scenario “Low cost + 5.24 kWh/RIN” with 41.2 TWh/year biogas capacity) in 2017.

Among different factors, the RIN equivalence value has the most significant impact on the rebate value. Biogas electricity generation cost also plays an important role in the annual rebate. When high biogas generation cost is coupled with the 22.6 kWh/RIN equivalence scenario, most of the credit value is used to reimburse generators to offset the high generation cost of biogas electricity. This factor results in a reduced impact on PEV market stimulation. Finally, the biogas capacity is also an important factor. As the capacity increases, there will be less competition among PEV users for the annual rebate in later years, thus maintaining the annual rebate per vehicle. Though not shown in Figure 3, the upfront value of annual rebates for PHEVs is lower in values due to lower eVMT by PHEVs (Carlson, 2015). However, the impacts by different factors (e.g., RIN equivalence value) are similar.

### 3.3 Impacts of E-RIN PEV annual rebates on sales, population, and energy use

With different perceived upfront values of annual rebates as shown in Figure 3, we are also interested in understanding how these scenarios affect PEV (including BEV and PHEV) market penetration and energy use at the entire national scale. We compare changes in PEV sales, PEV population, and energy use of the eight scenarios relative to the “No Program” scenario which excludes E-RIN credit program (i.e., no annual rebate).

Compared to the “No Program” scenario, Figures 4 and 5 show the increase in PEV sales and population, respectively. Results indicate that all these scenarios increase the PEV market share by 2030, with larger increase for the BEV technology that receives higher annual rebates. As shown in Figure 4, the temporary reduction in the sales growth
shortly before 2020 is mainly due to the phase-out of the ARRA credit incentive. This phase-out is triggered when each vehicle manufacturer reaches a 200,000 cumulative PEV sales. After that dip, the E-RIN PEV annual rebate program continues to increase the sales of both BEVs and PHEVs, despite the decreasing value of the annual rebate (2017 vs. 2030) as shown in Figure 2. These stimulated sales result in larger PEV population in later years as shown in Figure 5.

As the upfront value of lifetime annual rebates differs dramatically between scenarios (see Figure 3), differences in their impacts on sales and population are also noticeable. Optimistically, under the “Low cost + 5.24 TWh/RIN + 41.2 TWh/year” scenario, the sales are increased by up to 1.56 million for BEV and 0.72 million for PHEVs in 2030 (2.3 million in total). The corresponding increase in population is 13.2 million for BEVs and is 6.5 million for PHEV in 2030 (19.7 million in total). In contrast, in the

FIGURE 5 Changes in BEV and PHEV population compared to the “No Program” (6.09 million BEVs and 2.54 million PHEVs in 2030) scenario with two biogas generation cost levels (high or low cost) and two biogas capacity levels (15.6 or 41.2 TWh/year)

FIGURE 6 Changes in energy use in 2030 compared to the “No Program” scenario
“High cost + 22.6 TWh/RIN” scenario, there is negligible impact on either sales or population, no matter which biogas capacity level is realized. Thus, the impact of this program, as modeled here, depends on the cost of biogas generation, the biogas capacity, and the E-RIN equivalence value.

Figure 6 shows the associated changes in national LDV energy use by the eight scenarios relative to the "No Program" scenario. The energy use is estimated and outputted by MA3T which takes many factors into the calculation, including calculated vehicle population, fuel economy by technology, and distributions on driving intensity Results show that the E-RIN program can significantly reduce fossil fuel (gasoline and diesel) consumption, but would also increase electricity consumption. Note that the increase in electricity consumption (in Btu) is much less than the decrease in fossil fuel, as electric drive by PEVs has better fuel efficiency than running on gasoline or diesel. Therefore, the E-RIN program decreases the total energy consumption in the LDV fleet while still meeting the same level of travel demand.

3.4 | Impacts of percentage of E-RIN credit value allocated to consumers

In the E-RIN program framework modeled above, the vehicle manufacturers spend part of the earned credits to offset potential higher generation cost, and the remaining credits are used as annual rebates to stimulate PEV sales. However, in real-world operations, there may be other types of costs, such as the insurance cost to cover potential risks and the permit cost for signing up the program. In these cases, PEV users would likely receive a smaller annual rebate and, consequently, there would be smaller impact on the PEV market penetration.

