Energy Policy 41 (2012) 537–547

Contents lists available at SciVerse ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Life cycle analysis of energy supply infrastructure for conventional and electric vehicles

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ARTICLE INFO

Article history:
Received 29 July 2011
Accepted 4 November 2011
Available online 25 November 2011

Keywords:
Electric vehicle
Infrastructures
Life cycle analysis

ABSTRACT

Electric drive vehicle technologies are being considered as possible solutions to mitigate environmental problems and fossil fuels dependence. Several studies have used life cycle analysis technique, to assess energy use and CO_2 emissions, addressing fuels Well-to-Wheel life cycle or vehicle's materials Cradle-to-Grave. However, none has considered the required infrastructures for fuel supply. This study presents a methodology to evaluate energy use and CO_2 emissions from construction, maintenance and decommissioning of support infrastructures for electricity and fossil fuel supply of vehicles applied to Portugal case study. Using Global Warming Potential and Cumulative Energy Demand, three light-duty vehicle technologies were considered: Gasoline, Diesel and Electric. For fossil fuels, the extraction well, platform, refinery and refuelling stations were considered. For the Electric Vehicle, the Portuguese 2010 electric mix, grid and the foreseen charging point's network were studied. Obtained values were 0.6–1.5 gCO_{2eq}/km and 0.03–0.07 MJ_{eq}/km for gasoline, 0.6–1.6 gCO_{2eq}/km and 0.02–0.06 MJ_{eq}/km for diesel, 3.7–8.5 gCO_{2eq}/km and 0.06–0.17 MJ_{eq}/km for EV. Monte Carlo technique was used for uncertainty analysis. We concluded that EV supply infrastructures are more carbon and energetic intensive. Contribution in overall vehicle LCA does not exceed 8%.

1. Introduction

Climate change, increasing oil prices, security of supply and environmental concerns, have led to a growing interest in alternative sources of energy and a more efficient way of using it. Academics and policy makers strive to achieve clear data through sector analysis and energy management studies, as foundations to energy policy developments and establishment of goals. Presently, in the EU-27, the transportation sector is responsible for approximately 32% of final energy use (DGGE, 2011) from which road vehicles represent 80% of that usage within the sector. This situation only tends to aggravate, considering that between the period of 1997 and 2007, these values have increased approximately 5%. Regarding environmental impacts, this sector alone emits 19% of the total Green House Gases (GHG).

In Portugal, the situation has reached higher values. In 2009, the transportation sector represented 38.4% (DGGE, 2011) in terms of final energy use, with almost 30% of emissions resulting from this activity. To achieve the environmental goals set by the EU with the 20–20–20 agreement and Portugal's own ambitious goals, the transportation sector presents itself as an important area of analysis. Among several solutions being implemented in Europe, the electric vehicle (EV) is considered in Portugal as the main solution to reduce oil dependency. In order to reduce and replace conventional internal combustion engine vehicles (ICEV) with EVs, it is critical to provide a wide and well distributed charging infrastructure. The Portuguese government is implementing policies to promote the adoption of EVs. One of these policies is promoting the implementation of a pilot charging network in several municipalities that began in 2010. To accomplish this goal, a consortium of companies (MOBI.E) was created to develop this network and has selected 25 municipalities to implement this pilot charging network. During the pilot stage, 1300 normal and 50 fast charging points are being implemented and made available to general public. The pilot stage will provide government, researchers and industry, inputs to model future widening of the network. Campos (2010) for example, developed a multi-criteria algorithm to select the number and the location to place charging points needed to comply with a predicted demand

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Abbreviations: GHG, Green House Gas; LCA, Life Cycle Analysis; CD, Charge Depleting; WTW, Well to Wheel; WTT, Well to Tank; TTW, Tank to Wheel; CTG, Cradle-to-Grave; PISI, Port Injection Spark Ignition; DISI, Direct Injection Spark Ignition; DICI, Direct Injection Compression Ignition; ICEV, Internal Combustion Engine Vehicle; FCHEV, Fuel Cell Hybrid Electric Vehicle; FCPHEV, Fuel Cell Plug-in Hybrid Electric Vehicle; EV, Full Electric Vehicle; OEM, Original Equipment Manufacturers; GWP, Global Warming Potencial; CED, Cumulative Energy Demand; SMR, Steam Methane Reforming; NEDC, New European Driving Cycle; FTP, Federal Test Procedure.

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doi:10.1016/j.enpol.2011.11.015

over several years. Portuguese EV strategic plan envisages a ratio of 0.15 and 0.25 (chargers/car) for diurnal and nocturnal/balanced areas in a future stable penetration scenario. To evaluate the real effectiveness of EVs, energy and emissions life cycle from this technology, including facilities, should be assessed. An important question is raised, what is the impact of energy supply infrastructures per MJ of supplied fuel, and what is its contribution to the vehicle life cycle analysis, including Well-to-Wheel (WTW) and materials Cradle-to-Grave (CTG) studies?

