

Cost-Effective Reduction of Greenhouse Gas Emissions via Cross-Sector Purchases of Renewable Energy Certificates

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ABSTRACT

Over half of the greenhouse gas (GHG) emissions in the United States come from the transportation and electricity generation sectors. To analyze the potential impact of cross-sector cooperation in reducing these emissions, we formulate a bi-level optimization model where the transportation sector can purchase renewable energy certificates (REC) from the electricity generation sector. These RECs are used to offset emissions from transportation in lieu of deploying high-cost fuel efficient technologies. The electricity generation sector creates RECs by producing additional energy from renewable sources. This additional renewable capacity is financed by the transportation sector and it does not impose additional cost on the electricity generation sector. Our results show that such a REC purchasing regime significantly reduces the cost to society of reducing GHG emissions. Additionally, our results indicate that a REC purchasing policy can create electricity beyond actual demand. This extra capacity can be used to make clean fuel for vehicles and thereby further cut emissions from fossil fuel powered vehicles.

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INTRODUCTION

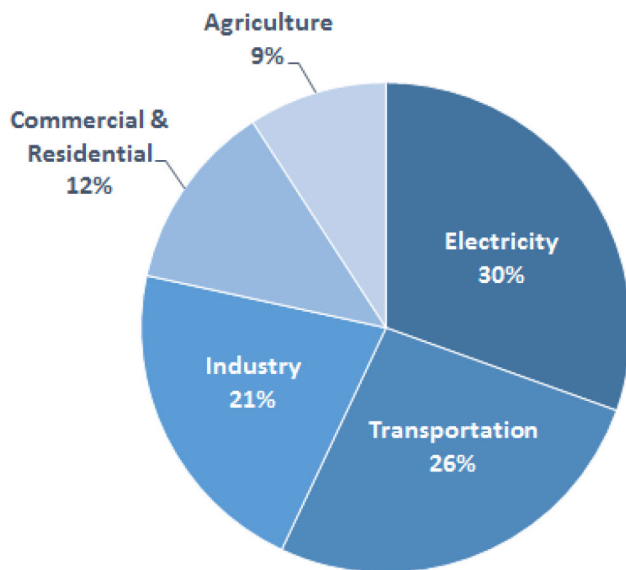
According to Hansen, et al. [1], the global surface temperature increased nearly 0.2 °C per decade from 1976 to 2006, mainly due to increasing amounts of GHG in the air. As seen in Figure 0.1b and EPA 2016 report [2], most of the GHG is from CO₂. According to the U.S. Environmental Protection Agency (EPA) report on the inventory of U.S. GHG emissions, the two economic sectors most responsible for the United States' GHG emissions are the electricity generation sector (30% of 2014 GHG emissions) and the transportation sector (26% of 2014 GHG emissions) [2] (refer to Figure 0.1a).

Transportation GHG emissions are primarily due to burning fossil fuels in cars, trucks, ships, trains, and airplanes. Over 90% of the fuel used for transportation is petroleum-based gasoline (see Ribeiro, Kobayashi, et al. [3]). Therefore, for the U.S. to reduce its GHG emissions, it is imperative that the transportation and electricity generation sectors reduce their CO₂ emissions.

There are various means for emission reduction for these two sectors. For electricity generation, renewable energy sources with low emissions, such as solar or wind, can be used to replace the high emission coal-fired generators. Unfortunately, for now and in the foreseeable future (e.g. EIA annual energy outlook 2015 [4]), renewable generators are more costly than traditional generators;

