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Well-to-wheel costs, primary energy demand, and greenhouse gas emissions for the production and operation of conventional and alternative vehicles

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A B S T R A C T

This study provides a comprehensive comparison of well-to-wheel (WTW) energy demand, WTW GHG emissions, and costs for conventional ICE and alternative passenger car powertrains, including full electric, hybrid, and fuel cell powertrains. Vehicle production, operation, maintenance, and disposal are considered, along with a range of hydrogen production processes, electricity mixes, ICE fuels, and battery types. Results are determined based on a reference vehicle, powertrain efficiencies, life cycle inventory data, and cost estimations. Powertrain performance is measured against a gasoline ICE vehicle. Energy carrier and battery production are found to be the largest contributors to WTW energy demand, GHG emissions, and costs; however, electric powertrain performance is highly sensitive to battery specific energy. ICE and full hybrid vehicles using alternative fuels to gasoline, and fuel cell vehicles using natural gas hydrogen production pathways, are the only powertrains which demonstrate reductions in all three evaluation categories simultaneously (i.e., WTW energy demand, emissions, and costs). Overall, however, WTW emission reductions depend more on the energy carrier production pathway than on the powertrain; hence, alternative energy carriers to gasoline for an ICE-based fleet (including hybrids) should be emphasized from a policy perspective in the short-term. This will ease the transition towards a low-emission fleet in Switzerland.

1. Introduction

The transportation sector is the largest contributor to greenhouse gas (GHG) emissions in Switzerland, representing over 30% of total annual emissions, followed by industrial and household sector emissions (accounting for approximately 20% each) (Swiss Federal Office for the Environment, 2011a). Passenger vehicles account for approximately 70% of all GHG emissions within the transportation sector (Swiss Federal Office for the Environment, 2011b). The relatively large proportion of emissions due to road transport in Switzerland presents an opportunity to reduce national emissions through the adoption of

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alternative powertrain technologies and energy carriers, in conjunction with urban planning and multi-modal transportation schemes.

A range of powertrain technologies and energy carrier production pathways have been proposed with the potential to reduce passenger car well-to-wheel (WTW) primary energy demand (PED) and cumulative greenhouse gas (GHG) emissions compared to a reference gasoline internal combustion engine vehicle (ICEV) in Switzerland in the authors' previous work (Yazdanie et al., 2014). However, only powertrain operation was considered in this study. Costs, as well as vehicle production (including vehicle body, powertrain, battery, and fuel cell production), maintenance, and disposal aspects were not included. Hence, the objective of the current investigation is to build upon the assessment in Yazdanie et al. (2014) by additionally considering these aspects.

The goal of this study is to identify powertrain and production pathways which demonstrate remarkable potential to reduce WTW energy demand, GHG emissions, and costs compared to a reference gasoline ICEV in Switzerland. This is achieved by determining the total WTW primary energy demand and cumulative GHG emissions associated with powertrain operation, production, maintenance, and disposal. Relative costs are determined for key cost differentiators, including energy carrier and battery or fuel cell system production costs.

Powertrains, energy carriers, and production pathways have been selected for evaluation based on their demonstrated potential in Yazdanie et al. (2014). Alternative powertrains include hydrogen fuel cell, battery-electric, and hybrid-electric powertrains; and alternative energy carriers to gasoline and diesel include hydrogen, electricity, biogas, and compressed natural gas (CNG). Lithium-ion (Li-ion) batteries are evaluated, and sensitivity analyses consider variations in battery parameters, electric driving ranges and component costs. Infrastructure requirements and infrastructure costs are not included in the scope of this study.

Various publications have analyzed life cycle or well-to-wheel energy demand, GHG emissions, and/or costs for alternative vehicles. However, studies using life cycle data specific to Switzerland, which also provide a comprehensive comparison of all three evaluation categories for the range of powertrain technologies and energy carrier production pathways evaluated in this study, are not available. The scope of existing studies is also limited to conventional means of hydrogen production, including electrolysis, steam methane reforming, and coal gasification, for example, in Bauer et al. (2015), Campanari et al. (2009), Elgowainy et al. (2009), Huang and Zhang (2006), Wang (2002), and Weiss et al. (2000). Cost impacts of alternative powertrains have also been considered in Eaves and Eaves (2004), Granovskii et al. (2006), Hackney and de Neufville (2001), and van Vliet et al. (2011, 2010); however, a new feature of this study is that it provides a comprehensive comparison of key cost differences amongst powertrains for a wide range of hydrogen production processes and fuels.

This study relies on life cycle inventory data from the Swiss Centre for Life Cycle Inventories' ecoinvent database v.2.2 (Swiss Centre for Life Cycle Inventories, 2011). In contrast to other life cycle inventory databases, such as those provided by North American GREET and GHGenius models, ecoinvent includes data specific to energy production pathways in Switzerland and Europe, which are relevant to this study. The ecoinvent database v.2.2 applies life cycle assessment (LCA) analyses according to the International Organization for Standardization (ISO) guidelines in International Organization for Standardization (ISO) (2006a, 2006b). It also follows IPCC 2007 climate change guidelines (Hischier et al., 2010), which employ IPCC AR4 global warming potential values (IPCC, 2007).

The following sections detail the approach and present results for WTW primary energy demand, WTW GHG emissions, and powertrain costs. Results may be applied in the domain of public policy decision-making in order to develop a roadmap for low-emission mobility in Switzerland.

2. Methodology

2.1. Framework

The general framework of this study is outlined in the following sections.

2.1.1. Powertrains and energy carriers

Key powertrain technologies and energy carriers have been selected based on the results of Yazdanie et al. (2014), as detailed in Table 1. Powertrains include internal combustion engine, electric, fuel cell, and hybrid-electric powertrains, and energy carriers include gasoline, diesel, CNG, biogas, hydrogen, and electricity.

2.1.2. Reference vehicle

A reference vehicle is defined based on Swiss fleet statistics (Swiss Federal Office for Spatial Development, 2006; Swiss Federal Roads Office, 2012). Base vehicle characteristics are provided in Table 2; these parameters were also applied to the reference vehicle in Yazdanie et al. (2014).

Base vehicle characteristics are used to determine all powertrain energy carrier consumption rates as detailed in Section 2.2.1.