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Well-to-wheel analysis of direct and indirect use of natural gas in passenger vehicles

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ABSTRACT

The abundance of natural gas in the United States because of the number of existing natural gas reserves and the recent advances in extracting unconventional reserves has been one of the main drivers for low natural gas prices. A question arises of what is the optimal use of natural gas as a transportation fuel. Is it more efficient to use natural gas in a stationary power application to generate electricity to charge electric vehicles, compress natural gas for onboard combustion in vehicles, or re-form natural gas into a denser transportation fuel? This study investigates the well-to-wheels energy use and greenhouse gas emissions from various natural gas to transportation fuel pathways and compares the results to conventional gasoline vehicles and electric vehicles using the US electrical generation mix. Specifically, natural gas vehicles running on compressed natural gas are compared against electric vehicles charged with electricity produced solely from natural gas combustion in stationary power plants. The results of the study show that the dependency on the combustion efficiency of natural gas in stationary power can outweigh the inherent efficiency of electric vehicles, thus highlighting the importance of examining energy use on a well-to-wheels basis.

1. Introduction

Recent forecasts for natural gas resources in the United States suggest that this fuel will be abundant and low cost for many decades [1], giving reason to study efficiencies and the environmental impact of the multiple paths for its use. For example, growth of natural gas use in transportation can be achieved by directly fueling combustion engines in trucks and cars, by conversion to a liquid fuel for combustion, or by conversion to electricity for use in the expanding number of electric vehicles in the United States. Consideration of longer-range options might include conversion of natural gas to hydrogen for fuel cell vehicles.

Besides its lower cost, natural gas is an attractive fuel for stationary power applications as well as for transportation due to its reduced criteria air pollutants compared to petroleum-derived fuels such as gasoline and diesel for mobile applications and coal for stationary applications. The lower carbon content of methane (CH_4), the primary constituent of natural gas, has increased interest in natural gas as a low-carbon fuel [2] and provides the additional benefit of lower GHG (greenhouse gas) emissions compared to transportation fuels or coal. To assess the overall GHG impacts of numerous paths for natural gas use, a so-called well-to-wheels analysis is needed.

Methane, the primary component in natural gas, has a high octane number (120) and low boiling point (−161.5 °C), making it an applicable fuel for SI (spark ignition) ICEs (internal combustion engines) [3]. To achieve an acceptable vehicle range between refueling, it is necessary to densify natural gas because CH_4 in its gaseous form has a density of 15.4 g/m^3 at standard temperature and pressure compared to gasoline, which has a density of 744,000 g/m^3. For light-duty vehicle applications, natural gas is typically carried as CNG (compressed natural gas) in tanks pressurized to 3600 psi (248 bar), which brings its energy density to about 26% of that of gasoline. Natural gas has been used as a transportation fuel in the form of CNG for many years in the United States and around the world, though in the United States only approximately 0.1% of the total natural gas consumption is in the form of a transportation fuel [4].This is equivalent to less than ½ billion gallons of gasoline per year. Natural gas compression is often done at a refueling station using industrial compressors and storage tanks, although home refueling compressors have been available for CNGVs (CNG vehicles). In the United States there are currently 112,000 CNGVs on the road, with approximately 574 public CNG filling stations [5]. This is in contrast to the nearly 14.8 million

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natural-gas-powered vehicles around the world [5]. For heavy-duty vehicle applications, cryogenically cooling natural gas to LNG (liquefied natural gas) at −162 °C increases the density but adds substantially to the cost [4]. It is also possible to chemically convert natural gas into a liquid fuel such as DME (dimethyl ether), which has autoignition characteristics similar to diesel fuel, or through a FT (Fischer-Tropsch) or gas-to-liquid process for a fuel that has ignition characteristics more similar to either gasoline or diesel fuel depending on the process. Other possible conversions of natural gas to a transportation fuel include reforming CH_4 into hydrogen for use in hydrogen fuel cells either onboard the vehicle or beforehand in a reforming plant. Natural gas can also be used indirectly as a transportation fuel by firing a power plant to generate electricity for charging EVs (electric vehicles). This is not an exclusive list of natural gas to transportation fuel pathways but serves to illustrate the range of possible fuel pathways.

Both EVs and CNGVs have additional energy storage requirements compared to the standard liquid hydrocarbon fueling system common to conventional gasoline or diesel vehicles. For EVs, considerable additional weight is added to the vehicle with the electric ESS (energy storage system), electric motor, and PEs (power electronics). With HEVs (hybrid electric vehicles), the vehicle has the conventional ICE and hydrocarbon fueling system with the addition of an ESS and PEs. In the case of the HEV, the weight penalty is usually somewhat minimized with the selection of smaller ICE and smaller ESS and PE-electric motor systems. With CNG vehicles, there is an SI ICE with a high-pressure natural gas cylinder in the vehicle. For bi-fuel systems, both a natural gas cylinder and a liquid hydrocarbon fueling system are in place. Besides the additional weight incurred by both EVs and CNGVs, the range of both is markedly smaller than that of a conventional gasoline or diesel vehicle. The vehicle range for a CNG passenger vehicle is about 402 km (250 mi), and the range for a similarly sized EV is about 161 km (100 mi), depending on conditions and driving style [6].

