Available online at www.sciencedirect.com
SCIENCE DIRECT®
Energy 31 (2006) 2064–2087
ENERGY
www.elsevier.com/locate/energy

Future fuel cell and internal combustion engine automobile technologies: A 25-year life cycle and fleet impact assessment

Andreas Schäfer[a,*], John B. Heywood[b], Malcolm A. Weiss[c]

[a]Department of Architecture, University of Cambridge, Cambridge CB2 2EB, UK
[b]Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139-4307, USA
[c]Laboratory for Energy and the Environment, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139-4307, USA

Received 21 September 2004

Abstract

Hydrogen fuel cell (FC) vehicles are receiving increasing attention as a potential powerful technology to reduce the transportation sector's dependence on petroleum and substantially decrease emissions of greenhouse gases (GHGs) at the same time. This paper projects energy use and GHG emissions from different FC vehicle configurations and compares these values to the projected characteristics of similarly sized and performing gasoline and diesel fueled automobiles on a life cycle, well to wheels and cradle to grave basis. Our analysis suggests that for the next 20 or more years, new internal combustion engine (ICE) hybrid drive train vehicles can achieve similar levels of reduction in energy use and GHG emissions compared to hydrogen FC vehicles, if the hydrogen is derived from natural gas. The fleet impact of more fuel-efficient vehicles depends on the time it takes for new technology to (i) become competitive, (ii) increase its share of the new vehicles produced, and finally (iii) penetrate significantly into the vehicle fleet. Since the lead times for bringing improved ICE vehicle technology into production are the shortest, its impact on vehicle fleet energy use and emissions could be significant in 20–30 years, about half the time required for hydrogen FC vehicles to have a similar impact. Full emission reduction potential of FC vehicles can only be achieved when hydrogen is derived from zero or very low-carbon releasing production processes on a large scale—an option that further increases the impact leadtime. Thus, a comprehensive short- and long-term strategy for reducing automobile energy use and emissions should include both the continuous improvement of ICE vehicles and simultaneous research and development of hydrogen FC cars.

Keywords: Fuel cell vehicle; Vehicle technology; Life-cycle assessment; Transportation; Greenhouse gas emusions

1. Introduction

Recent advances in fuel cell (FC) technology paired with the long-term vision of a hydrogen economy have raised widespread enthusiasm for hydrogen FC vehicles. The potential benefits of this novel technology are

*Corresponding author. Tel.: +44 1223 331719; fax: +44 1223 331701.
E-mail address: as601@cam.ac.uk (A. Schäfer).

0360-5442/$ - see front matter
doi:10.1016/j.energy.2005.09.011

compelling, i.e., a simultaneous reduction in oil dependence and greenhouse gas (GHG) emissions, and inherently low air pollutant emissions, resulting in major benefits to society. Since FC vehicles depend on a completely new and expensive hydrogen supply infrastructure, some intermediate solutions aim at designing small-scale chemical reactors, which reform gasoline (or methanol) to hydrogen onboard the vehicle.

Largely driven by expectations of rapid technological progress, numerous studies have projected a strongly growing market for carbonaceous fuel reforming onboard or pure hydrogen storing FC vehicles. In 1997, after successfully developing a series of prototypes, one major vehicle manufacturer projected to selling 100,000 methanol FC cars by 2004 [1]. Such exaggerated enthusiasm for future technology has a long history. At the beginning of the first oil crisis in 1973/74, many analysts expected alternative engines (e.g., Stirling engine, gas turbine) to displace the internal combustion engine (ICE). Due to the substantial potential for improving the performance of the ICE and overoptimistic projections of the performance of these alternatives, these projected displacements never materialized.[1] Are we in a similar situation today? While FC vehicles seem to threaten the long-term dominance of ICE vehicles, a wide range of improved component technologies exists that promise extrapolating historical gains in fuel efficiency of ICE vehicles well into the future. A comparison of the future (20 years ahead) potential of FC vehicles to continuously improving gasoline and diesel engine technology is the purpose of this paper.

While many vehicle studies exist that have evaluated the future performance of road vehicles equipped with different fuel-saving technologies (see [2] for a summary), only recently, has substantial research focused on the comparative performance of FC and ICE vehicles. In addition to [3,4], the subject of this paper's life-cycle analysis, we have found several studies [5–9] reporting similar analyses. Common to the latter five studies, which are all important contributions to the field, are two main omissions. None of these studies takes into account the energy use associated with, and GHG emissions from the production of the vehicle itself. Our analysis shows that with rising vehicle fuel efficiency and the extra energy input for producing lighter weight and energy-intensive materials, that life-cycle component becomes increasingly important, in some cases exceeding energy use and emissions from fuel processing and distribution. In addition, neither [5–9] assess the impact of fuel-saving technologies on vehicle fleet energy use and emissions. Such impact analysis is essential in assessing which technologies to invest in, at what points in time, and to what extent in order to achieve substantial reductions of GHG emissions.

We continue by describing the life-cycle analysis that consists of three components, the fuel cycle (well-to-automobile tank), the vehicle on-the-road cycle (automobile tank-to-wheels), and the vehicle material cycle (cradle-to-grave). We then add up all life-cycle components to evaluate total energy use and emissions. In the final stage of this paper we examine the potential impact of ICE hybrid and FC technologies on total US light-duty vehicle fleet energy use and emissions. The broadening focus from an automobile based life-cycle analysis to a light-duty vehicle based fleet impact analysis is important due to the continuously increasing share of pick-up trucks, vans, and sport-utility vehicles in the US vehicle fleet, which now accounts for some 50% of all new light duty vehicles.

2. Overview of the life-cycle analysis

When conducting comparisons of different technology/fuel combinations, the choice of system boundary within which one accounts for energy use and emissions is critical. Since energy use and emissions upstream of the vehicle associated with fuel processing and distribution vary for different transportation fuels, this study considers the entire life cycle, from well-to-vehicle tank and vehicle tank-to-wheels. In addition, highly fuel-efficient vehicles typically incorporate lower resistance vehicle components, including lightweight bodies; since the amount of embodied energy in these components can be significant, such strategies may shift some of the driving related emissions to the factories producing these materials. Hence, in addition to the fuel well-to-wheels approach, we include a cradle-to-grave analysis of the vehicle itself. Together, these two life-cycle components ensure that the system boundary encompasses all significant contributors to energy use and emissions.

[1] An additional barrier to the large-scale introduction of methanol FC vehicles cited above is the extension and conversion of the existing oil-based fuel infrastructure.