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CLIMATE IMPACT OF THE ELECTRIFICATION OF ROAD TRANSPORT IN A SHORT-TERM PERSPECTIVE

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ABSTRACT

To reduce greenhouse gas (GHG) emissions within the transport sector, replacing conventional vehicles with electric vehicles (EVs) is considered a desirable alternative. Due to increased integration of renewable energy sources in electricity generation, EVs are often considered emission-free although current electricity generation is largely dependent on fossil fuels. By 2018, the European Union (EU) requires biofuels to ensure 60% emission reductions in a lifecycle perspective, in order to avoid unsustainable production. No such criteria apply to EVs, although several European countries aim for an EV mass market by 2020. This study aims to show how a rapid, large-scale deployment of EVs will affect the GHG emissions, using Sweden as an example. GHG emissions from the energy use of electric and conventional vehicles are compared, applying a life cycle perspective on the fuels. Results show that with assumed electricity generation, EVs cause GHG emissions 25% higher than emissions from conventional vehicles. Hence, in a short-term perspective, a large-scale introduction of EVs is not beneficial for the climate. Nonetheless, a comprehensive approach to EVs, similar to EUs biofuel sustainability policy, may help reduce GHG emissions from the electricity generation system.

Keywords: Electric vehicles, energy efficiency, greenhouse gas emissions

INTRODUCTION

In 2009, the transport sector generated 19% of greenhouse gas (GHG) emissions in the European Union (EU). While GHG emissions from other sectors (e.g. manufacturing industry) decrease, transport-induced emissions have increased by 21% since 1990 (European Commission, 2012). To curb this development, the EU's Renewable Energy Directive (RED) includes measures aimed at the transport system. The RED proposes reduced GHG emissions through extended use of renewable fuels and increased energy efficiency within transport (European Commission, 2009).

According to the RED, a main measure for increased energy efficiency in transport is extended use of electric vehicles (EVs) (European Commission, 2009). This notion is embraced by several member states. For example, by 2020, Germany aims to have 1 million EVs, France 2 million EVs, the United Kingdom 1.5 million EVs and Sweden 600 000 EVs (Leurent and Windisch, 2011; Pasaoglu et al., 2012). The Swedish 2020 EV goal will correspond to approx. 13% of passenger cars (Statistics Sweden, 2012).

Swedish EVs are generally assumed to use electricity produced in Sweden, where electricity is generated mainly in hydro and nuclear power plants, rendering low GHG emissions (Energimyndigheten, 2011). As electricity generation capacity is large and electricity is seen as relatively inexpensive, electricity consumption is high (Henning and Trygg, 2008). Using electricity in transport is uncontroversial from economic as well as environmental perspectives, and EVs are generally considered favourable options for mitigating climate change (Swedish Government, 2008b). The other major item concerning transport within the RED, namely biofuels, is more controversial. Despite measures to increase biofuel use (Swedish Government, 2008a), merely 6% of Swedish passenger cars use ethanol or biomethane and the popularity of biofuels is declining (Statistics Sweden, 2012; Transport Analysis, 2011).

The EU and other international actors have recently voiced concern about negative environmental effects of biofuel production (Smyth et al., 2010). To ensure sustainability in production, the RED contains sustainability criteria for biofuels. One criterion states that from 2018, biofuels shall reduce life cycle GHG emissions by 60% compared to conventional fossil fuels. This regulation does not apply to EVs (European Commission, 2009), possibly since the link between vehicle and fuel is less obvious. Although tailpipe emissions from electric propulsion are zero, life cycle GHG emissions are not. These emissions depend on the energy used when manufacturing the vehicle and on the electricity generation.

Sweden is part of the European electricity grid, where roughly half of the electricity mix is based on fossil fuels (European Commission, 2012). In the common European electricity market, an increase in Swedish electricity consumption necessitates an increase in European electricity production, thereby possibly increasing GHG emissions. In light of that, EVs may not be very effective means to mitigate climate change. In a longer time-span (e.g. 2050) however, European electricity generation may be more energy efficient and based mainly on renewable energy sources, rendering EVs a better option. But in the meantime, how will the plans for an EV mass market affect GHG emissions?

