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A hybrid life cycle assessment of the vehicle-to-grid application in light duty commercial fleet

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ABSTRACT

The vehicle-to-grid system is an approach utilizing the idle battery capacity of electric vehicles while they are parked to provide supplementary energy to the power grid. As electrification continues in light duty vehicle fleets, the application of vehicle-to-grid systems for commercial delivery truck fleets can provide extra revenue for fleet owners, and also has significant potential for reducing greenhouse gas emissions from the electricity generation sector. In this study, an economic input–output based hybrid life cycle assessment is conducted to analyze the potential greenhouse gas emissions emission savings from the use of the vehicle-to-grid system, as well as the possible emission impacts caused by battery degradation. A Monte Carlo simulation was performed to address the uncertainties that lie in the electricity exchange amount of the vehicle-to-grid service as well as the battery life of the electric vehicles. The results of this study showed that extended range electric vehicles and battery electric vehicles are both viable regulation service providers for saving greenhouse gas emissions from electricity generation if the battery wear-out from regulation services is assumed to be minimal, but the vehicle-to-grid system becomes less attractive at higher battery degradation levels.

1. Introduction

The U.S. electricity sector (including the generation, transmission and distribution of electricity) is the largest GHG (greenhouse gas) emission contributor in the U.S., accounting for about 31% of the total national GHG emissions [1]. Due to an increasing demand for electricity in today's world, GHG emissions from the electricity sector have grown significantly. Meanwhile, fossil fuels have remained the dominant electricity sources in the U.S., with only about 10% of electricity generation coming from renewable sources [2]. Furthermore, electricity (as an “unusual” commodity) has a unique nature in that its generation and consumption must take place simultaneously for it to be truly efficient; otherwise, if the demand for electricity is less than its generation level, the abundant electric power generated is ultimately wasted because, aside from the limited power storage of hydroelectric pumps, the current power grid has very little storage capacity [3]. On the other hand, extra electricity must be generated on short notice if the peak hour demand exceeds scheduled generation; this is now mainly accomplished by turning large generators on and off to meet the fluctuating end user load [4]. Nevertheless, studies have revealed that electricity storage methods are not only helpful for smoothing out grid fluctuations in a much shorter response time, but may also be two to three times as effective as a conventional gas turbine for grid supporting purposes [5].

The total power capacity of U.S. light vehicles is 24 times that of the whole utility system [6]. Furthermore, EVs (Electric Vehicles) are expected to have a growing market penetration in the future with the introduction of government incentives and large-scale battery production. Therefore, with respect to the electric grid, the future light vehicle fleet is potentially a huge power source. A study by Kempton et al. shows that vehicles are parked 90% of the time [7], during which time they can be plugged in to support or store extra electricity for the grid, and this long idle time makes it economically more suitable for utility companies to purchase electricity from fleet operators or private EV owners instead of purchasing expensive stationary batteries.

There are four types of electricity markets:

- The first market provides **base-load power** via large coal-powered or nuclear-powered power plants on a round-the-clock basis. Base-load electricity has the lowest price, but base-load generators usually take days to start or shut down.

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- The second market is the **peak power** market. Peak power is purchased when a higher level of electricity demand/consumption than usual is expected for a relatively short period of time. And only several hundreds of hours of peak power supply are needed per year.
- **Spinning reserves** and **regulation services**, are also known as **ancillary services**, and are priced separately from the large-scale power generation markets described above. Spinning reserves provide backup capacity to the grid, and respond immediately in the event of a power plant failure or other such emergency. Regulation services are used to stabilize the system's voltage and to maintain the grid frequency as close to the required 60 Hz as possible; based on demand fluctuations and/or the signals from ISOs (Independent System Operators) and/or RTOs (Regional Transmission Organizations), the regulation service provider will ramp up or ramp down the generator power output as necessary.

Although electric passenger cars have undoubtedly the largest capacity potential available, the willingness of users to provide V2G (vehicle-to-grid) services remains unclear, whereas a small amount of vehicle connection would only add noise to the power grid [8]. Therefore, this study will use commercial delivery fleet vehicles as its research objective, as the operation and/or parking times of such fleet vehicles tend to be more predictable [9]. Also, electric truck batteries usually have large capacities, as 18 light trucks with average outputs of 60 kW are able to provide a maximum of 1 MW in electricity support [10], which is a typical ancillary service contract's minimum quantity [6]. Based on this data, a fleet of 20–30 electric vehicles would have the potential to be an ancillary electricity provider.