In the last few years, decision-makers have started looking at LCA for critical inputs, typically related to transportation fuels or the vehicles themselves (Baptista et al., 2010a; 2009; Ferreira et al., 2010; Thomas, 2009). A life cycle considers the stages of a product or service system, from the extraction of natural resources to final disposal (ISO, 2006). Some authors, have also complemented LCA studies with economical evaluations (Veziroglu and Macário, 2011; Huang and Zhang, 2006). In order to effectively mitigate and compare environmental impacts from the various transportation modes, life-cycle environmental performance have to be considered, including both the direct and indirect processes and services required to operate the vehicle. This includes raw materials extraction, manufacturing, construction, operation, maintenance, vehicle's end of life, infrastructure and fuels (Chester and Horvath, 2009; Mulder et al., 2007; Wietschel et al., 2006). Chester and Horvath (2009) developed a comprehensive study regarding support facilities for several powertrains. Specifically for light-duty vehicles, it accounts for facilities such as roads and parking lots. Even though it is of undeniable importance to know its absolute value, it gives little input about the differences between vehicle technologies, due to the fact that these facilities are common to all powertrains. Some attempts have been made to consider the energy supply infrastructure required for some types of vehicle technologies, comparing it with the LCA of fuel. Nansai et al. (2001), performed a LCA of charging stations for electric vehicles (EVs) dividing it in three stages, production, transportation and installation of the charging equipment, which consists of charger, battery and stand. However, it neglects the pathways of energy use and its upstream infrastructure as well as the comparison with other alternative vehicle technologies. Edwards et al. (2008), in CONCAWE study did not consider the environmental load of infrastructures in each technology analysed. Ally and Pryor (2006) study, however comprehensive, did not address the construction, maintenance and decommissioning of refinery facilities. Spath et al. (1999, 2000, 2001, 2004) developed a series of ample studies for power plants in joint collaboration with the National Renewable Energy Laboratory (NREL). Infrastructure inventories are presented and values reported, regarding the contribution of construction and decommissioning in the plant's LCA, vary between 0.4 and 1%. Concerning electricity transport and distribution grid, Harrison et al. (2010), presents an extensive inventory work for Great Britain's grid, estimating values of 0.4 gCO_{2eq}/kWh, while values from Cigre (2004) report a carbon intensity of 0.25 gCO_{2eq}/kWh for the Swedish transmission system. All these studies reveal a great concern with the estimation of CO_2 emissions and energy use of infrastructures and technologies for carbon capture; however, a direct comparison considering different pathways was not conducted and not applied to vehicle technologies, while integrating the whole value chain.

The main goal of this study is to estimate the impact of energy supply infrastructures, on CO_2 emissions and energy use, regarding conventional and electric vehicles, for the specific case of Portugal. Despite being applied to a specific case, the methodology can be extended to other countries/regions. Recent data on the number of gasoline and diesel light-duty vehicles, ratio of stations per vehicle and political electric mobility plans were used for the calculations. For conventional fuels (Gasoline/Diesel) the oil well, platform, refinery, main distribution pipelines and refuelling stations were analysed in the LCA. For the electric vehicle, a natural gas pipeline supply infrastructure, power plants according to an electric mix, transport and distribution grid and charging points were examined. Ultimately, the contribution of these values to the vehicle LCA was estimated. The first step assessed MJ based units, taking into account the energy and carbon intensity efforts associated with the construction, maintenance and decommissioning of each energy supply infrastructure, divided by the total lifetime output energy. Lifetimes can be seen in Tables 1–3 of supporting information (SI). The second step, presents estimations in a km based units, resulting from the multiplication of energy use or carbon intensity MJ based of the first step by the TTW value (MJ/km) of the studied vehicles. This enabled the comparison of the impact of assessed facilities, with values of other LCA stages already performed, for each vehicle technology. This procedure allows the adaptation of the LCA to a different vehicle technology, mix, service ratio and values of TTW. It was also considered the impacts of using an EV, regarding its energy supply infrastructure when compared to the present conventional situation. For ICEV base scenario, the 2005 Portuguese Diesel and Gasoline share data were used. Concerning EV technology, data from MOBI.E (2011), the Portuguese Electric Mobility Programme, were used. For all technologies, driving range average values of 12,800 km per year and a total of 150,000 km during lifetime were assumed ACAP (2006). The data obtained from the inspections dates from 2004, 2005 and 2006. The LCA will be performed according to the Principles of ISO 14040 (ISO, 2006), which are: Goal and scope definition, Inventory, Life cycle impact assessment, Interpretation and improvement. Monte Carlo method was applied for uncertainty analysis.

2. Methodology

Scope and boundaries were outlined for the considered technologies until reaching the vehicle. Three major groups could be identified: primary fuel handling infrastructure, transport system of end fuel and distribution facilities.

In the Inventory stage, Simapro was considered as the reference database and used in triangulation with GEMIS database and existing literature. Scaling techniques were used in order to adjust raw data from the databases, to the Portuguese installations characteristics (ex: installed power, capacity factor or mix). For refinery maintenance estimations, due to lack of data, a parallelism was made between, the cost of infrastructure and its resulting emission and energy use of construction and decommissioning, and the cost per year of maintenance. Knowing how much in terms of materials it represented, it was possible to extrapolate the energy and carbon intensity of the maintenance activity. For non-existing data in the database, such as construction, fuel storage and refinery buildings, estimates were made and included in the inventory. Those values were taken into account in the uncertainty analysis.

Charging points were also missing from literature or databases, with few exceptions (Nansai et al., 2001; ETEC, 2010) where although small inventories were conducted, they were somehow scarce in information and quantities regarding the three charging methods: normal, fast and home charging developed in Portugal. Direct contact with the leading manufacturer of charging stations in Portugal (EFACEC) was made and through direct assessment it was possible to inventory, material, weight and quantities. In addition, also fuel stations had to be inventoried, because values of Simapro, although existing, did not correspond to the size of an average fuel station in Portugal. Furthermore, because fuel stations