The aim of this paper is to estimate how a large-scale introduction of EVs by 2020 will affect GHG emissions from the energy system. The full vehicle life cycle is not considered, merely that of the vehicle fuel, as that is the concern of the RED. In order to illustrate the consequences of applying different system perspectives, the case of Swedish EVs is chosen. Conclusions are however assumed to be valid not only for Sweden but for similar countries and regions as well. Although several studies have estimated GHG emissions from EVs (see e.g. Doucette and McCullouch, 2011; Ma et al., 2012; van Vliet at al., 2011), this study adds the dimension of achieving GHG emission reductions through system perspective awareness in policy-making.

METHOD

Primary energy use and GHG emissions from vehicle propulsion are estimated using different system perspectives and the results are compared. For a reliable comparison between fuels, all energy balances and emission calculations are based on a life cycle perspective.

Vehicles

EVs may be either plug-in hybrids (PHEV), where the vehicle has both an electric motor and an internal combustion engine (ICE), or purely battery-powered (BEV). In this context, only BEVs are considered as to simplify the comparison with conventional ICE vehicles (ICEVs). According to the REDs sustainability criteria, biofuels shall be compared to petrol (European Commission, 2009). In this paper, BEVs are compared to petrol ICEVs but also to diesel and biofuel ICEVs. Diesel ICEVs are progressively taking Swedish market shares from petrol, within the passenger car segment (Transport Analysis, 2011). Biofuel ICEVs are used for comparison since their environmental impact is much debated while that of EVs is rarely discussed.

The compact 5-seater (e.g. Volkswagen Golf) is a common car model in European daily travel; hence it is used for the estimations made in this paper. A BEV of that size is assumed to use 20 kWh/100 km, based on actual EV data and simulated data (Doucette and McCullouch, 2011; Offer et al., 2011, Torchio and Santanelli, 2010; van Vliet et al., 2010). Data for ICEVs with comparable functionality is gathered from JEC (2011), which contains a thorough analysis of the life cycle energy use and GHG emissions of various vehicle fuels when used in compact 5-seater cars manufactured in 2010 or later. As the methodology is consistent throughout the JEC (2011) report, comparisons between fuels may be considered reliable.

Emissions accounting

To estimate GHG emissions from electricity use, there are five common principles (Dotzauer, 2010). One of those, *average electricity*, is frequently used when considering the environmental impact from e.g. EVs. Emissions from the system's average electricity mix are used in calculations. However, Dotzauer (2010) argues that this principle is valid only for bookkeeping, i.e. for electricity already used. When performing a short-term consequence analysis, of electricity use that has yet to occur, the *marginal electricity* principle should be applied (Dotzauer, 2010). A change in electricity use demands a change in electricity generation, which is assumed to affect the production unit in the system which has the highest operational costs, i.e. the marginal unit. The three remaining principles, which account for the impact of long-term development, emission trading and contracted delivery respectively, are not considered applicable when analysing short-term consequences of increased electricity use and are therefore not used in this paper.

The validity of using the *marginal electricity* principle is debated by Grönkvist (2005), who also adds impacts of price flexibility and the rebound effect to the discussion. Grönkvist (2005) argues that applying any of the here mentioned principles for emissions accounting simplifies the analysis too much, and that for a reliable estimation a more specific method should be applied. Nevertheless, the application of emissions accounting principles is not considered problematic here, as the purpose of this paper is discussing consequences rather than providing precise figures.