therefore significant exogenous monetary stimulation, such as renewable feed-in tariff (see e.g., Couture and Gagnon [5]) is necessary to encourage the electricity generation sector to deploy more renewable capacity. For the transportation sector, fuel cell and electrified vehicles, like plug-in hybrid electric vehicles (PHEVs) in electric mode and battery electric vehicles (BEVs), are considered zero-emission alternatives to vehicles powered by fossil fuels. However, while the more expensive electrified vehicles have very low tank-to-wheel emissions, they may have very high well-to-tank emissions. For instance, a BEV powered by electricity from a high-emission coal-fired generator actually emits more CO₂ than a similar vehicle with a gasoline fueled hybrid electric powertrain (HEV) (Elgowainy, Burnham, et al. [6]). Additionally, electrification can only be reasonably applied to light duty vehicles (LDV). For other non-LDV transportation, such as freight trains, airplanes, heavy duty trucks, etc., electrification has extremely high capital cost and low return on investment (e.g. see Friedemann [7]). Non-LDV transportation consisted of nearly 40% of total GHG emission in the transportation sector in 2012 according to EPA report [8], therefore the transportation industry needs to develop other alternatives for emission reduction in non-LDVs in order to decrease its overall contribution to GHG emissions.

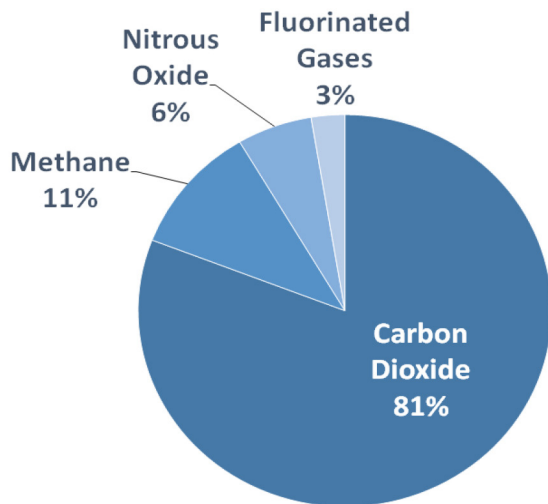
Total U.S. Greenhouse Gas Emissions by Economic Sector in 2014



U.S. Environmental Protection Agency (2014).
U.S. Greenhouse Gas Inventory Report: 1990-2014.

a. GHG emission by sectors

U.S. Greenhouse Gas Emissions in 2014



U.S. Environmental Protection Agency (2014).
U.S. Greenhouse Gas Inventory Report: 1990-2014.

b. Different GHGs

Figure 0.1. Graphs from EPA 2016 report [2]

From the above paragraph, there are many technologies with varying costs available to reduce GHG emissions over the different sectors. Thus, careful analysis is needed to efficiently allocate the limited resources. Moreover, cost-efficient emission reduction among the transportation and electricity generation sectors should not be

considered independent tasks because of the potentially large deployment of electrified vehicles. Previous research (see Chen, Klampfl, et al. [9]) has also proven that the two sectors satisfying a joint emission target (as opposed to each satisfying their own individual targets) can save money for the society as a whole; therefore, cross-sector cooperation should be encouraged. Unfortunately, while the two sectors operate independently, there is no way for the system to have an operator who can control both sectors' investment plans. Moreover, Chen, Klampfl, et al. [9] showed that cooperative emission reduction, while lowering the total cost to the transportation sector, increases the total cost to the electricity generation sector. As a result, without appropriate policy, cross-sector cooperation is not realistic.

One potential solution is cap-and-trade policy. That is, both sectors have their own emission targets, but emission allowances can be traded freely among these two sectors. Cap-and-trade is a popular policy world-wide, especially in Europe, but it is not widely applied in the United States. Note that the emission reduction target for U.S. is to achieve the 80% annual emission reduction (based on the 2010 or 2005 emission levels) in 2050, which is consistent with the target in Chen, Klampfl, et al. [9] and the State Department Fact Sheets [10]. In order to achieve this target smoothly, the transportation and electricity generation sector have to decrease their annual emission by nearly 4% each year. Although the transportation sector already has such an emission reduction target (e.g. see State of California [11]), the equivalent annual emission reduction rate of generation sector, however, is less than 2% according to EPA [12]. Therefore, to successfully achieve the emission reduction target with cap-and-trade policy, the current emission reduction plan has to be changed, which has its own obstacles.

