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Energy use, cost and CO_2 emissions of electric cars

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ABSTRACT

We examine efficiency, costs and greenhouse gas emissions of current and future electric cars (EV), including the impact from charging EV on electricity demand and infrastructure for generation and distribution.

Uncoordinated charging would increase national peak load by 7% at 30% penetration rate of EV and household peak load by 54%, which may exceed the capacity of existing electricity distribution infrastructure. At 30% penetration of EV, off-peak charging would result in a 20% higher, more stable base load and no additional peak load at the national level and up to 7% higher peak load at the household level. Therefore, if off-peak charging is successfully introduced, electric driving need not require additional generation capacity, even in case of 100% switch to electric vehicles.

GHG emissions from electric driving depend most on the fuel type (coal or natural gas) used in the generation of electricity for charging, and range between 0 g km^{-1} (using renewables) and 155 g km^{-1} (using electricity from an old coal-based plant). Based on the generation capacity projected for the Netherlands in 2015, electricity for EV charging would largely be generated using natural gas, emitting 35–77 g $CO_{2\,eq}$ km^{-1}.

We find that total cost of ownership (TCO) of current EV are uncompetitive with regular cars and series hybrid cars by more than 800 € year^{-1}. TCO of future wheel motor PHEV may become competitive when batteries cost 400 € kWh^{-1}, even without tax incentives, as long as one battery pack can last for the lifespan of the vehicle. However, TCO of future battery powered cars is at least 25% higher than of series hybrid or regular cars. This cost gap remains unless cost of batteries drops to 150 € kWh^{-1} in the future. Variations in driving cost from charging patterns have negligible influence on TCO.

GHG abatement costs using plug-in hybrid cars are currently 400–1400 € tonne^{-1} $CO_{2\,eq}$ and may come down to −100 to 300 € tonne^{-1}. Abatement cost using battery powered cars are currently above 1900 € tonne^{-1} and are not projected to drop below 300–800 € tonne^{-1}.

1. Introduction

Worldwide, more than 90% of the transport sector is powered by fuels derived from oil. However, the consumption of diesel and petrol is considered problematic due to costs of oil, doubts about of security of oil supplies [1,2], greenhouse gas (GHG) emissions, and the emissions of air pollutants such as NO_x, PM_{10} and volatile organic compounds [3,4].

To reduce dependence on oil in the transport sector, alternatives like biofuels and more efficiency (hybrid) cars are used in increasing volume and numbers [5,6]. The cost and potential emission benefits of biofuels and hybrid vehicles have been pointed out in numerous studies (c.f. [7–14]). For example, costs of sugar cane ethanol are already competitive with traditional fuels, and second generation ethanol can become so in the near future. In addition, using biofuels reduces emissions of GHG when produced sustainably, and also reduces emissions of other air pollutants. Fuel consumption and therefore emissions from efficient hybrid cars are lower than those from traditional cars. Drawbacks of these alternatives concern the uncertainty about the available supply of sustainable biofuels, the currently higher costs of hybrid vehicles, and the remaining tailpipe emissions of GHGs and air pollutants.

Electric driving is also considered a promising alternative and has been advocated for decades [15–17]. It does not cause any tailpipe emissions but may cause emissions of GHGs and other air pollutants, depending on the mix of electricity sources used. Three

Abbreviations: BPEV, battery powered electric vehicle; CHP, combined heat and power; CM, central motor; GHG, greenhouse gas; ICE, internal combustion engine; JRC, Joint Research Centre (directorate of the European Commission); MRT, maintenance, repair and tires; NGCC, natural gas combined cycle; O&M, operation and maintenance; PHEV, plug-in hybrids electric vehicle; SHEV, series hybrid electric vehicle; SUV, sports utility vehicle; TCO, total cost of ownership; TTW, tank to wheel; VAT, value added tax; WM, wheel motor; WTT, well to tank; WTW, well to wheel.

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basic designs for electric driving can be distinguished: the first is a series-parallel hybrid car, which has an internal combustion engine (ICE) and an electric motor that are both connected to the wheels and supplement each other when needed (see [18]). The second is a plug-in series hybrid vehicle (PHEV), which has a small battery for trips up to approximately 50 km and a generator using an ICE to provide power for long range driving. The third is a fully battery powered electric vehicle (BPEV), which has a large battery for longer trips (200–300 km). The series-parallel car has been in use for over a decade and is not considered in detail in this study. PHEV and BPEV are currently introduced into the market: major car manufacturers all over the world are working on new models [19–23]. Electric utilities and governments in various countries support the emergence of this market (e.g. [24]).

The additional costs of plug-in hybrid and fully electric cars compared to regular ICE cars largely depend on the high costs of batteries [13,25,26]. With current battery costs in the order of €1000 kWh^{-1}, plug-in cars with a battery-powered range of 50 km or more (which requires a battery of $\pm$7 kWh) are prohibitively expensive. However, to determine the total cost of owning and driving an EV in the short term and to determine prospects on longer term, requirements for additional electricity generation and distribution, and technological improvements and cost reductions should be taken into account [27–29].

It has been projected that an electric vehicle increases the electricity consumption of a household in an industrialised country by 50% [30]. Introducing a large number of electric vehicles therefore introduces new challenges, like building infrastructure for charging, improving the electricity distribution grid, and taking care of legal and privacy issues regarding coordinated 'smart' charging systems. The extent of these challenges is strongly determined by the timing and pattern of charging EVs [31,32].