Greenhouse gas emissions from electricity generation

Although the EU aims to increase the share of renewables in the energy system (European Commission, 2009), the share of fossil fuels used in near-future electricity generation is assumed to equal the current share (Möst and Fichtner, 2010). By 2020, 55-60 GW of European coal condensing (CC) power capacity is expected to reach the end of its lifetime, but 50 GW of new coal capacity is projected to be deployed (Butcher, 2012; European Commission, 2006). In order to reduce emissions, the EU shows an interest in carbon capture and storage (CCS) (European Commission, 2006). The number of natural gas combined cycle (NGCC) power plants is currently increasing, and assumptions are that this trend may continue (Möst and Fichtner, 2010).

In 2020, *marginal electricity* may be old CC power, new CC power or NGCC power (Swedish Energy Agency, 2008). Currently, the marginal units are old CC power plants (Dotzauer, 2010; Henning and Trygg, 2008). Assuming no radical changes in the electricity generation system until 2020, old CC power is here expected to remain constituting *marginal electricity*. For comparison, emissions are also estimated with new CC power plants, new CC power plants with CCS and NGCC power plants as marginal units. To illustrate the distinction between marginal and average emission accounting principles, emissions from *average electricity* are calculated for the Swedish and European electricity generation. Table 1 shows GHG emissions from the various power sources.

Table 1 – GHG emissions from Swedish electricity generation, applying average and marginal electricity principles. All emissions are calculated using a life cycle perspective.

Electricity generation	GHG emissions [g CO_2 eq/kWh]
Swedish mix[a]	79
European mix[a]	578
Old CC power plant[b]	1039
New CC power plant[b]	874
New CC power plant with CCS[b]	241
NGCC power plant[c]	585

[a] Derived from Covenant of Mayors (2012).
[b] Derived from Schreiber et al. (2010). Figures apply to hard coal with low heating value.
[c] Derived from Spath and Mann (2000).

Greenhouse gas emissions from liquid and gaseous fuels

Fossil GHG emissions from liquid and gaseous fuels used in ICEVs are listed in table 2. Emissions from biofuels vary immensely depending on production pathways, why three extreme values are selected for comparison. For ethanol and biodiesel "worst case" values are selected, while for biogas the "best case" value is selected. This selection was made in order to show the span of GHG emissions from biofuels and because production of biogas is often considered more ecologically sustainable than production of ethanol and biodiesel (see e.g. Smyth at al., 2010).

Table 2 – GHG emissions from fossil fuels and biofuels. All emissions are derived from JEC (2011), which applies a life cycle perspective. For the biofuels, production pathways are noted.

Liquid and gaseous fuels	GHG emissions [g CO_2 eq/km]
Petrol	166.9
Diesel	155.3
Ethanol (from wheat; lignite CHP)	108.7
Biodiesel (from palm oil)	90.9
Biogas (from liquid manure)	23.7

Primary energy use

A main reason for promoting EVs is their higher powertrain efficiency, compared to ICEVs (Swedish Government, 2008b). However, when estimating primary energy use by applying a life cycle perspective, the energy used by the powertrain is complemented by the energy used in fuel production and distribution. This is summarised in table 3.

Table 3 – Energy used in production and distribution of fuels, applying a life cycle perspective, and energy used when utilising the fuel in a vehicle powertrain. kWh_p denotes the primary energy used to produce 1 kWh fuel or electricity.

Fuel	Fuel energy balance [kWh_p/kWh]	Corresponding powertrain energy use [kWh/km]
Electricity[a]	2.57	0.20
Biogas[b]	0.97	0.52
Biodiesel[b]	1.18	0.48
Ethanol[b]	0.58	0.53
Petrol[b]	0.22	0.53
Diesel[b]	0.24	0.48

[a] Derived from Schreiber et al. (2010) and Ditsele and Awuah-Offei (2012).
[b] Derived from JEC (2011).

RESULTS

Figure 1 shows the resulting GHG emissions from electricity, biofuels and fossil fuels. As may be seen, if old CC power plants constitute marginal units in 2020, BEVs do not reduce GHG emissions. In fact, BEV emissions exceed petrol ICEV emissions by 25%. It is noteworthy that biofuels, even those that require a lot of fossil energy during production and have been criticised for lacking ecological sustainability (Smyth et al., 2010), emit a lot less GHGs than both their fossil counterparts and BEVs.

