Applied Energy 127 (2014) 55–63

Contents lists available at ScienceDirect

Applied Energy

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

Current and theoretical maximum well-to-wheels exergy efficiency of options to power vehicles with natural gas

Michael G. Waller, Eric D. Williams *, Schuyler W. Matteson, Thomas A. Trabold

Golisano Institute for Sustainability, Rochester Institute of Technology, 1 Lomb Memorial Dr., Rochester, NY 14623, United States

HIGHLIGHTS

- Calculated current and theoretical maximum well-to-wheel exergy efficiencies.
- Current efficiency ranking: battery electric > internal combustion > fuel cell.
- Theoretical limit ranking: fuel cell > battery electric > internal combustion.
- Efficiency limiting steps include heat engines, methane reforming and fuel cells.

ARTICLE INFO

Article history:
Received 14 October 2013
Received in revised form 17 March 2014
Accepted 31 March 2014
Available online 3 May 2014

Keywords:
Well-to-wheels
Exergy analysis
Compressed natural gas vehicle
Battery electric vehicle
Fuel cell electric vehicle
Hydraulic fracturing

ABSTRACT

Lower prices and increased supply of natural gas from hydraulic fracturing could lead to widespread use of natural gas in transportation. There are three primary ways that natural gas could be used in personal vehicles: compressed natural gas (CNG) in a combustion engine, as a source of hydrogen for a fuel cell electric vehicle (FCEV), and to generate electricity for a battery electric vehicle (BEV). In this work, we compare these three paths by analyzing their current and theoretical maximum well-to-wheels (WTW) exergy efficiencies. Each pathway begins with the extraction of natural gas and ends with delivery of work to the vehicle's wheels. The best current and theoretical maximum well-to-wheels exergy efficiencies for CNG, FCEV, and BEV pathways are found to be 31%/63%, 25%/87% and 44%/84% respectively. The largest exergy destruction for the CNG pathway occurs within the vehicle's internal combustion engine (ICE) plant, which has a best current efficiency of 35%. For the FCEV pathway the main current sources of exergy destruction are the reforming stage and within the fuel cell engine plant, with best current efficiencies of 69% and 50% respectively. For the BEV pathway, the largest exergetic loss occurs during the conversion from natural gas to electricity at a combined cycle power plant, with a best current efficiency of 59%. While the theoretical maximum succeeds in identifying process steps that limit efficiency, it does not inform how much progress could be made to improve efficiency with what effort.
© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

The automotive transportation sector consumes approximately 27% of U.S. total energy demand, translating to 32% of national greenhouse gas emissions and generating a dependence on foreign oil [1,2]. Consumption of petroleum and its negative side effects not only result from onboard automotive combustion, but also from the entire fuel supply chain including fuel extraction, transport, production, and distribution. In order to address the environmental and social externalities of petroleum, we must transition to a sustainable energy system relying on alternative fuel chains.

In the long term, transportation needs to be based on renewable energy sources. In the meantime, natural gas may serve as an intermediate stage in the transition away from oil as the primary transport fuel [3]. Recently, there has been renewed interest in the cost and future supply of natural gas (NG) due to advances in horizontal drilling and hydraulic fracturing. These advances that began to be widely used in 2005, allow local industries to economically tap into vast reserves of unconventional gas deposits, such as shale gas [4]. Since 1989, the number of onshore natural gas wells has nearly doubled from 2,60,000 to 5,14,637 in 2011 [5]. Additionally, it was estimated that 60% of all new oil and gas wells since 2010 were hydraulically fractured. By 2035, natural gas production in

* Corresponding author. Present/permanent address: Golisano Institute for Sustainability, Rochester Institute of Technology, 1 Lomb Memorial Dr., Rochester, NY 14623, United States. Tel.: +1 585 475 7211; fax: +1 585 475 5455.
E-mail address: exwgis@rit.edu (E.D. Williams).

http://dx.doi.org/10.1016/j.apenergy.2014.03.088
0306-2619/© 2014 Elsevier Ltd. All rights reserved.

the U.S. is expected to increase by 17.8% from 2011, largely resulting from hydraulic fracturing.

Switching from oil-based fuel chains to natural gas is advantageous for several reasons. Combusting natural gas releases far less carbon emissions than oil, partially mitigating our present carbon footprint [6]. Natural gas vehicles generally have low emissions of criteria pollutants such as particulate matter and nitrogen oxides [7]. Most current automobiles can be easily converted to run off of compressed natural gas. There is existing natural gas infrastructure in place providing gas to many residential, commercial, and refueling locations. Due to wide geographical distribution of natural gas resources, energy security issues for the U.S. and other regions are partially mitigated. Lastly, developing natural gas-based technologies would provide flexibility in the future for substitution of carbon neutral fuels such as biofuels and hydrogen.

