

Life-Cycle Greenhouse Gas and Criteria Air Pollutant Emissions of Electric Vehicles in the United States

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ABSTRACT

While electric vehicles including plug-in hybrid electric vehicles (PHEVs) and battery-powered electric vehicles (BEVs) are considered as promising alternative vehicle/fuel systems to significantly reduce petroleum consumption of the transportation sector, it is important to analyze the emission characteristics and to assess the emission reduction potentials of electric vehicles so that their environmental impacts in terms of climate change, air quality, as well as human health effects could be better understood. To fulfill this objective, we explicitly analyzed the emission characteristics of greenhouse gases (GHG) and criteria air pollutants (CAP, representing VOC, CO, NO_x, PM₁₀ and PM_{2.5}, and SO_x) of the U.S. power sector, a pivotal upstream sector that impacts the life-cycle GHG and CAP emissions associated with electric vehicles. In particular, we established statistically robust probability distribution functions (PDFs) to address the uncertainty and variation in both thermal and environmental performances of various types of power plants that can result in uncertainties of the life-cycle GHG and CAP emissions of electric vehicles. With the detailed characterization of the GHG and CAP emissions from the power sector, we performed a life-cycle analysis (LCA) of the GHG and CAP emissions of electric vehicles in the United States, with the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model developed at Argonne National Laboratory. The LCA results with the inherent uncertainties investigated illuminate the real-world chances of GHG and CAP emission reduction benefits that are influenced by uncertain factors when introducing electric vehicles to displace gasoline vehicles in the United States.

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INTRODUCTION

The U.S. Government has been encouraging shifting from internal combustion engine vehicles (ICEVs) to alternative fuel vehicles such as plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) for the purposes of reducing oil dependence, reducing greenhouse gas emissions, and mitigating Clean Air Act criteria pollutant emissions. Strong push on formulation of climate change mitigation policies has resulted in many of the biggest automobile producers increasing production of PHEVs such as the Chevrolet Volt and Renault Kangoo PHEV, and BEVs currently produced or near production including the Nissan Leaf, Renault Kangoo BEV, Ford Electric Focus, Think, Mitsubishi i-MiEV, and Tesla Roadster [1]. While electric vehicles have been attracting increasing worldwide interest as a promising potential long-term solution to fossil fuel depletion and greenhouse gas (GHG) and air pollutant emissions induced by increasing personal mobility demand, their true potentials to reduce GHG and air pollutant emissions can only be properly assessed by conducting life-

cycle analysis (LCA) of the environmental performances of electric vehicles in comparison with the counterpart conventional ICEVs they intend to displace within the same LCA boundary.

LCA of the energy use and the environmental impacts of electric vehicles dates to the 1990s [2, 3, 4, 5]. Daniel and Rosen [6] adopted the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model to examine the GHG and air pollutant emissions of various vehicle/fuel combinations including electric vehicles that were recharged by the U.S. average electricity generation mix, and indicated that for dedicated electric vehicles, as well as PHEVs, the mix of energy resources used for electricity generation can greatly affect the emissions produced during the fuel life cycle; Kintner-Meyer et al. [7] evaluated the regional variation in GHG and criteria air pollutants (CAP, including CO, VOC, NO_x, SO_x, PM₁₀, and PM_{2.5}) emission reduction potentials by PHEVs; EPRI [8] conducted NERC region based assessment of GHG emissions from PHEVs; both Elgowainy et al. [9] and Samaras and Meisterling [10]

provide detailed analyses of the impacts of electricity use by PHEVs and find increases in all-electric-range of the PHEVs resulted in lower life-cycle GHG emissions except when the electricity generation mix was dominated by coal or oil generation. These studies obtained rich findings on the environmental impacts and emission reduction potentials of electric vehicles in comparison with gasoline vehicles, and revealed the important impacts of the emission intensity of the power sector on the overall life-cycle GHG and CAP emissions of electric vehicles. In this study, our primary objective is to refresh our understanding of the environmental impacts of electric vehicles by thoroughly characterizing the thermal and environmental performances of the U.S. power sector, which has dominant impacts on the environmental performances of electric vehicles, by using the recently available comprehensive generator-level data. Besides, a Monte Carlo based uncertainty analysis is performed with the developed probability distribution functions (PDFs) based on the thoroughly characterized thermal and environmental performances of the power plants by fuel type and combustion technology, to quantify the uncertainties associated with the life-cycle GHG and CAP emissions of electric vehicles in the U.S., and to illuminate the real-world possibility of achieving life-cycle GHG and CAP emission reduction by electric vehicles compared to the gasoline counterparts, which deserves more efforts on this important issue due to limited studies so far [11].