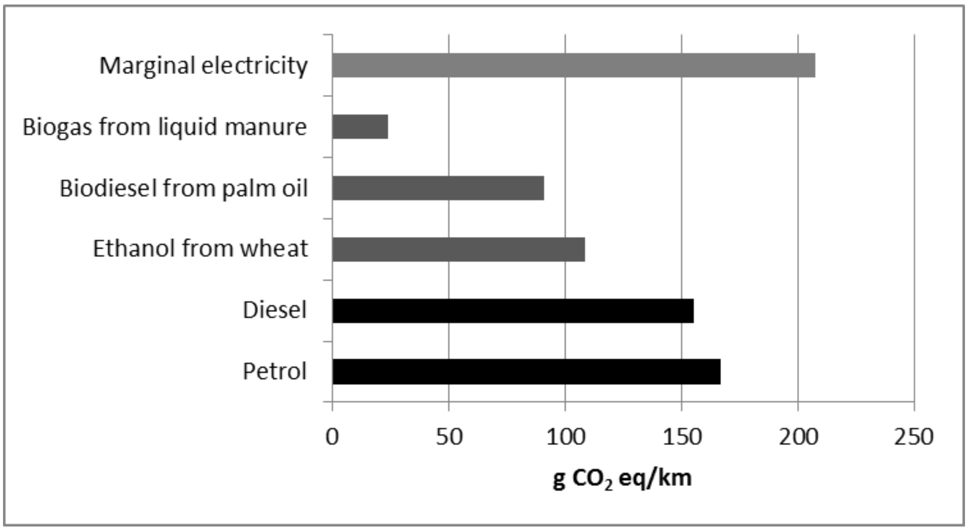

Figure 1 – GHG emissions from BEVs using marginal electricity and ICEVs using biofuels, diesel or petrol.

In order to view GHG emissions from EVs from other angles, emissions are estimated for diverse power sources. Figure 2 shows two examples of the *average electricity* principle and four examples of *marginal electricity* with different units on the margin. Evidently, results differ greatly depending on assumptions about where electricity is produced. However, BEVs still cannot be claimed to reduce GHG emissions considerably compared to ICEVs. Applying Swedish average mix, or assuming new CC power with CCS on the margin, are the only cases where emissions are reduced by more than 60% compared to petrol ICEVs, which is the reduction that biofuels must reach according to RED (European Commission, 2009).