This paper will investigate another policy called a renewable energy certificate (REC) purchasing policy which does not change the current emission reduction plan. Renewable energy certificates (RECs), a.k.a. Green tags, Renewable Energy Credits, Renewable Electricity Certificates, or Tradable Renewable Certificates (TRCs), are a tradable commodity that represent one megawatt-hour (MWh) of electricity generated from an eligible renewable resource (e.g. solar or wind) according to EPA REC definition [13]. By purchasing a REC, a firm can claim ownership of one MWh of green electricity. This policy is especially popular within the electricity generation sector. For example, a state might have a renewable energy requirement for electricity generation companies: 20% of its generated electricity must come from renewable generators in 2020. However, the cost of deploying renewable generators varies among different regions. While it is extremely expensive for electricity generation company A to construct wind turbines in a certain region, it is cheap for a different company B to do so in another region. Company B can therefore generate renewable energy (and RECs) beyond the required 20% level and sell the extra RECs to company A. Thus, company A can reach the 20% level without personally deploying costly wind turbines, and both company A and company B can satisfy the renewable energy requirements in a cost-effective manner.

We will extend such a trading scheme to cross-sector REC purchasing. For example, one MWh of renewable energy saves about 0.4 metric tons of CO₂ (see EIA report [14]) compared with one MWh of fossil fuel electricity.

electricity from a natural gas (NG) generator (which is one of the cheapest generators, not considering emission restrictions [14]). The policy maker says that if the transportation sector purchases one REC, equal to one MWh of renewable energy, it can have an extra 0.2 metric tons CO₂ (half of 0.4 metric tons of CO₂) emission allowance (or equivalently, it can claim 0.2 metric tons CO₂ cut in its total emission). The possible outcome: the transportation sector is happy because it can deploy cheaper HEVs instead of expensive PHEVs/BEVs by purchasing RECs with a reasonable price; the electricity generation sector, which will be paid to produce one additional MWh of renewable energy, is happy because it is paid to deploy renewable generators and its total cost will not increase; and finally, society is happy because each REC purchased actually saves 0.2 metric tons of CO₂ emissions. Ideally, if the REC price that the transportation sector is willing to pay is high enough, the energy generation sector will even deploy extra capacity beyond total demand which can then be used to create additional environmentally friendly fuels (i.e. hydrogen, see Turner [15]). These fuels, e.g. hydrogen, can be used in vehicles (like fuel cell vehicles) for further emission reduction. Consequently, the extra electricity can be considered as having "negative emission" (see Section for detailed discussion). Such a REC purchasing scheme is called *the one-for-two rule*. This policy is more implementable than the cap-and-trade policy because rather than change any emission reduction plans, the policy maker just tells the two sectors that they can trade RECs with one simple rule. The effectiveness of this policy was evaluated by building a mathematical model and running simulations in later sections.

For the organization of this paper, in section , the model will be introduced in detail and a demonstration of how to solve the model will be shown. In section , the assumptions and data needed to run simulations to evaluate the effectiveness of a REC purchasing policy are listed and simulation results are analyzed. Finally, in section , future research directions are detailed.

MODEL FORMULATION

Our model is largely based on our previous paper [9], and the assumptions made in that paper are still valid. However, the model in this paper is no longer a single optimization model but rather a Stackelberg, leader-follower, game theory model.