We wish to determine whether large scale use of EV is or can become feasible from a techno-economic perspective, and if so, under what conditions. We therefore examine efficiency and costs of current and future EV, as well as their impact on electricity demand and infrastructure for generation and distribution, and thereby on GHG emissions. Energy used and emissions from manufacture of EV are left outside the scope of this study (c.f. [33]).

Earlier studies have addressed some of these issues separately. Some important well-to-wheel (WTW) studies do not include PHEV and BPEV cars [7,34,35]. Campanari et al. [36] and Silva et al. [26] focussed on efficiency of EV using current technology and did not take uncertainty in various chain aspects into account. Van Vliet et al. [13] and Shiau et al. [25] included sensitivity analysis on various factors affecting EV performance, including battery cost and vehicle weight, but did not take charging patterns into account.

Earlier studies have also only partially addressed how increased electricity demand could be catered for. A study for Sweden assumed that only renewable energy sources are used for electricity generation [37]. A study for Germany used inflexible charging scenarios, not taking options for coordinated charging into account to smooth demand [31]. Studies for the US assumed that the capacity factors of power generation sources will remain the same with high numbers of EVs [32], or just evaluate how many cars the current grid can support [38]. Other studies did not take into account the load pattern of existing demand [16,39].

We therefore examine the feasibility of electric driving taking into account not only drivetrain choices, but also driving patterns, changes in the electricity mix, charging patterns, and energy losses in relevant parts of the WTW chain. There are three main aspects to this analysis:

Determine the effect of EV charging patterns on household and total electricity demand.

Derive GHG emissions and costs of charging of EVs in the 2015 Dutch context and beyond.

Compare GHG emissions and costs of PHEV and BPEV with those of regular cars.

We briefly discuss methods in Section 2, present data used in Section 3, present results in Section 4, discuss the applicability of our results in Section 5 and give a summary and conclusion of our findings in Section 6.

2. Methods

The car class we focus on is the compact 5-seater. It includes the Volkswagen Golf, Ford Focus, Renault Megane, Toyota Corolla and Opel Astra. We compare EV configurations to a regular petrol car, diesel car, parallel hybrid car and SHEV. Vehicle configurations are composed using the methodology and data described in Van Vliet et al. [13].

In order to compare vehicles, we use the same platform for all vehicle configurations and only exchange the drivetrain as is also done in Weiss et al., the EU Joint Research Centre (JRC) and Van Vliet et al. [40,7,13]. The vehicle platform is defined as a vehicle without the drivetrain and includes the chassis, suspension, wheels, doors, seats, windows, and assembly. This platform weighs 1016 kg, costs €15700, and is powered by a 74 kW ICE or equivalent [7]. The drivetrain consists of the engine and the transmission connecting it to the wheels. An EV can be designed with a single central motor connected to the wheel via a transmission like in a regular ICE car, or with electric motors built into the rims of the wheel [13].

Series hybrid vehicles (SHEV) and BPEV represent opposite ends of an electric drivetrain spectrum. The SHEV uses an ICE exclusively to power the electric motor, the BPEV uses a battery. A series drivetrain PHEV is somewhere within this spectrum. It uses a battery for short range driving, and switches to ICE-generated electricity when the battery is depleted.

Total WTW energy consumption in an EV (E_{total}) is expressed in MJ km^{-1} determined as follows:

$$E_{total} = E_{resistance}/\eta_{transmission}/\eta_{motor}/\eta_{fuel\ supply} \quad (1)$$

where $E_{resistance}$ is the mechanical energy required to move the car against resistance from inertia, wind and tire friction. Losses accumulate through the WTW chain, where $\eta_{transmission}$ is the transmission efficiency, η_{motor} is the efficiency of the electric motor or ICE motor, and $\eta_{fuel\ supply}$ is the fuel supply efficiency. For a wheel motor, by definition, $\eta_{transmission} = 1$.

Fuel supply efficiency depends on whether the EV is powered by an ICE or electric motor. The well-to-tank (WTT) efficiency (η_{WTT}) is determined as follows for liquid fuels and electricity:

$$\eta_{liquid\ fuel} = \eta_{distribution} \times \eta_{fuel\ plant} \times \eta_{resource\ extraction} \quad (2)$$

$$\eta_{electricity} = \eta_{charging} \times \eta_{grid} \times \eta_{power\ plant} \times \eta_{resource\ extraction} \quad (3)$$

where $\eta_{distribution}$ is the energy used for driving distribution trucks and filling stations, $\eta_{fuel\ plant}$ is most commonly the efficiency of an oil refinery, $\eta_{resource\ extraction}$ is the efficiency of mining or farming of energy resources, $\eta_{charging}$ is efficiency of charging and discharging the battery, and η_{grid} is the efficiency of the electricity distribution grid. If solar power or wind is used, $\eta_{resource\ extraction} = 1$.

The source of electricity used for charging EVs depends on the available power capacity and existing demand pattern of households, offices, industry, and public services (such as street lighting). We determine the total costs, marginal costs, and emissions of electricity at 15-min intervals by matching dispatch of electricity generation options to the demand pattern. The demand pattern uses household or national demand and includes additional load