Electricity provided by vehicles has been proven to be far less competitive in the base-load market than conventional large-scale power plants, which tend to have lower generation costs [11]. Likewise, peak power generation, due to its relatively predictable pattern, can still be achieved by adjusting generator output. Ancillary services, on the other hand, accounted for 5%–10% of electricity costs (a $12 billion market value), and 80% of this payment is made for spinning reserves and/or regulation services [12]. The high electricity unit price and the short but rapid power demand requirements of these ancillary services make V2G a perfect option. However, since spinning reserve services would require the vehicle(s) in question to be plugged in all the time [10], which may jeopardize the fleet's normal business operation, this study will only consider the use of the V2G system for regulation services.

2. Literature review

The economic as well as the life cycle environmental impacts incurred by the manufacturing and operation of electric vehicles have been presented in the literature [13]. The GHG and traditional air pollutant emission of hybrid and battery electric vehicles have also been compared to traditional vehicles from a life cycle perspective [14]. Zhang et al. presented the GHG emission impact and charging cost of electric vehicles in different operating conditions, and the "smart grid charging" (providing V2G service) scenario has been proved to be more economically appealing [15]. Kempton et al. [7] conducted a study comparing the availability and capacity of BEVs (battery electric vehicles), HEVs (hybrid electric vehicles) and fuel cell vehicles, as well as the relevant costs of V2G application and the value of the V2G system from the perspectives of utility companies and customers. The fundamental elements of the V2G system have also been researched in two different studies in terms of both market availability [6] and vehicle owner's revenue [4], the former of which revealed that V2G technologies are highly suitable for electricity ancillary services (more specifically, regulation services) and also designed and analyzed real life V2G operation strategies and business models. The latter study offered a quantitative understanding of the revenues of various types of vehicles as well as how electric vehicles can be incorporated as part of the grid. Theoretically, BEVs, HEVs and fuel cell vehicles can all be connected to the grid and provide electric power, but only HEVs and BEVs were considered in this study because there is no currently available fuel cell vehicle that has power grid accessibility. Sioshansi and Denholm simulated the V2G system's ancillary services through a unit commitment model and thereby proved its positive effects to the grid and to vehicle fleet owners, demonstrating that HEVs providing grid supporting services take less time than other vehicle types to repay the initial capital investments [16].

In addition, an experiment has been performed using a real life HEV for frequency regulation service [17], during which the regulation signal/value and the battery SOC (state of charge) during connection were recorded and analyzed. Guille and Gross analyzed the features of the V2G system's components and proposed a possible framework based on their analysis, as well as possible V2G implementation procedures [8]. The operational cost as well as benefits of electric vehicles providing V2G services in a smart grid have been analyzed [18]. More specifically, an upcoming EREV (Extended Range Electric Vehicle) has been studied in terms of commercial truck fleet owners' economic risks and benefits [10], and scenarios are assumed based on the uncertainty of battery regulation cycle lifetimes and the unpredictability of regulation signals. Similarly, the integration of electric commercial fleets to the grid has been proven to be reasonable and profitable [9]. The long-term impact to global energy system and electricity market brought by V2G application has been explored and discussed [19].

In addition to the economic aspects covered previously, the GHG reduction potential of vehicle-to-home (passenger car V2G system) was also studied from a life cycle perspective [20], while another study calculated GHG emission impacts in the U.S. based on various HEV market penetrations with V2G services [21]. Battery degradation, as the most important trade off consideration in V2G application, has also been evaluated in multiple studies: Cicconi et al. summarized the lifetime of typical vehicle batteries and presented that second-life batteries can be reused in V2G systems [22]. In addition, the battery degradation caused by V2G service has also been proved to be minimal [23]. The aforementioned literature summarized the feasibility of the V2G system and the roles and functions of HEVs or BEVs within the system, as well as the positive economic and environmental effects of fleet-level electricity storage. However, few studies are currently available that have analyzed the GHG emission impacts caused by integrating V2G technology into a commercial delivery truck fleet. To this end, this study will conduct an Input-Output based hybrid life cycle assessment with respect to both EREVs and BEVs, first under a "business as usual" scenario (i.e. without the V2G system included), and a "V2G regulation service" scenario to simulate the impacts of the V2G system.

3. Methods

3.1. Scope of the analysis

As mentioned before, our research objectives more specifically pertain to HEVs and BEVs. However, the mass-produced conventional hybrid vehicles have considerably less electric drive power than mechanical power, and have low capacity batteries (1–2 kWh) and no connections to the grid, making them far less viable than other electric vehicle types as V2G units in the fleet [4]. On the