In this article, we assume that inexpensive and domestically sourced natural gas make it an attractive option for transport and explore the efficiencies of different technological paths to achieve this. There are several options. Direct combustion of compressed natural gas in a vehicle engine is one option, a route that already has achieved a degree of scale in certain markets (e.g. buses, government light duty fleets) [6]. Natural gas is also the most widely used feedstock for hydrogen production, opening the way to power vehicles with highly efficient (though still expensive) fuel cells. Alternately, natural gas can be used to power the expanding fleet of electric and plug-in hybrid vehicles through high efficiency combined cycle power plants.

Realizing motive power at vehicle wheels from natural gas involves a chain of process steps. Life cycle assessment (LCA) is often applied to understand efficiency and material flows in process chains, and in the vehicle world LCA is often termed a well-to-wheels analysis [8,9]. Well-to-wheels analyses have been used to assess the advantages/disadvantages of various pathways [10,11]. LCA alone is not sufficient to address the question of the efficiency of utilizing natural gas for transport because many of the technologies involved are rapidly changing, fuel cells and batteries in particular. LCAs are temporal snapshots that quantify only current or past processes. While there are some efforts to characterize temporal trends [12], in general LCA is silent on the question of future potential for improvement.

To address the critical question of technological progress, here we propose to characterize the current and theoretical physical limits for each energy conversion step in the well-to-wheels pathway. While a physical law limit does not necessarily inform how close an efficiency can approach the limit in practice, nor how difficult it will be to make progress, it does clarify what will not be possible, setting an absolute bound for future progress in a technology path.

This paper presents four contributions to existing literature through:

- Conducting an exergy analysis of competing alternative transport fuels.
- Developing exergy efficiency process chains for each well-to-wheels fuel pathway.
- Assessing the maximum theoretical potential for technological improvement.
- And highlighting major stages in the process chains that need improvement, and the co-benefits from development for various stages.

In the following section we present the methods used to complete this study, while Section 3 describes efficiencies for the individual steps of each process chain. Section 4 provides the results of the study and Section 5 concludes with recommendations for future technological development.

2. Methods

In this work, we pursue a bounding approach to characterize the theoretical maximum efficiency of three transportation fuel supply paths, beginning with natural gas, and compare these physical law limits with current efficiency. The fuels/vehicles analyzed here are:

- Compressed natural gas (CNG) vehicles powered by conventional internal combustion engines (ICE) using natural gas as a fuel supply.
- Battery electric vehicles (BEV) driven by electric motors powered from batteries that store energy taken from the electricity grid; in this study, the electricity is assumed to be generated from natural gas combined cycle (NGCC) power plants.
- Fuel cell electric vehicles (FCEV) that use a proton exchange membrane (PEM) fuel cell stack to generate electricity that powers an electric drive train; the fuel cell engine converts on board compressed hydrogen and oxygen from the air to generate electricity.

An exergy approach was chosen for this analysis because exergy properly accounts for the capacity of a system to do physical work [13,14]. First Law efficiency, often termed "energy efficiency", assumes that all forms of energy (kinetic, chemical, electric, heat, etc.) are equivalent. The capacity of a device to obtain useful work from a given quantity of heat is however, very different from the same quantity of electricity. Exergy, or second law efficiency, describes how some forms of energy have a greater ability to do useful work than others. Exergy, measured in Joules, is thus defined as the maximum useful work that can be obtained when a system is brought to equilibrium with a reference environment. For this analysis, the reference environment described in [15] is used.

The different pathways for this study have been broken into multiple stages where individual exergy efficiencies are calculated and multiplied together for the total pathway efficiency. Common to all pathways are the initial natural gas extraction and distribution steps. The stages following for the CNG pathway include distributed refueling, internal combustion, and vehicle transmission efficiency. For the BEV pathway, additional stages include electricity generation at a natural gas combined cycle (NGCC) power plant, distribution via the electric grid, onboard battery charging/discharging, and vehicle transmission efficiencies. For the FCEV, the stages included are hydrogen (H_2) production through centralized or distributed steam methane reforming (SMR) (in the case of centralized SMR H_2 distribution to individual refueling stations through an H_2 pipeline is necessary), vehicle refueling, onboard power generation, and FCEV transmission efficiency. All considered processes are shown graphically in Fig. 1.

There are a number of prior well-to-wheels analyses of alternative fuel chains such as [3,9,16–19]. This paper differs from prior work by calculating the well-to-wheel theoretical maximum efficiencies for each path, and comparing them with current exergy efficiencies. Additionally, various studies have calculated exergy efficiencies for the individual processes discussed in this work, e.g. [20–22], but none have chained processes together to compare current and limiting efficiencies from exergy source to service.

2.1. Process efficiency analysis

The fuel pathways are compared using the well-to-wheels approach, a term originally created to take into account the emissions associated with fuel extraction and distribution, in addition to on-board vehicle combustion. Using this approach but from an exergy efficiency perspective, all stages in a fuel pathway are

Download English Version:

https://daneshyari.com/en/article/242739

Download Persian Version:

https://daneshyari.com/article/242739

Daneshyari.com