Briefly speaking, there is a leader (the electricity generation sector in this case) that tries to maximize the total amount of RECs sold by deciding the REC price each year such that its total cost minus the RECs sale revenue is not higher than its business-as-usual (BAU) case (where REC purchasing is not allowed). The followers (in this case the LDV and non-LDV sectors) then decide how many RECs to purchase in order to minimize their total cost. However, care must be taken in the case of the two followers. The LDV sector can be flexible in making decisions regarding the number of RECs to purchase because their emissions target can alternatively be satisfied by deploying PHEVs/BEVs. For non-LDVs, as stated in Section 1, electrification in general can be very difficult to apply widely due to high capital costs. Consequently, the non-LDV's increasing emissions

caused by escalating demand cannot be offset by slight engine efficiency improvements. The non-LDV sector has no choice but to buy RECs from the electricity generation sector in order to achieve their emission target. The amount of RECs purchased each year by the non-LDV sector is known given the complete information of everything in the model. Thus, there is actually only one real follower - the LDV sector. The non-LDV sector is a decision-taker who will affect the results of the model, but cannot actually make any decisions on its own. Details of the model will be described in the following sub-sections.

Inputs

In this section, we will introduce the sets (e.g. vehicle types, generator types, etc.) and parameters. First, let us specify different types of vehicles and generators.

Vehicle Types

- CV = conventional vehicle.
- HEV = hybrid electric vehicle.
- PHEV = plug-in hybrid electric vehicle.
- BEV = battery electric vehicle.

Generator Types

- C = coal-fired generator.
- NG = natural gas generator.
- N = nuclear generator.
- R = renewable generator.

Next, we define the index sets.

Sets

- Set of vehicles: $V := \{CV, HEV, PHEV, BEV\}$.
- Set of generators: $G := \{C, NG, N, R\}$.
- Set of vehicle ages (all vehicle types have the same lifetime): $A^V := \{0, 1, \dots, \gamma^V\}$.
- Set of generator ages (different generator types have different lifetime): $A_g^G := \{0, 1, \dots, \gamma_g^G\}$ for all $g \in G$.
- Set of the time horizon: $T := \{2010, 2011, \dots, 2150\}$.

Note that although the time horizon is from 2010 to 2150, the decisions are actually made from 2026 to 2100. It is assumed that REC purchasing begins in 2026, and prior year actions are easily predictable: the LDV sector spends the least amount of money necessary to satisfy its demand and emissions target; the energy generation sector easily meets its emissions target by replacing old coal-fired generators with cheap natural gas generators. The end of the time horizon is assumed to be 2100, and years after 2100 have no vehicle and generator deployment or REC trading. The years 2101-2150 are used only for calculating the total cost (lifetime operation cost) of both sectors.

Parameters

- γ^V : vehicle lifetime length.
- γ_g^G : generator lifetime length of generator type $g \in G$.
- $\bar{\gamma}_g^G$: extended lifetime length of generator type $g \in G$ if it is deployed during or before 2010, $\bar{\gamma}_g^G \geq \gamma_g^G$ for all $g \in G$. This is to match the fact that there are a lot of very old generators now, especially coal-fired generators.
- $c_{v,t}^V$: total lifetime cost of vehicle type $v \in V$ deployed at year $t \in T$ which includes the deployment cost, discounted fixed and variable cost. Operation cost is discounted because of the survival rate of vehicles.
- $dc_{g,t}^G$: deployment cost of generator type $g \in G$ deployed at year $t \in T$.
- $oc_{g,t,\tau}^G$: operation (fixed and variable) cost of generator type $g \in G$ of age $\tau \in A^G$ at year $t \in T$.
- $rc_{g,\tau}^G$: retirement cost of generator type $g \in G$ at age $\tau \in A_g^G$. (Note that the model does not allow for forced retirement of vehicles because it is both difficult and costly. See Chen, Klampfl, et al. [9])
- d_t^V : demand of new vehicles at year t . (Note that in [9], it is the demand of all vehicles including the old ones; but it can certainly be made equivalent to demand of new vehicles as the model no longer allows vehicle early forced retirement.)
- d_t^G : demand of electricity at year $t \in T$. Note that this does not include the demand from PHEVs and BEVs. Also, this demand is already the result of total electricity demand minus the power generated from hydro generators (See Chen, Klampfl, et al. [9]).
- $le_{v,t}^V$: lifetime emission of vehicle type $v \in V$ deployed at time $t \in T$.
- $ae_{g,t,\tau}^G$: annual emission of generator type $g \in G$ of age $\tau \in A_g^G$ at year $t \in T$.
- $l\beta_t^V$: lifetime emission target of all newly deployed vehicles at time $t \in T$. Note that in [9] the target is the annual emission target of all vehicles on the road. It is made equivalent to the lifetime emission target of newly deployed vehicles for convenience as the model does not allow for vehicle early retirement.
- $a\beta_t^G$: annual emission target of the whole generator fleet at time $t \in T$.
- $R_{0,t}$: amount of RECs purchased by non-LDV sector at time $t \in T$ for $t \geq 2026$.
- C_0^G : total cost of the generation sector in BAU case.
- v_t : emission allowance for each unit (MWh) REC.
- $n_{g,t,\tau}^G$: amount of generator capacity $g \in G$ of age $\tau \in A_g^G$ for $2010 \leq t \leq 2025$. They are obtained from data input in 2010 and running the BAU optimization model before 2026.
- π_τ^V : survival rate of LDVs at the age $\tau \in A^V$.
- m : annual amount of miles traveled by a vehicle.
- $k_{v,t}^V$: reciprocal of miles per MWh of a vehicle type $v \in \{PHEV, BEV\}$ at $t \in T$.
- ζ : percentage of gasoline-driving mode for PHEV.