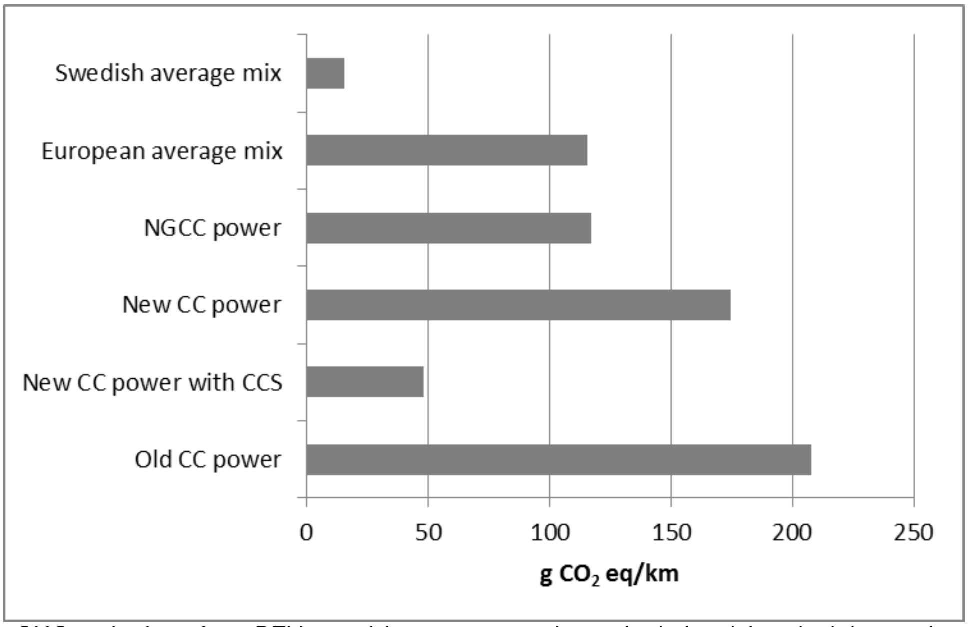

Figure 2 – GHG emissions from BEVs, applying average and marginal electricity principles and considering different electricity generation pathways.

Assuming that in 2020, new CC power plants with CCS will constitute the marginal units would ensure GHG emission reductions when using BEVs. However, Schreiber et al. (2010) show that CCS, when retrofitted on a power plant built between 2010 and 2020, leads to a 29% decrease in power plant efficiency. This requires incineration of 41% more coal, if the same electricity generation is to be achieved. Even though GHG emissions are reduced, primary energy use is increased.

Figure 3 shows the primary energy used when driving 1 km using various fuels. Although powertrain efficiency is greater in a BEV than in an ICEV, a BEV using CC power requires more energy than an ICEV using petrol. Adding CCS would further worsen the balance by increasing the energy use by up to 32%.

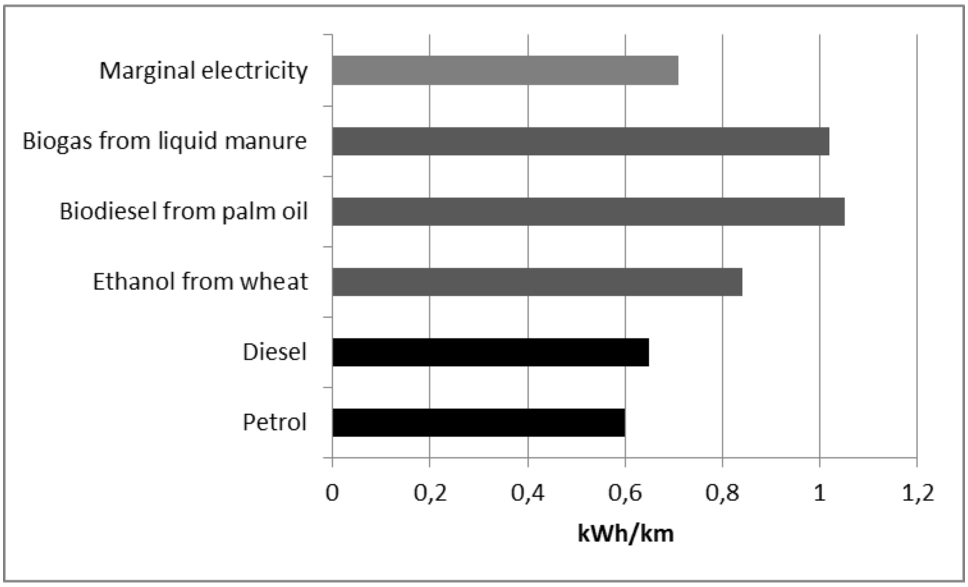

Figure 3 – Primary energy use of BEVs and ICEVs.