Because the use of natural gas for transportation requires compressing, liquefying, or conversion, it is important to determine the best use of natural gas as a transportation fuel. Specifically, to minimize GHG emissions and total energy use, is it better to use natural gas in a stationary power application to generate electricity to charge EVs, to compress natural gas for onboard combustion in vehicles, or to reform natural gas into a denser transportation fuel? To perform a comprehensive analysis of vehicle platforms with varying upstream fuel pathways, a modified cradle-to-grave lifecycle analysis, known as a WTW (well-to-wheels) analysis, is often performed [7–9]. The WTW analysis is broken down by upstream and downstream energy use, criteria air pollutants, and GHG emissions, as shown in Fig. 1. The upstream or WTP (well-to-pump) part captures the fuel production energy costs and emissions, including T&D (transmission and distribution) pathways, from the point of fuel feedstock extraction to the point where the fuel is transferred to a vehicle in units of kilojoules or grams per megajoule of fuel at the pump for energy use and emissions, respectively. The TTW (tank-to-wheels) part of the analysis only considers the vehicle use energy and emissions in units of kilojoules or gallons per kilometer, respectively.

With pending national and international policies concerning the regulation of GHGs from power generation, transportation, and industrial processes, including proposed rules on GHG limits on vehicles, more attention is being paid to carbon dioxide (CO_2) and other GHG emissions than ever before [10–12]. There are three widely accepted GHGs that result from stationary power generation from combustion: CO_2, CH_4, and nitrous oxide (N_2O) [13].The greatest bulk contributor to GHG emissions is CO_2, which results from the combustion of any hydrocarbon fuel. CO_2 emissions make up between 87% and 99% of the total GHG emissions from stationary power, assuming proper emissions controls are in place. The GWPs (global warming potentials) of CH_4 and N_2O are greater than that of CO_2 over a given time scale (often 100 years). Commonly agreed upon GWP values for CH_4 and N_2O for use in regulations come from the IPCC (Intergovernmental Panel on Climate Change) [13]. For example CH_4, which has a strong role in atmospheric chemistry, has a GWP that is 21 times greater than that of CO_2. Nitrous oxide, which is only produced in very small amounts from combustion, has a GWP that is 310 times greater than that of CO_2, meaning that even small amounts of N_2O can have a very strong effect on GHG emissions. GHG emissions values are presented in terms of CO_2 equivalent (CO_{2eq}), taking into account all of the generated GHGs and their GWPs, which are shown in Table 1. To report GHG emissions on a CO_{2eq} basis, the resultant emissions for each of the GHGs are multiplied by their individual GWP and added.

The primary sources of CH_4 emissions from using power generation from natural gas are small leaks in the natural gas infrastructure, known as CH_4 leakage, or from incomplete combustion during engine operation, known as CH_4 slip. The GHG benefits of using natural gas as a fuel depend on minimizing CH_4 leakage and slip during the entire fuel pathway [13–15]. GHG emissions from centralized stationary power depend on the electrical generation mix, which varies regionally depending on the service provider. In the United States, the electrical generation mix varies considerably

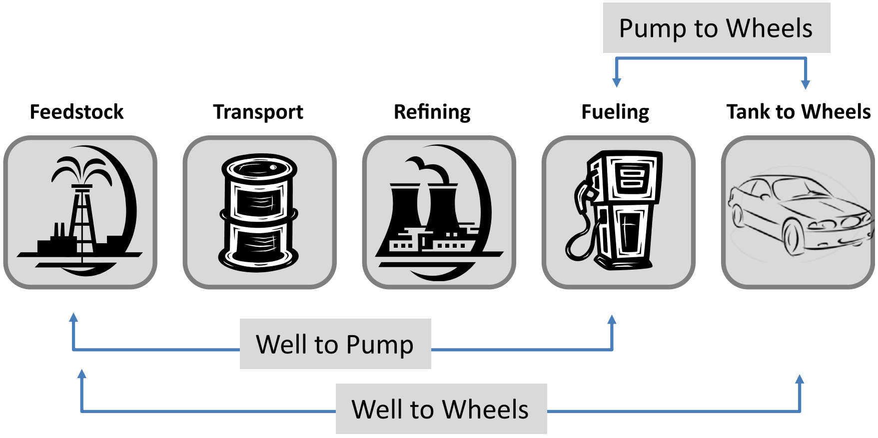

Fig. 1. WTW fuel pathway.