To account for these other possibilities, we also consider a series of scenarios with different amounts of credits going toward the consumer while the remaining is distributed for other purposes. Figure 7 shows changes in PEV market penetration in 2030 relative to the “No Program” scenarios with 25%, 50%, 75%, and 100% of the credit value passed on to the consumer. As an illustrative example, these scenarios assume low-cost scenario and are based on the 5.24 kWh/RIN equivalence value with either the 15.6 or 41.2 TWh/year biogas capacity levels. It is shown that as fewer credits are allocated to consumers, the E-RIN program has a smaller impact on the PEV market. This observation indicates that maximizing the value received by customers maximizes the impact of the E-RIN program in stimulating the PEV market penetration.

3.5 | Impacts of eligible program time and perceived program time

In this study, we assume that both $T_1$ and $T_2$ equal 15 years, which are the average vehicle lifetime. However, vehicle manufacturers may choose to consider a shorter duration of time, with $T_1 < 15$ years. Consumers may also undervalue the program due to policy uncertainty or the potential for a shorter vehicle life expectancy, which would result in $T_2 < T_1$. Therefore, we further evaluate different combinations of $T_1$ and $T_2$. As mentioned before, we only consider scenarios when $T_2 \leq T_1$, because consumers should not expect to receive annual rebate for longer time than suggested by the eligible program time ($T_1$).

Table 1 shows the impacts on both BEV sales and population in 2020 and 2030. As both $T_1$ and $T_2$ increase, the BEV market penetration also increases, because BEV owners expect longer period in receiving rebates. However, if only
the eligible program time $T_1$ is increased but the perceived program time $T_2$ is decreased, the benefits of the program in stimulating the BEV market are reduced. The decreased $T_2$ downplays the consumer valuation of the rebate program. Therefore, for maximizing impacts of the E-RIN pathway, it is important to ensure that consumers understand the full value.

### DISCUSSION

This study assesses one potential framework for allocating E-RIN credits and evaluates its impact on the PEV market penetration in the LDV fleet. In the allocation framework considered here, vehicle manufacturers take the role to generate E-RIN credits and spend or re-allocate the credits to maximize their PEV sales. We consider two major parties influenced by the program. One is the electricity generators who obtain reimbursement from manufacturers to produce biogas electricity, and the other is the consumers who obtain annual rebates for running PEVs powered by biogas electricity. We adopted an iterative simulation process using the MA3T model to determine the E-RIN PEV annual rebate schedules and their perceived upfront value to consumers and to evaluate their impacts on the PEV market acceptance and energy use.

We observe that the proposed E-RIN program can significantly stimulate PEV market penetration and displace petroleum use. With the potential to generate $11.8$ billion in E-RIN credits, this pathway could potentially increase total PEV sales by $2.3$ million and the PEV population could be up by $19.7$ million in 2030 that contributes to an estimated reduction in on-road conventional fuel usage by 700 trillion BTUs in 2030. This analysis shows that an annual rebate can further stimulate the emerging PEV market beyond the existing state and federal incentives.

However, the actual impact is subject to many technical and economic factors, including biogas electricity generation cost, E-RIN equivalence value, biogas electricity generation capacity, and actual percentage of the entire credit value allocated to consumers. The effectiveness of the E-RIN program also relies on how consumers value the annual rebates obtained in later years at the point of purchase. All these technical, economic, and social factors could vary between geographic locations and time points. Correctly evaluating these factors is important for governments and vehicle manufacturers to understand and maximize the program impact.

### ACKNOWLEDGEMENTS

The authors are grateful for the support of the Office of Strategic Programs, the Bioenergy Technologies Office, and the Vehicle Technologies Office within the Office of Energy Efficiency and Renewable Energy (EERE) at the Department of Energy (DOE). The views expressed in the article do not necessarily represent the views of the DOE or the United States Government.