Considering a common European electricity grid where the marginal unit is an old CC power plant implies that BEVs are neither more energy efficient than ICEVs, nor do they emit less GHGs. A few EVs may not make much of a difference, but a European mass market could seriously affect GHG emissions. For example, replacing 600 000 Swedish petrol ICEVs with BEVs would increase GHG emissions by approx. 370 000 tonnes CO_2 eq annually, corresponding to a 2% increase from current levels of GHG emissions from Swedish transport (Swedish Energy Agency, 2011). Replacing half of those with best case biogas ICEVs and the other half with worst case biodiesel would instead reduce GHG emissions by approx. 1 million tonnes CO_2 eq annually.[1]

DISCUSSION

This study shows that EVs are no silver bullet for climate change mitigation just because they use electricity. Invoking vehicle-based arguments, e.g. that the electric motor is highly efficient and that there are no tailpipe emissions, is misleading. Drawing the system

[1] Assuming an annual driving distance of 15 000 km.

boundary around the vehicle, or around national borders, gives results that differ a lot from when the system boundary is drawn around the European energy system. In the wider system, EVs are neither energy efficient nor emission-reducing. Hence, the problem lies in the electricity generation system, not in the vehicles. As long as fossil fuel power plants constitute the marginal electricity production units, efficiency will be low and GHG emissions high.

Which kind of power plants constitutes marginal production units may be affected in two ways; through production modifications or demand side management (DSM) measures. Weisser (2007) argues that DSM measures reduce GHG emissions more effectively than production modifications, and studies show that vast GHG reductions may be achieved through reduced electricity consumption in e.g. manufacturing industry (Henning and Trygg, 2008). Despite this, increasing electricity consumption is encouraged within the transport sector.

One reason for this is improving urban environment, which is often affected by noise and local air pollution arising from traffic. EVs may help reduce these problems. Also, as driving conditions affect GHG emissions, EVs are particularly suited to urban traffic. BEVs perform better than ICEVs in situations where speed and load are low while ICEVs perform better than BEVs at higher speed and load (Ma et al., 2012). Hence, in an urban context, a BEV may emit less GHGs than is shown in figure 1. However, increased use of public transport, walking and cycling would probably improve the urban environment even more. Studies show that relying on technology to mitigate climate change is not enough; changes in attitudes and behaviour are necessary, and transport demand must not continue to increase according to the present trend (Hickman and Banister, 2007; Åkerman and Höjer, 2006).

However, EU transport policy focuses on economic growth (European Commission, 2011), which is not consistent with reduced transport demand. Hence, in order to reduce GHG emissions from road transport through introduction of EVs, modifications are required within the electricity generation system. More renewable energy sources and less fossil ones are needed. By adopting sustainability criteria similar to those applying to biofuels in the RED, GHG emissions from EVs would be more visible and the connection between energy and transport systems would become clearer. The sustainability of transportation fuels could be addressed in a wider perspective.

Although the RED is supposed to ensure sustainability in biofuel production, its criteria and methodology lack some elements. For instance, biomass may achieve the largest emission reductions when used in electricity production (Wetterlund, 2012), something which is not accounted for in RED methodology. When evaluating the effectiveness of the REDs biofuel sustainability criteria, Soimakallio and Koponen (2011) request a wider system perspective. Their argument is that by focusing only on emission reductions compared to petrol, biomass use may be sub-optimised. An extension of the methodology for calculating GHG emissions, to include the entire energy system, is suggested. Such a methodology would include EVs as well, and could help achieve substantial GHG emission reductions.

In a longer time-span, where electricity generation is largely based on renewable energy sources, EVs may reduce GHG emissions considerably. In order to reach such a future, it may be necessary to initiate a large-scale introduction of EVs already by 2020. Illuminating GHG emissions from electricity use in a life cycle perspective may increase the share of renewable energy sources in electricity generation faster than would otherwise be the case. Hence, by issuing a comprehensive framework for reducing GHG emissions, such as an extended version of the RED, the EV deployment might help reduce GHG emissions from the electricity generation system.

CONCLUSIONS

This paper has shown that a large-scale introduction of EVs, in order to achieve GHG emission reductions in the transport system, will in a short-term perspective increase GHG emissions from the energy system. However, measures to really reduce GHG emissions may be recognised by applying a wider system perspective. A comprehensive approach to EVs and electricity, similar to the biofuel sustainability criteria in RED, may contribute to reducing emissions from the electricity generation system.

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