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Well-to-wheels energy consumption and emissions of electric vehicles: Mid-term implications from real-world features and air pollution control progress

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HIGHLIGHTS

- We conduct a fine-grained WTW analysis to the city level based on real-world data and end-of-pipe control progress.
- Beijing's BEVs can reduce WTW CO_2 emissions than MPFI even in a coal-rich region.
- Increasing non-fossil power plus improved flue gas control can lower WTW NO_X emissions of BEVs.
- This study provides a timely contribution to promote e-mobility in a megacity for sustainability concerns.

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ABSTRACT

Previous well-to-wheels (WTW) analyses on electric vehicles (EVs) have reported tremendous results of potential energy and environmental effects. However, there remains a challenge to lower the uncertainties that were introduced when obtaining life-cycle parameters from a macro perspective (e.g., nationwide or regional scales). This study takes Beijing as a case, because it is an important regional hub for EV promotion and represents megacities with severe urban air pollution issues and congested traffic conditions. We collected up-to-date data concerning the electricity generation mix, fuel transport, end-of-pipe controls, real-world fuel economy and emissions, and estimated the WTW energy consumption and CO_2 and air pollutant emissions for various light-duty passenger vehicle technologies currently (2015) and in the mid-term future (2030). Unlike previous results, battery electric vehicles (BEVs) are shown to significantly reduce WTW CO_2 emissions by 32% for the present model year (MY) 2015 compared with their conventional gasoline counterparts, primarily due to the shift from coal to gas in local power plants in Beijing and the significantly higher real-world fuel consumption of conventional vehicles compared with the type-approval value. By 2030, WTW CO_2 emissions by BEVs should approach 100 g km^{-1} due to the increased importation of non-fossil electricity, even lower than that of hybrid electric vehicles. Furthermore, significant improvements in end-of-pipe controls for coal-fired power plants have effectively lowered WTW emissions of air pollutants. In terms of VOCs and NO_X that are of most concerns among all pollutants emitted from passenger vehicles, the WTW emissions of VOCs for MY 2015 BEV are already significantly lower than their conventional counterparts by 95%. Although WTW NO_X emissions for BEVs are currently higher by 66% than conventional gasoline vehicles, we expect that BEVs can achieve WTW emission reduction benefit of NO_X (41%) by 2030. This study indicates the

Abbreviations: AER, all electric range; BEV, battery electric vehicle; CD, charge depleting; CEMS, continuous emission measurement system; CO_2, carbon dioxide; CS, charge sustaining; EMBEV, the EMission factor model for the BEijing Vehicle fleet; EV, electric vehicle; FGD, flue gas desulfurization; GDI, gasoline direct injection; GPF, gasoline particle filter; GPS, global positioning system; GREET, the Greenhouse gases, Regulated Emissions, and Energy use in Transportation model; HEV, hybrid electric vehicle; HPC, hybrid particulate collector; ICEV, internal combustion engine vehicle; JJJ, the Jing-Jin-Ji region, including Beijing, Tianjin and Hebei; LDPV, light duty passenger vehicle; LEV, low emission vehicle; LNG, liquefied natural gas; MPFI, multiport fuel injection; MY, model year; NGCC, natural gas combined cycle; NO_X, nitrogen oxides; ORVR, on-board refueling vapor recovery; PHEV, plug-in hybrid electric vehicle; $PM_{2.5}$, fine particle matter, with the aerodynamic diameter less than 2.5μm; SCR, selective catalytic reduction; SO_2, sulfur dioxide; TTW, tank-to-wheels; UF, utility factor; USC, ultra supercritical; VOCs, volatile organic compounds; WLTP, worldwide harmonized light vehicle test procedures; WTW, well-to-wheels; WTT, well-to-tank.

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significance of fine-grained and real-world features when assessing the WTW energy and environmental effects of EVs.

1. Introduction

Hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) have been globally developed in the past years. The development of electric vehicles (EVs, including PHEV and BEV, hereinafter) could enhance the fuel diversity and utilize renewable energy (e.g., renewable electricity), which is considered a promising long-term solution to reduce high dependence on fossil fuels and alleviate climate change impacts from a global perspective [1]. In addition, the EV deployment is considered capable of improving urban air quality by reducing on-road emissions for traffic-populated areas [2]. Many countries have provided substantial fiscal policies (e.g., subsidy and tax exemption) [3,4], leading to a rapid growth of the global EV sales [5]. Approximately 550,000 electric passenger vehicles were sold globally in 2015, which was a 72% increase from a year ago [6].