METHODS AND DATA

LCA Boundary

The Well-to-Wheels (WTW) approach, which covers the feedstock production and transport, as well as fuel production, distribution and use, whilst omitting the vehicle life cycle associated with the manufacturing, distribution, maintenance and disposal of raw material, components and whole vehicle assembly, is applied in this study. This means that our analysis focuses on the fuel cycle analysis, assessing the impacts of the U.S. power sector on the environmental impacts of electric vehicles, while the vehicle cycle dealing with the potential contributions by vehicle production, particularly battery manufacture for PHEVs and BEVs, is not included by our LCA boundary, since the differences relating to vehicle production are relatively minor within the context of the life cycles of BEVs using fossil-based electricity as the use phase, which is responsible for 60-90% of life cycle GHG emissions [1].

The WTW GHG and CAP emissions of U.S. electric vehicles and gasoline ICEVs are calculated by using the fuel-cycle model developed and consistently being updated by Argonne National Laboratory - the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model [12,13]. In GREET, the CH₄, N₂O, and CAP emissions from Well-to-Pump (WTP) activities of each fuel production pathway are calculated based on the use of various process fuels in each activity along the pathway as

well as the emission factors of the different combustion technologies using these fuels. For CO₂ emissions, GREET takes a carbon-balance approach by subtracting the carbon contained in combustion emissions of VOC, CO, and CH₄ from the carbon contained in the fuel burned [12], with the carbon in VOC and CO oxidized back into CO₂. The vehicle technologies assessed in this work are passenger BEVs utilizing electricity from a variety of generation mixes and PHEV10 and PHEV40 with an operational all-electric-range of 10 and 40 miles, respectively, and charged by the U.S. average generation mix, which are compared with baseline gasoline ICEVs. The target year for analysis is set to be 2015, when BEVs and PHEVs are expected to be commercially available on the U.S. market. Besides, the functional unit used in this work is per mile driven.

Well-to-Pump Emissions

For electric vehicles, characterization of the GHG and CAP emission burdens from electricity generation is pivotal to quantify the WTP emissions induced by electric vehicle operations. The emission factors of the U.S. power sector differ by fuel types, like coal, natural gas, residual oil and biomass, and by combustion technologies, like boilers, turbines, internal combustion engines, and combined cycles, and therefore require explicit investigation to characterize. In this study, we made tremendous efforts to update these GHG and CAP emission factors of the U.S. power sector based on available databases from the U.S. Environmental Protection Agency and the U.S. Energy Information Administration.

CO₂, CH₄, N₂O, NO_x and SO_x emission factors

With the recent release of the Emissions & Generation Resource Integrated Database, known as eGRID [13], which contains comprehensive unit-level emission data for electric generating units (EGUs) and plant performance data like the heat input and electricity generation for a total of 5172 power plants for year 2007, we calculated the CO₂, CH₄, N₂O, NO_x and SO_x emission factors for each plant in the power generation sector, which are required to perform life-cycle analyses using GREET. We calculated the averaged CO₂, CH₄, N₂O, NO_x and SO_x emission factors by fuel type and combustion technology by dividing the annual total emissions by the annual total net electricity generated (NEG) that is supplied to the grid from that technology, as shown in Equation (1).

$$EF_{p,f,ct} = \frac{\sum_i Emission_{p,f,ct,i}}{\sum_i NEG_{f,ct,i}} \quad (1)$$

Where $EF_{p,f,ct}$ (expressed in g/kWh) is the averaged emission factor of a GHG species or pollutant p (e.g., NO_x or SO_x) emitted by all power plants burning fuel f using combustion technology ct ; $Emission_{p,f,ct,i}$ (expressed in

grams) is the emissions of a GHG species or pollutant p from power plant i burning fuel f using combustion technology ct ; and $NEG_{f,ct,i}$ (expressed in kWh) is the net electricity generated by power plant i burning fuel f using combustion technology ct .

To obtain $Emission_{p,f,ct,i}$, we first sort the plants in eGRID by fuel type based on the primary fuel type indicated by eGRID: (1) coal, including the subtypes of bituminous coal (BIT), subbituminous coal (SUB), lignite (LIG), syncoal (SC), waste coal (WC), petroleum coke and tire-derived fuel; (2) natural gas (NG), including the subtypes of NG, landfill gas (LFG), blast furnace gas, digester gas, other gases, and other unknown; (3) oil, including the subtypes of residual fuel oil (RFO), distillate fuel oil (DFO), jet fuel (JF), kerosene, and waste oil; and (4) biomass, including the subtypes of woody biomass solid (WDS), woody biomass liquid, black liquor, agricultural byproduct, biomass component of municipal solid waste, other biomass solid, and other biomass liquid. While most power plants employ a single fuel type, a small percentage of power plants burn multiple fuel types. For multiple-fuel-fired plants, the primary fuel type employed by the prime mover with the largest nameplate capacity is recognized as the primary fuel type for that plant.

