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Perspectives of electric mobility: Total cost of ownership of electric vehicles in Germany

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ABSTRACT

The transport sector is a major source of greenhouse gas emissions worldwide as well as in Germany and is therefore able to contribute significantly to the achievement of climate protection goals. With this in mind and the steadily increasing electricity generation from renewable energy sources in Germany, electrically driven vehicles can be an attractive option to reach the climate targets of the EU and the German government. The target of the German government to have at least one million electric vehicles registered by 2020 seems currently far from realisation. For this reason, this article analyses the total cost of ownership (TCO) of electric passenger vehicles in Germany on a component-based approach and gives an estimation about the further development until 2050. To represent the German market, we investigate different vehicle sizes, user types and drive technologies. Furthermore, we show the CO_2 abatement potential offered by different types of electric vehicles. Finally, we analyse buyer's premiums as an incentive to accelerate the uptake of electric vehicles on German roads.

In result, even without governmental subsidies, full and mild hybrid electric vehicles are already an economic option for a wide range of vehicle sizes and user types. To achieve nowadays cost competitiveness for full electric vehicle powertrains, considerable buyer's premiums are necessary. For plug-in hybrid electric vehicles and battery electric vehicles, the premiums range from about 8,600 to 32,400 EUR_{2010}/vehicle depending on the vehicle size and user type. Eventually, following the future cost estimations, full electric vehicles can reach economic viability from 2030 onwards for many of the investigated vehicles and users.

1. Introduction

The transport sector is one of the most important sources of greenhouse gas (GHG) emissions worldwide due to a high transport activity and a high share of fossil fuels used in this sector. The transport sector (road, rail, air, sea) causes about 23% (7.4 Gt CO_2 in 2013) of global CO_2 emissions from fuel combustion (International Energy Agency (IEA), 2016). In Germany, the transport sector is responsible for about 20% (152 Mt CO_2 in 2013) of the country's CO_2 emissions from fuel combustion, mainly related to road transport (i.e. 97%) (International Energy Agency (IEA), 2016). Vehicles with electric drive systems are discussed as an option to reduce transport's emissions in the political and scientific context. Their main advantages are a higher efficiency of electric motors compared to internal combustion engines (ICEs), the absence of local pollutants emissions, reduced noise pollution and the possible reduction of GHG emissions compared to ICEs using low-carbon electricity generation. Current disadvantages comprise high overall investment costs, long battery charging times, low driving ranges and limited public and private charging infrastructure.

Due to the GHG emission reduction potential of electric mobility, extensive research is carried out within this field. This concerns both basic research as well as research on the environmental impact of electric cars and potential future market shares. Basic research focuses mainly on the improvement of battery technology. So far, batteries do not reach a sufficiently high energy density in the storage of electrical energy, which leads to significantly lower achievable driving range compared to conventional drives. The state-of-the art battery technology are lithium-ion batteries with an energy density of about 100–240 Wh/kg (battery cell) (Scrosati et al., 2013; Thielmann et al., 2012).

In Germany, the federal government has set the goal of one million electric vehicles by 2020 (Bundesministerium für Wirtschaft und Energie (BMWi), 2015). Electric vehicles within that context are defined as vehicles that emit not more than 50 g CO_2/km (with electricity evaluated at 0 g CO_2/kWh) or have an electric

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driving range of at least 40 km (Deutscher Bundestag, 2015). To encourage electric mobility, the federal 'National Development Plan for Electric Mobility' (NEPE) supports research and development activities, market preparation and market introduction. Recently, German manufacturers have started a product offensive, e.g. with the introduction of the BMW i3 or the Volkswagen e-Golf. Powerful incentives such as a buyer's premium were missing to date in the German market and the German motorists have been reluctant in buying electric cars: the vehicle stock of battery electric vehicles and plug-in electric vehicles was 28,264 in 2015 (Bundesministerium für Wirtschaft und Energie (BMWi), 2015). However, in May 2016, the German government introduced a buyer's premium of 4,000 EUR for battery electric vehicles and a premium of 3,000 EUR for plug-in hybrid electric vehicles (Bundesregierung, 2016).

To evaluate the perspectives of electric mobility in Germany, this paper conducts a total cost of ownership (TCO) comparison of a range of vehicles, user types and drive technologies. We first give an overview on articles in the context of total cost of ownership analysis and show central points of the methodology used in the considered studies. We underline the novelty of the research conducted in this paper. The first part of this article also includes a comprehensive literature review of cost of batteries and fuel cells and their likely future development. Second, we present the method and the basic assumptions made for the TCO analysis. Third, the results of TCO of the various vehicle concepts are presented. Additionally, we calculate CO_2 abatement potential and cost of electric vehicles in Germany. Finally, policy recommendations are given comparing the recently introduced buyer's premium to the calculated premium to reach cost parity of electric vehicles in Germany.

