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The potential impacts of electric vehicles on air quality in the urban areas of Barcelona and Madrid (Spain)

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HIGHLIGHTS

- Modelling air quality impacts upon EV introduction in Barcelona and Madrid.
- EV offers potential air quality improvements, especially related to NO_2 and CO.
- Lower improvements related to PM due to the high weight of non-exhaust emissions.
- A high EV introduction is required (26–40%) to significantly improve air quality.
- Electricity generation emissions due to EV charging imply slight NO_2 rises (<3 μg m^{-3}).

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ABSTRACT

This work analyses the potential air quality improvements resulting from three fleet electrification scenarios (~13, 26 and 40%) by replacing conventional vehicles with Electric Battery Vehicles (EBVs), Plug-in Hybrid Electric Vehicles (PHEVs) and Hybrid Electric Vehicles (HEVs). This study has been performed for the cities of Barcelona and Madrid (Spain), where road transport is the primary emission source. In these urban areas, several air quality problems are present, mainly related to NO_2 and particulate matter. The WRF-ARW/HERMESv2/CMAQ model system has been applied at high spatial (1×1 km^2) and temporal (1 h) resolution. The results show that fleet electrification offers a potential for emission abatement, especially related to NO_x and CO. Regarding the more ambitious scenario (~40% fleet electrification), reductions of 11% and 17% of the total NO_x emissions are observed in Barcelona and Madrid respectively. These emissions reductions involve air quality improvements in NO_2 maximum hourly values up to 16%: reductions up to 30 and 35 μg m^{-3} in Barcelona and Madrid, respectively. Furthermore, an additional scenario has been defined considering electric generation emissions associated with EBVs and PHEVs charging from a combined-cycle power plant. These charging emissions would produce slight NO_2 increases in the downwind areas of <3 μg m^{-3}. Thus, fleet electrification would improve urban air quality even when considering emissions associated with charging electric vehicles. However, two further points should be considered. First, fleet electrification cannot be considered a unique solution, and other management strategies may be defined. This is especially important with respect to particulate matter emissions, which are not significantly reduced by fleet electrification (<5%) due to the high weight of non-exhaust emissions. Second, a significant introduction of electric vehicles (26–40%) involving all vehicle categories is required to improve urban air quality.

1. Introduction

Air pollution is a major environmental risk to health (WHO, 2011; 2013). A significant proportion of Europe's population live in cities, where exceedances of air quality standards occur. In 2011, 42% of traffic stations reported exceedances of the nitrogen dioxide (NO_2) annual limit value (40 μg m^{-3}). Regarding particulate matter (PM) with a diameter up to 10 μm (PM_{10}), the 24-h limit value (50 μg m^{-3}) was exceeded at 43% of traffic sites. In terms of potential to harm human health, the finer PM; up to 2.5 μm ($PM_{2.5}$) is the fraction of most concern. The $PM_{2.5}$ target value threshold (25 μg m^{-3}) was exceeded at 10% of traffic sites (EEA, 2013). In

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Spain, higher NO_2 levels occur in major urban areas such as Barcelona and Madrid. The annual limit value was exceeded in both areas in 2011, while the hourly limit value (200 μg m^{-3}) was also exceeded in Madrid. These areas also recorded air quality problems related to PM_{10}, while the $PM_{2.5}$ target value threshold was not exceeded (MAGRAMA, 2012).

The largest contribution of atmospheric pollutant emissions in urban areas today is from on-road transport (Colvile et al., 2001; Belis et al., 2013). In recent years, there have been significant efforts to study the effects of strategies designed to reduce on-road traffic emissions and the subsequent impacts of these emissions on air quality. Currently, the main objectives of these strategies are either 1) reducing the emission per vehicle by adopting lower-polluting fuels and technologies (fleet renewal by updating the vehicle emission standards, e.g., Che et al., 2011; natural gas vehicles, e.g., Gonçalves et al., 2009; fuel cell vehicles, e.g., Stephens-Romero et al., 2009; use of biofuels, (e.g., Liaquat et al., 2010), or 2) adopting mobility management strategies to reduce either the maximum speed of circulation (e.g., Baldasano et al., 2010), or the vehicle kilometres travelled (VKT) (e.g., Soret et al., 2011).

Fleet electrification is one of the strategies under consideration for improving urban air quality. It comprises a wide spectrum of technology options that range from the early stages of hybrid vehicles to pure electric battery vehicles (EBVs). Hybrid electric vehicles (HEVs) represent the first step away from a purely combustion engine vehicle, allowing reduced fuel consumption compared to conventional gasoline or diesel vehicles (CVs). Furthermore, plug-in hybrid electric vehicles (PHEVs) can be also charged from a power grid and can be driven in electric mode over longer distances and higher speeds than HEVs (Pistoia, 2010). Finally, EBVs are entirely propelled by stored electricity with no direct exhaust emissions. Thus EBVs and PHEVs (hereafter referred to as electric vehicles, EVs) would help to reduce road transport emissions. Because of the limited driving range in electric mode, EVs are particularly suitable to improve urban air quality, where short distances and low speeds are prevalent. Furthermore, higher potential benefits of reducing air emissions are found in highly populated areas (Ayalon et al., 2013). Depending on the type of power plant which supplies electric energy for EV, other potential benefits that can be attributable to fleet electrification are an increase in energy efficiency, and reductions in: energy dependence, fuel consumption and greenhouse gas (GHG) emissions (ETC/ACC, 2009).