Next, we sort plants of the same fuel type by combustion technology, using information on the prime mover type of each generator within each power plant as provided in eGRID. Since many plants have multiple generators driven by different prime mover types, the prime mover type of the generators whose summed capacities represent the largest fraction of the entire capacity of a power plant is recognized as the prime mover type of that plant. For these plants, the $NEG_{f,ct,i}$ is determined by the annual electricity generation of power plant i burning fuel type f with the combustion technology ct that defines the prime mover type of that plant.

To avoid the biases caused by individual EGUs with unrealistically high or low emission factors, these potential outliers are detected using the modified Z-score, which is defined by Equation (2) [14]:

$$M_i = \frac{0.6745 \times (x_i - \tilde{x})}{\text{median}(|x_i - \tilde{x}|)} \quad (2)$$

Where M_i is the modified Z-score; x_i are the GHG and CAP emission factors of an individual EGU $_i$; $\tilde{x}$ is the median GHG and CAP emission factor of all EGUs; and

$\text{median}(|x_i - \tilde{x}|)$ is the median absolute deviation.
 x_i is calculated from Equation (3):

$$x_i = \frac{Emission_i}{NEG_i} \quad (3)$$

Where $Emission_i$ is the annual GHG or CAP emission of an individual EGU $_i$; and NEG_i is the annual net electricity generation of an individual EGU $_i$.

Equation (2) was performed for each specific GHG and CAP emission factor of EGUs using the same fuel subtype and combustion technology. Potential outliers are detected when the modified Z-scores have an absolute value of greater than 3.5. Although the median absolute deviation has been recognized to be a robust measure for outlier detection, there is a possibility that the detected outliers could be due to real fluctuation in the data. Therefore, an additional rejection threshold for outlier detection was set at 1.96 standard deviations (σ) of the observations, to allow for real fluctuation in the data. Emission factors with Z-scores larger than 3.5 and exceeding the rejection threshold are removed before Equation (1) is employed to calculate the GHG and CAP emission factors by fuel subtype and combustion technology.

CO, VOC, PM₁₀ and PM_{2.5} emission factors

Owing to the lack of direct information on CAP emissions other than NO_x and SO_x in eGRID, we utilized the internet version of the Factor Information Retrieval Data System (WebFIRE¹) [15] and data in the open literature, in conjunction with heat input and NEG data in eGRID, to derive the emission factors of CO, VOC, PM₁₀ and PM_{2.5}.

We employed the fuel-use-related information from eGRID (annual heat input by plant) and the emission factors (expressed in g/unit fuel use) from WebFIRE or the open literature for each specific fuel and combustion technology to calculate CO, VOC, PM₁₀ and PM_{2.5} emission factors using Equation (4) [12]:

$$EF_{out,p,f,ct} = \frac{\sum_i \sum_{ec} \frac{HI_{f,ct,i}}{HHV_f} \times EF_{in,f,ct,p} \times (1 - ER_{p,ec})}{\sum_i NEG_{f,ct,i}} \quad (4a)$$

$$EF_{out,p,f,ct} = \frac{\sum_i \sum_{ec} HI_{f,ct,i} \times EF'_{in,f,ct,p} \times (1 - ER_{p,ec})}{\sum_i NEG_{f,ct,i}} \quad (4b)$$

Where $EF_{in,f,ct,p}$ is the uncontrolled emission factor of CAP p for EGUs burning fuel type f using combustion technology ct in grams per ton of coal or WDS, per 1000 gallons of oil, or per million standard cubic feet of NG; $EF'_{in,f,ct,p}$ is the uncontrolled emission factor of CAP p for

¹WebFIRE is a database management system containing EPA's recommended emission factors for criteria and hazardous air pollutants (<http://cfpub.epa.gov/webfire>).

EGUs burning fuel type f using combustion technology ct in g/mmBtu; $ER_{p,ec}$ is the emission reduction efficiency of CAP p using control technology ec ; $HI_{f,ct,i}$ is the annual heat input (based on the fuel's higher heating value, HHV) to plant i from the burning of fuel type f using combustion technology ct , in mmBtu; HHV_f is the HHV of fuel type f , in mmBtu; $NEG_{f,ct,i}$ is the annual net electricity generation by plant i burning fuel type f using combustion technology ct ; and $EF_{out,p,f,ct}$ is the emission factor of CAP p for EGUs burning fuel type f using combustion technology ct , in g/kWh of NEG.