Researchers have discussed whether EVs, particularly BEVs, would be as "clean" or energy-saving as expected compared with internal combustion engine vehicles (ICEVs) for quite a long while [7]. To address this issue, previous studies mostly applied the life-cycle assessment method and estimated well-to-wheels (WTW) energy consumption and emissions for various propulsion and fuel systems [8–18]. These WTW analyses were mostly conducted at national or regional levels, which were generally compatible to the research scale of power grids. Nevertheless, in the early stage of deploying EVs, the market penetration of EVs is largely influenced by stimulative or supportive schemes, which would significantly vary from city to city and further lead to a spatial heterogeneity of EV diffusion. Thereby, using macro-scale average data would lead to great uncertainties in the life-cycle energy and environmental benefits from promoting EVs.

When the research scope is more fine-grained and real-world orientated, such as down to the city level, several aspects of city-level features are crucial to WTW energy consumption and emissions for on-road vehicles. First, real-world traffic conditions [19–21] and vehicle usage profiles [22,23] are leading factors affecting on-road energy consumption, emissions and actual electrified mileage for EVs [24,25]. For example, Rangaraju et al. reported the importance of applying real-world energy consumption data when evaluating WTW emissions of EVs in Belgian [24]. Traffic conditions and vehicle usage characteristics are affected by population density, vehicle ownership, accessibility of public transportation system, and local traffic regulations, which can be greatly different from inner cities and metropolitan areas [22]. Second, it is noted that recent studies have identified the gap between real-world fuel consumption and type-approval levels for modern ICEVs can exceed 30% [19,26], which suggests substantial underestimates of WTW energy consumption and emissions for previous studies which were based on type-approval data or lower road-to-lab ratios [12,13]. Third, rapid progresses regarding air pollution control and energy structure optimization (e.g., promoting non-fossil fuels) have been made in several developing countries (e.g., China) [27], which could be in a more aggressive pace for megacities with frequent pollution episodes (e.g., Beijing) [28]. Therefore, more localized and real-world features as well as from the update of air pollution control processes should be taken into account to improve current macro-level analysis of WTW energy and emissions for on-road vehicles.

In 2015, China has achieved total annual sales of 331,000 EVs and become the leader in the global EV market for the first time and stronger market performances are expected in the future years for China [29,30]. In some megacities with favorable policies for developing EVs, the growth momentums of EV sales are more powerful than inner cities. For example, in Beijing, the city's license control policy now annually assigns 60 thousand license plates to EVs, which makes up 40% of newly registered passenger cars [31]. However, many studies [8,12–15] including our previous results [8,14] highlighted a concern that the extremely high share of coal-fired electricity in total regional power generation mix (approximately 95%) could result in negative benefits in WTW energy consumption and emissions from fleet electrification in the Beijing-Tianjin-Hebei (JJJ) region. As the concerns we noted above, a city-level report regarding WTW energy consumption and emissions of air pollutants by taking account of real-world impacts and up-to-date changes is required for Beijing [28]. In this paper, we explicitly select Beijing as a case city and compare WTW energy consumption and emissions of greenhouse gases (CO_2) and major air pollutants among HEVs, PHEVs, BEVs and ICEVs in 2015 (i.e., present) and through 2030 (i.e., mid-term future). Furthermore, using a sensitivity analysis of key parameters, implications regarding real-world features and air pollution control progress are explored in detail. This study is a first-ever report to assess WTW emissions of air pollutants for current and future LDPV technologies in China based on sufficient data concerning real-world emissions of air pollutants, on-road fuel consumption and vehicle usage together. The results highlight the significance of fine-grained and real-world features when assessing the WTW energy and environmental effects of EVs, and can provide policy makers with a timely and useful evaluation for the fleet electrification.

2. Method and data

2.1. Scope and model

We calculated the WTW energy consumption and emissions for diverse vehicle propulsion and fuel combinations (e.g., ICEVs, HEVs, PHEVs and BEVs) for Beijing's light-duty passenger vehicle (LDPV) generations in the model years (MY) of 2015 and 2030, which represent the status quo and midterm future scenarios, respectively. For ICEVs, we considered two types of gasoline engine technologies: multiport fuel injection (MPFI) and gasoline direct injection (GDI). For PHEVs, the specific all-electric range (AER) of 20 km (i.e., PHEV20) was considered, close to the rated AER of Prius Plug-in, of which the real-world data on energy efficiencies and pollutant emissions were collected by on-road tests (see Tables 1 and S1). For energy-related metrics, distance-based petroleum use and fossil-fuel use were selected in this study. In addition to CO_2 emissions, the distance-based emissions of primary $PM_{2.5}$, nitrogen oxides (NO_X), volatile organic compounds (VOCs) and sulfur dioxide (SO_2) were also estimated.

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model (GREET1_2012), developed by the Argonne National Laboratory, U.S. Department of Energy, was applied as the computational platform for calculating the WTW energy use and emissions of various fuel pathways, which combine the upstream well-to-tank (WTT) stage (e.g., extraction, production,