However, EVs entail an additional load on the electricity power system, resulting in increased emissions from electrical generation, dependent on power mix. EPRI (2007a,b) forecasted fleet electrification in the United States and determined that their electric demand will cause an increase in coal-fired capacity. That study showed significant GHG emission reductions. However, modest effects on nitrogen oxides (NO_x) and sulphur dioxide (SO_2) were found, and there was even the possibility of increases in PM in certain areas. In this way, several studies have explored emission reductions based on fleet electrification, considering various factors related to the percentage of electric vehicle introduction and the power source affected by EV demand (e.g., Jansen et al., 2010; Ji et al., 2012). A clear majority of these studies focus on vehicle charging at night, coinciding with periods of lower electrical demand; this approach helps to improve the overall utility system performance and allows for the least expensive electrical production (Parks et al., 2007). Beyond emissions analyses, the number of studies concerning the air quality impact of fleet electrification is lower, and, in most cases, the spatial resolution used (EPRI, 2007b: 36 × 36 km^2) does not allow for extracting urban air quality conclusions. In other cases, despite the spatial resolution increase (e.g., Thompson et al., 2009, 2011; 12 × 12 and 2 × 2 km^2) only ozone (O_3) variations are analysed.

The main objective of this work is to analyse how fleet electrification (introduction of EBVs, PHEVs and HEVs) would reduce present urban emissions and improve air quality levels (NO_2, PM_{10}, $PM_{2.5}$, O_3, SO_2 and CO) in the urban areas of Barcelona and Madrid. Three fleet electrification scenarios are compared with the Base Case scenario. Furthermore, for the case of Barcelona, an additional scenario has been defined, considering overnight electric generation emissions associated with EV charging in a natural gas combined-cycle power plant on the outskirts of Barcelona city. The state-of-the-art WRF-ARW/HERMESv2/CMAQ model system has been applied at high spatial (1 × 1 km^2) and temporal (1 h) resolution. Detailed information about on-road traffic and power generation has been collected as input information for the emission model. This study has been performed for an air pollution episode (worst-case) that affected the Iberian Peninsula during 2011.

Section 2 presents the applied methodology: modelling system and study scenarios. Then, Section 3 examines model simulations: emissions and air quality. Finally, in Section 4, the main conclusions are discussed.

2. Methodology

2.1. Modelling system

The air quality impacts of fleet electrification in the cities of Barcelona and Madrid were analysed using the Community Multiscale Air Quality (CMAQ) model (Byun and Schere, 2006). The meteorological fields for CMAQ were generated by the Weather Research and Forecasting (WRF) meteorological model (Michalakes et al., 2004; Skamarock and Klemp, 2008) and the High Elective Resolution Emission Modelling System v2.0 (HERMESv2.0) (Guevara et al., 2013) provided the emissions for CMAQ. HERMESv2.0 is a high-resolution emission model which uses mainly bottom-up approaches and Spanish local data.

To obtain adequate boundary and initial conditions, the modelling system was initially run on two regional scales: the European domain (12 km × 12 km and 1 h) and the Iberian Peninsula domain (4 km × 4 km and 1 h) (Fig. 1a)). A one-way nesting was performed from one domain to the other to retrieve the meteorological and chemical conditions to the inner domains. The final working domains cover areas of 148 × 148 km^2 and 148 × 160 km^2 (Barcelona and Madrid domains, respectively). These domains are configured with high horizontal (1 km × 1 km) and temporal (1 h) resolution. 33 σ vertical levels are defined, with 12 characterising the planetary boundary layer, for both meteorological and air quality simulations. The top of the model is defined at 50 hPa to resolve the troposphere–stratosphere exchanges properly. The specifications and parameterisations for the WRF-ARW and CMAQ models are summarised in Table 1. Further information is available in the Supplementary Material.

2.2. HERMESv2.0 and specific emission factors

HERMESv2.0 (Guevara et al., 2013) is a high-resolution emission model specifically developed for Spain; it updates and improves the original HERMES2004 model (Baldasano et al., 2008). It combines a comprehensive database with updated methodologies for estimating anthropogenic and biogenic emissions. Given the main emission sources regarding fleet electrification, the specific modules for estimating road transport emissions and combustion processes in energy industries are detailed below.

Combustion emissions from the natural gas combined-cycle plants have been estimated according to data measured on an