For EGUs fired by a specific fuel type, $HI_{f,ct,i}$ and $NEG_{f,ct,i}$ are obtained from eGRID. For BIT-, SUB-, LIG-, NG-, RFO-, DFO-, JF- and WDS-fired EGUs, the HHV_f values are obtained from the fuel specifications incorporated in GREET 1_2012. The HHV, rather than the lower heating value (LHV), is adopted because HHV is used for calculating the heat input in eGRID, which is originally obtained from EPA's CAMD [16] or EIA's Form 923 data [17] when the former is not available. For other fuel-fired EGUs which account for a small percentage of the total generation, e.g.,

$$\frac{HI_{f,ct,i}}{HHV_f}$$

SC-, WC- and LFG-fired EGUs, the term $\frac{HI_{f,ct,i}}{HHV_f}$ in Equation (4-1), representing the quantity of fuel consumption, is obtained from EIA's Form 923 data [17].

As mentioned earlier, $EF_{in,f,ct,p}$ and $EF'_{in,f,ct,p}$ are mainly obtained from WebFIRE. WebFIRE includes information about various industries and their processes, the chemicals emitted, and the associated emission factors. WebFIRE allows easy access to criteria and hazardous air pollutant emission factors obtained from the Compilation of Air Pollutant Emission Factors (AP-42) [18], the Locating and Estimating documents [19], and the retired Aerometric Facility Subsystem Emission Factors and Crosswalk/Air Toxics Emission Factors documents.

We used a four-step procedure to determine the emission factors from WebFIRE for each type of EGU burning a specific type of fuel using a certain combustion technology with a particular control technology. For example, the CAP emission factors of a BIT-fired power plant using a cyclone furnace can be obtained by following these four steps:

Step 1. Identify the combustion technology, e.g., external combustion boilers;

Step 2. Identify the emission source category, i.e., electricity generation sector;

Step 3. Identify the fuel type, e.g., bituminous/subbituminous coal;

Step 4. Identify the combustion technology type and emission control technology, e.g., pulverized coal, cyclone furnace.

Usually, the above four-step procedure narrows down the emission factors to one set of CAPs reflecting the effects of

the boiler type, the firing type and the specific emission control measures in operation. It is therefore necessary to identify the combustion technology type and the emission control measures in operation at each EGU covered in eGRID in order to obtain the appropriate emission factor from WebFIRE. Here, the boiler type and firing type of individual EGUs are obtained from EPA's CAMD [16]. Furthermore, EPA's CAMD unit-level data, including information on emission control equipment at existing EGUs [16], are used to identify the different emission control measures adopted by each EGU.

PM₁₀ and PM_{2.5} emission factors are complex functions of boiler bottom and firing configuration, boiler operation, pollution control equipment, and fuel properties. Here, the plant-level-controlled PM emission factors are calculated using Equation (5), which accounts for the emission reduction efficiency of the emission control technology and the prime mover-level heat input as obtained from EPA's CAMD. The uncontrolled emission factors and some controlled emission factors are obtained from WebFIRE. The emission reduction efficiencies of control technologies are based on AP-42 and open-literature data, and the fuel quality data are from EIA [20].

$$EF_{PM_{controlled},f,ct,i} = EF_{PM_{uncontrolled},f,ct,i} \times \sum_j [(1 - ER_j) \times HI(\%)_j] \quad (5)$$

Where $EF_{PM_{controlled},f,ct,i}$ and $EF_{PM_{uncontrolled},f,ct,i}$ are the controlled and uncontrolled PM emission factors, respectively, for plant i burning fuel type f using combustion technology ct ; ER_j is the emission reduction efficiency of control technology j , such as electrostatic precipitator or baghouse; and $HI(\%)_j$ is the heat input share of generators that are employing control technologies j within the same plant.

Following the methodology we developed, the GHG and CAP emission factors by fuel type and combustion technology for the power sector in the U.S. are finally calculated, as summarized by Table 1.

Thermal efficiencies

Since the LHV of fuels are used by default in GREET to evaluate transportation fuels, we calculate the LHV-based energy efficiencies for EGUs employing the same fuel type and combustion technology, using Equation (6):

$$\eta_{LHV,f,ct} = \frac{elec.gen._{f,ct} \times kWh2mmBtu}{heatinput_{f,ct} \times \frac{LHV_f}{HHV_f}} \times 100\% \quad (6)$$

Where $\eta_{LHV,f,ct}$ is the LHV-based energy efficiency (%) by fuel type and combustion technology; $elec.gen._{f,ct}$ is the net electricity generation (kWh) by fuel type and combustion technology; $kWh2mmBtu$ is the unit converter of per-kWh electricity to mmBtu, which is 3412 Btu per kWh;