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A comparative analysis of well-to-wheel primary energy demand and greenhouse gas emissions for the operation of alternative and conventional vehicles in Switzerland, considering various energy carrier production pathways

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HIGHLIGHTS

- Operational GHG emissions and energy demand are found for alternative drivetrains.
- Well-to-wheel results are compared for several H_2/electricity production pathways.
- Pluggable electric cars (PECs) yield the lowest WTW GHG emissions and energy demand.
- Fuel cell car WTW results are on par with PECs for direct chemical H_2 production.
- ICE and hybrid cars using biogas and CNG also yield some of the lowest WTW results.

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ABSTRACT

This study provides a comprehensive analysis of well-to-wheel (WTW) primary energy demand and greenhouse gas (GHG) emissions for the operation of conventional and alternative passenger vehicle drivetrains. Results are determined based on a reference vehicle, drivetrain/production process efficiencies, and lifecycle inventory data specific to Switzerland. WTW performance is compared to a gasoline internal combustion engine vehicle (ICEV). Both industrialized and novel hydrogen and electricity production pathways are evaluated. A strong case is presented for pluggable electric vehicles (PEVs) due to their high drivetrain efficiency. However, WTW performance strongly depends on the electricity source. A critical electricity mix can be identified which divides optimal drivetrain performance between the EV, ICEV, and plug-in hybrid vehicle. Alternative drivetrain and energy carrier production pathways are also compared by natural resource. Fuel cell vehicle (FCV) performance proves to be on par with PEVs for energy carrier (EC) production via biomass and natural gas resources. However, PEVs outperform FCVs via solar energy EC production pathways. ICE drivetrains using alternative fuels, particularly biogas and CNG, yield remarkable WTW energy and emission reductions as well, indicating that alternative fuels, and not only alternative drivetrains, play an important role in the transition towards low-emission vehicles in Switzerland.

1. Introduction

The transportation sector is the largest contributor to GHG emissions in Switzerland, accounting for over 30% of annual emissions (see Fig. 1a). Passenger cars alone account for nearly 70% of emissions within this sector (Fig. 1b). The Swiss passenger car fleet today is dominated by gasoline and diesel internal combustion engine (ICE) vehicles; however, several alternative drivetrain technologies and energy carriers exist with the potential to reduce transportation sector emissions. Alternative drivetrains include hydrogen fuel cell, battery-electric, and hybrid-electric drivetrains; and alternative energy carriers include hydrogen, electricity, biogas, and CNG.

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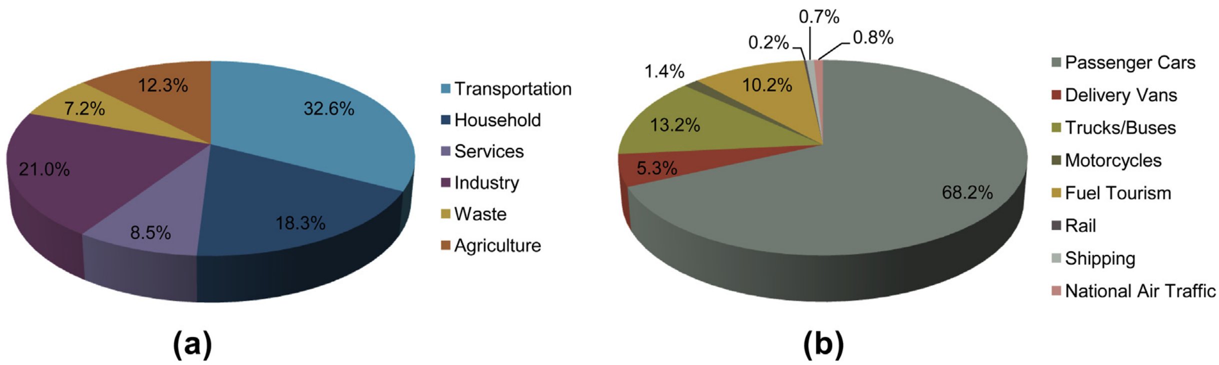

Fig. 1. Annual GHG emissions in Switzerland by sector (a) [1] and within the transportation sector (b) [2].