2. Literature review

Various studies have been carried out recently covering the total cost of vehicle ownership (Table 1). Notably, most TCO research is focussed on the United States and limited studies are available on the future TCO of electric mobility in Germany (e.g. Plötz et al., 2012). Whereas TCO of electric passenger vehicles have been analysed quite widely, a small number of authors (e.g. Al-Alawi et al., 2013; Gilmore et al., 2013) include further transport modes such as light or heavy duty vehicles. Quite established is the disaggregation of passenger transport into different vehicle categories and/or user types to cover the range of possible driving behaviour. Additionally, some research compares TCO with vehicle emissions to compare cost and environmental benefits.

The here presented study is the first which combines a component-based total cost of ownership analysis for German passenger cars for a comprehensive set of electric drive technologies until the year 2050. This includes a detailed vehicle assessment covering different vehicle sizes and different user behaviours. Doing so, we are able to deduce policy recommendations to foster the economic feasibility of electric vehicles in Germany towards the aim of one million electric vehicles in 2020.

To determine the future TCO of electric vehicles, the price-development of the batteries and fuel cells is of crucial importance due to their high contribution to the investment costs of the total vehicle. Li-ion battery technology is the dominant automotive battery technology today, thanks to its relatively high energy density and power density and a long lifetime (Han et al., 2014). Within automotive batteries, different technological generations can be distinguished. Currently used Li-ion-batteries represent the second generation. The third generation comprises enhanced Li-ion-batteries whereas the fourth generation includes post-lithium-ion batteries, as for example lithium-sulphur batteries (Thielmann et al., 2012). The main cost drivers of a battery pack are the battery cells with about 50–65% of total costs (Dinger et al., 2010; International Renewable Energy Agency (IRENA), 2013). Dinger et al. (2010) estimate that 70% of cell costs and 75% of battery pack costs are dependent on the production volume. Hence, higher production volumes offer an opportunity to reduce the costs significantly.

Literature gives numerous projections on the battery costs. Fig. 1 shows capacity-specific investment costs of Li-ion batteries (for BEVs or PHEVs) based on a comprehensive literature review with 35 data sets.

For the past years, the indicated values differ for several reasons such as different sources of information (e.g. manufacturer's data, estimations/calculations in literature), different sizes of the battery and different assumed production volumes. All studies expect a cost reduction over the considered time period in all scenarios. The main reasons for this assumption are further R&D activities as well as higher production volumes in the future. A growing energy density in combination with unchanged costs also leads to a decrease of the capacity-specific costs. The biggest cost reduction is expected to occur until 2020. The median decreases from 800 EUR_{2010}/kWh in 2010 to 186 EUR_{2010}/kWh in 2050, which corresponds to a decrease of 77% or 3.6%/a.

As well as BEVs, fuel cell hybrid electric vehicles (FCHEVs) suffer from high investment costs, due to the costly fuel cells. Besides the costs, the fuel cell technology also faces challenges in robustness, reliability and durability, mainly due to degradation of the materials (Wang, 2015).

The dominant technology in transport applications are Proton Exchange Membrane (PEM) fuel cells, where electrical energy is generated through an electrochemical reaction of hydrogen and oxygen. The reaction product is water, thus FCHEVs operate locally emission-free. Like in the case of batteries, fuel cell costs and quality would highly benefit from mass-manufacturing. A main obstacle to the success of fuel cells in road vehicles and the associated mass-manufacturing is the missing hydrogen infrastructure (Wang, 2015). Fig. 2 shows capacity-specific investment costs of automotive PEM fuel cell systems resulting from a literature review with 14 data sets. It can be seen from Fig. 2 that major cost reductions are expected until 2050. This is due to high expected learning rates as observed in many other energy technologies (Rösler et al., 2014). The median decreases from 380 EUR_{2010}/kW in 2010 to 46 EUR_{2010}/kW in 2050, i.e. by 88% or 5.2%/a.

3. Methodology and assumptions

3.1. Cost model

A TCO analysis considers the costs during the whole service life of a product, i.e. from the purchase until the end of the ownership period. These costs can be divided into different categories. In this paper, we analyse capital expenditures (CAPEX), i.e. investment costs, and operational expenditures (OPEX), including fixed costs (insurance costs and vehicle tax) and variable costs (fuel costs, maintenance costs). Since we determine TCO from a user perspective, we include the German value added tax (VAT) of 19% in our calculations. External costs are not considered, besides CO_2-charges included in the fuel costs due to an assumed future taxation according to Schlesinger et al. (2014). The TCO given in this paper are for purchases in the years 2015, 2030 and 2050, referred to as investment years in the following. All monetary figures are given in real values with the base year 2010 (EUR_{2010}), unless otherwise specified. The exchange rate used for US Dollars is 1 USD_{2010} = 0.7543 EUR_{2010} (Deutsche Bundesbank, 2015).

As Eq. (1) shows, costs are calculated with annual cash flows to