**ORCID**

Fei Xie https://orcid.org/0000-0003-4325-2868

### REFERENCES

Carlson (2015). Electric vehicle mile traveled (eVMT): On-road results and analysis. Retrieved from http://energy.gov/sites/prod/files/2015/07/f24/vss171_carlson_2015_p.pdf

Davis, S. C., Williams, S. E., & Boundy, R. G. (2016). *Transportation energy data book edition 35*. Oak Ridge, TN: Oak Ridge National Laboratory.

DOE(2015). Fuel economy data. Retrieved from https://www.fueleconomy.gov/
DOE (2016a). 2016 Report, billion-ton. Advancing domestic resources for a thriving bioeconomy. Retrieved from https://energy.gov/sites/prod/files/2016/12/f34/2016_billion_ton_report_12.2.16_0.pdf

DOE (2017). Staff report to the secretary on electricity markets and reliability.

EIA (2016). International energy outlook 2016.

EIA (2016b). Table 5.6.D. Landfill gas: Consumption for electricity generation. Retrieved from http://www.eia.gov/electricity/annual/html/epa_05_06_d.html

EIA (2017a). Levelized cost and levelized avoided cost of new generation resources in the annual energy outlook 2017.

EIA (2017b). Power sector carbon dioxide emissions fall below transportation sector emissions. Retrieved from https://www.eia.gov/todayinenergy/detail.php?xml:id=29612#

EPA (2014). Renewable fuel standard, pathways II. Final Rule.

EPA (2016). Renewables enhancement and growth support rule. Proposed rule.

ICCT (2015). Memorandum on the equivalence value of electricity in the Renewable Fuel Standard. Retrieved from https://www.reginfo.gov/public/do/eoDownloadDocument?pubId=&eodoc=true&documentID=1719

IRENA (2012). Renewable energy technologies: Cost analysis series. Vol 1 (5). Biomass for Power Generation, p. 42.

Lin, Z., Dong, J., Liu, C., & Greene, D. (2012). Estimation of energy use by plug-in hybrid electric vehicles: Validating gamma distribution for representing random daily driving distance. Transportation Research Record: Journal of the Transportation Research Board, 2287, 37–43. https://doi.org/10.3141/2287-05

Liu, C., & Lin, Z. (2016). How uncertain is the future of electric vehicle market: Results from Monte Carlo simulations using a nested Logit Model. International Journal of Sustainable Transportation, 11(4), 237–247. https://doi.org/10.1080/15568318.2016.1248583

McCollum, D. L., Wilson, C., Bevione, M., Carrara, S., Edelenbosch, O. Y., Emmerling, J., … van Vuuren, D. P. (2018). Interaction of consumer preferences and climate policies in the global transition to low-carbon vehicles. Nature Energy, 3, 664–673.

NREL (2012). U.S. Transparent Cost of Energy Database. Retrieved from http://en.openei.org/wiki/Transparent_Cost_Database

OMB (1992). Circular A-94: Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs.

PFL (2016). Progressive fuels limited markets daily report. Retrieved from http://www.progressivefuelslimited.com/Web_Data/pfdaily.pdf

Podkaminer, K., Xie, F., & Lin, Z. (2017). Analyzing the impacts of a biogas-to-electricity purchase incentive on electric vehicle deployment with the MA3T vehicle choice model. Oak Ridge National Laboratory.

Saur, G., & Milbrandt, A. (2014). Renewable hydrogen potential from biogas in the United States. NREL.

USDA, EPA, DOE (2014). Biogas roadmap. Retrieved from https://www3.epa.gov/climatechange/Downloads/Biogas-Roadmap.pdf

Xie, F., & Lin, Z. (2017). Market-driven automotive industry compliance with fuel economy and greenhouse gas standards: Analysis based on consumer choice. Energy Policy, 108, 299–311. https://doi.org/10.1016/j.enpol.2017.05.060

How to cite this article: Xie F, Lin Z, Podkaminer K. Could a bioenergy program stimulate electric vehicle market penetration? Potential impacts of biogas to electricity annual rebate program. GCB Bioenergy. 2019;11:623–634. https://doi.org/10.1111/gcbb.12581