Given the range of drivetrain, energy carrier, and energy carrier production processes available, it is imperative to understand the well-to-wheel (WTW) primary energy demand and cumulative greenhouse gas (GHG) emissions associated with each option. This information enables a comparative analysis of drivetrain options and is essential in the domain of public policy decision-making in order to develop a roadmap for electric mobility in Switzerland, reduce road transport emissions, and plan infrastructure.

Primary energy (PE) refers to the energy contained in raw fuels, such as oil, natural gas, or biomass, for example. When primary energy undergoes a conversion process, it can be transformed into secondary or useful energy, such as electricity or hydrogen fuel. The primary energy demand for electricity production using a natural gas power plant, for example, encompasses all upstream energy inputs from resource extraction to plant construction and disposal (also known as gray energy). Cumulative greenhouse gas emissions refer to the equivalent carbon dioxide emissions associated with the processing and combustion of primary energy. A well-to-wheel analysis considers PE demand and GHG emissions from resource extraction to vehicle propulsion. Together, WTW energy demand and GHG emissions can serve as performance indicators for alternative drivetrains compared to conventional gasoline internal combustion engines.

This study aims to determine the WTW primary energy demand and GHG emissions associated with the operation (i.e., energy carrier demand) of alternative drivetrains while considering a broad range of hydrogen production and electricity generation pathways in the Swiss context. All energy carrier lifecycle inventory data applies to end-use in Switzerland. The hydrogen production processes investigated include mature technologies, such as steam methane reforming (SMR), gasification, and partial oxidation, as well as relatively novel processes, such as solar thermochemical decomposition and photobiological splitting. A number of drivetrains and energy carriers are examined. Vehicles include fuel cell, electric, hybrid-electric, and conventional ICE drivetrains, while energy carriers include gasoline, diesel, compressed natural gas, biogas, hydrogen, and electricity.

A WTW analysis is also presented according to natural resource categories. This approach provides a unique perspective, pertinent to questions regarding optimal resource allocation in the context of primary energy demand and GHG emissions.

Several studies have presented lifecycle or well-to-wheel energy and greenhouse gas emissions analyses for alternative vehicles and hydrogen production processes; however, studies in the Swiss context, an evaluation according to natural resource categories, and a comprehensive comparison including both mature and novel hydrogen production processes are not available. The scope of current studies is limited to conventional means of hydrogen production, including electrolysis, steam methane reforming, and coal gasification. For instance, Huang and Zhang examine the well-to-wheel energy demand and GHG emissions for hydrogen production via steam methane reforming, coal gasification, and electrolysis for fuel cell vehicles in Ref. [3]. Campanari et al. also perform a WTW analysis for the same hydrogen production pathways in Ref. [4], but they consider ICE, electric, and hybrid fuel cell vehicles, in addition to fuel cell vehicles. Comparative assessments for a similar range of drivetrains are presented in Refs. [5,6,7,8,9,10], but again, the range of hydrogen and electricity generation pathways is limited to conventional means. An exergetic lifecycle assessment (LCA) focused on hydrogen production via electrolysis and SMR for automotive applications is also presented in Refs. [11,12].

This study is novel in three respects. First, it provides a comprehensive, comparative analysis which considers the performance of both commercially-mature and novel hydrogen production processes, multiple electricity generation pathways, and several alternative drivetrains. Second, it applies directly to the Swiss situation; and third, the analysis offers a unique comparison of drivetrain and energy carrier production pathways based on natural resource categorizations.

2. Objective

The objective of this investigation is to determine the well-to-wheel primary energy demand and greenhouse gas emissions associated with the operation of a number of drivetrains, while considering an array of possible hydrogen and electricity production pathways.

The aim is to identify the drivetrain and production pathways which demonstrate the greatest potential to reduce operational WTW energy demand and GHG emissions compared to a conventional gasoline ICE vehicle (ICEV) in the Swiss context. Several possible natural resource pathways are considered. A reference passenger vehicle is defined and serves as the basis for this comparison. Vehicle configurations improving upon the WTW energy demand and GHG emissions of the gasoline ICEV are denoted as competitive options for the purposes of this study.

3. Background information

The following sections provide information on the hydrogen production processes and electricity mixes evaluated in this investigation.

3.1. Hydrogen production processes

3.1.1. Electrolysis

3.1.1.1. Low temperature electrolysis. Electrolysis is a process in which a direct electric current is applied to water via electrodes in