- $\bar{x}_{v,t}^V$: newly deployed vehicles from year 2010 to 2025. Obtained from the input data and the BAU case.

Decision and Dependent Variables

This section introduces the decision variables and the dependent decision variables.

Decision variables

- $x_{v,t}^V$: quantity of newly deployed vehicles of type $v \in V$ at time $t \in T$.
- $x_{g,t}^G$: quantity of newly deployed generators of type $g \in G$ at time $t \in T$.
- $y_{g,t,\tau}^G$: quantity of forced retired generator capacity of type $g \in G$ of age $\tau \in A^G$ at time $t \in T$.
- p_t : price of each unit of REC at time $t \in T$ decided by the generation sector for $t \geq 2026$.
- R_t : quantity of RECs purchased at time $t \in T$ decided by the LDV sector for $t \geq 2026$.

Dependent variables

- $z_{g,t,\tau}^G$: existing generator capacity of type $g \in G$ of age $\tau \in A_g^G$ at time $t \in T$.
- d_t^{PHEV} : electricity demand from PHEVs at time $t \in T$.
- d_t^{BEV} : electricity demand from BEVs at time $t \in T$.

Thus the total electricity demand in year t is $d_t^G + d_t^{PHEV} + d_t^{BEV}$. All decision and dependent variables are continuous and non-negative.

The Leader's Problem

The model is a Stackelberg game with a leader and a follower. This section introduces the leader's problem, i.e. the optimization problem of the electricity generation sector. No matter the sector, the first objective is always to minimize total cost. However, this paper aims to evaluate the emission reduction performance of a REC purchasing policy. The number of RECs that each sector purchases needs to be calculated. The amount of purchased RECs is positively correlated with the total emissions savings. Therefore, the leader's problem is no longer to minimize the total cost, but to maximize the total purchased RECs while the total cost does not exceed that of the BAU case C_0^G . Note that although our model only minimizes the total cost of the transportation sector, later results will show that in the calculated solution, the total cost of the electricity generation sector is also decreased significantly (see Section for details). The REC purchasing rules can be generalized as follows:

1. At each year, the leader (electricity generation sector) decides the REC price and how much renewable capacity to deploy ($x_{R,t}^G$).
2. $x_{R,t}^G$ (MW) renewable capacity generates $24 \times 365 \times \gamma_R^G x_{R,t}^G$ units (MWh) of RECs (have to be at least $R_{0,t}$ because otherwise