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Well-to-wheel assessment of natural gas vehicles and their fuel supply infrastructures – Perspectives on gas in transport in Denmark

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ABSTRACT

In this paper, potential natural gas and renewable natural gas supply pathways and natural gas vehicles (NGVs) have been selected and evaluated with regards to well-to-wheel energy expended, greenhouse gas (GHG) emissions, and regulated (air pollutant) emissions. The vehicles included in the evaluation are passenger cars, light-duty vehicles (LDVs), and heavy-duty vehicles (HDVs) for road-transport applications, and a short-range passenger vessel for maritime transport applications. The results show that, compared to conventional fuels, in both transport applications and for all vehicle classes, the use of compressed and liquefied natural gas has a 15–27% GHG emissions reduction effect per km travel. The effect becomes large, 81–211%, when compressed and liquefied renewable natural gas are used instead. The results are sensitive to the type and source of feedstock used, the type of vehicle engine, assumed methane leakage and methane slip, and the allocated energy and environmental digestate credits, in each pathway. In maritime applications, the use of liquefied natural gas and renewable natural gas instead of low sulfur marine fuels results in a 60–100% SOx and 90–96% PM emissions reduction. A 1% methane slip from a dedicated LNG passenger vessel results, on average, in 8.5% increase in net GHG emissions.

1. Introduction

The EU-27 countries reduced their total greenhouse gas (GHG) emissions during 1990–2014 by 23%. However, due to increased transport demand and low share of renewables, in the same period, the transport sector's GHG emissions increased by 20.1% (European Enviromental Agency, 2017). Road transport accounted for 73% of the total emissions in 2014.

Recently, in addition to improving vehicle efficiency, the development and use of alternative fuel vehicles has become increasingly important to decarbonise the transport sector. With a high energy-to-carbon ratio, stable and low price, and abundant availability natural gas (NG) is an alternative to conventional transport fuels. Its low energy density (resulting in limited driving ranges) and low cetane number (restricting its use in compression engines without pilot diesel injection) are technical limitations. However, generally, natural gas vehicles (NGVs) could increase the fuel diversity by adding renewable natural gas (RNG) and NG into the petroleum-dominated transport sector while alleviating the driving range shortcomings of battery electric vehicles (BEVs) and hydrogen fuel cell vehicles (HFCVs). This approach could potentially reduce air pollutant emissions in metropolitan areas.

Globally, as of 2016, there are more than 23 million NGVs are on the road, comprising 1.32% of the total vehicle population

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(IANGV, 2016); 66% in Asia Pacific, 24% in Latin America, 8.6% in Europe, and 1.4% in Africa and North America. Compared to the market development in Asia Pacific and Latin American countries, in Europe the development is slow, except for a few countries such as Italy, Germany, and Sweden (Engerer and Horn, 2010; IANGV, 2016).

The environmental advantages of NGVs are mostly reported in terms of on-board combustion alone or tank-to-wheel (TTW) analysis. In this regard, knowledge of the well-to-wheel (WTW) overall emissions, energy demand, and fuel production cost of alternative technologies is critical for its adoption and metering its true economic values over conventional transport technologies.

Diesel is the primary fuel in heavy duty vehicles (HDVs). In road-transport, HDVs are a main source of air pollutants, mainly NOx and PM (Durbin et al., 2008; Huai et al., 2006). In Europe, HD trucks account for around 10% of the vehicle population in urban areas, but their emission and noise levels account for more than 40% (Zunder and Ibanez, 2004). As a clean burning fuel, NG most importantly could replace diesel in HDVs for air pollutants abatements better than other fossil fuel-based alternative fuels (Osorio-Tejada et al., 2017). Alamia et al. (2016) showed the WTW GHG emissions reduction of biomethane (based on thermal gasification of woody biomass) and compressed/liquefied natural gas (CNG/LNG) over diesel, in HDVs, to be as high as 67% and 15%, respectively; however, the WTW energy consumption of biomethane was almost twice that of diesel in most cases. CNG buses were found to have lower marginal cost of GHG emissions reduction than diesel buses (McKenzie and Durango-Cohen, 2012). In DENA (2014), it was shown that the source and transport distance of LNG to retail points and the thermal efficiency of the engine largely determines the environmental advantages of LNG in HD trucks. In the European C-segment (medium) car applications, CNG showed a lower WTW GHG emissions but a higher WTW energy consumption than petrol/diesel cars (JRC, 2014). In Arteconi et al. (2010), based on the European gas mix, the use of an LNG import terminal showed a 10% WTW environmental advantage over diesel while an on-site small scale LNG plant showed zero advantage. On the other hand, Curran et al. (2014) suggested using NG in gas turbines for powering EVs instead of direct on-board combustion in NGVs.

Recently, real-world emission characteristics of NGVs were investigated, i.e. bi-fuel (CNG and gasoline) cars (Yao et al., 2014), light-duty vehicles (LDVs) (Huo et al., 2012; Karavalakis et al., 2012; Zhang et al., 2010), and HDVs (Lou et al., 2013; Zhang et al., 2014), questioning the energy and environmental advantages of using NG as vehicle fuel. CNG refuse trucks showed a substantial cut in NOx and PM emissions, but limited effect for CO and HC emissions, compared to diesel refuse trucks (Fontaras et al., 2012). In Karavalakis et al. (2012), it was shown that the NG composition has a direct impact on the fuel economy and CO_2 and non-methane hydro carbon (NMHC) emissions of LDVs.

For maritime transport applications, LNG is becoming widely accepted as a potential alternative fuel, driven by the newly imposed 0.1% sulfur limit on vessels cruising within emission control areas (ECA)[1] and the increasingly stringent environmental regulations for open seagoing vessels at large (International Maritime Organization (IMO), 2016). As of 2015, globally, about 70 LNG ships (excluding LNG carriers) were in operation, predominantly regional ferries (38%) and platform supply vessels (27%), and 80 ships were under construction (expected to be ready by 2018). Norway is in the vanguard with more than 59% of the worldwide operational LNG ships. The main market drivers in Norway are the nationally allocated NOx fund[2] and taxes imposed on NO_x, CO_2 and SO_x (Høibye, 2014). Globally, some of the challenges often referred to are lack of bunkering standards and regulatory framework, reduced cargo space (due to LNG fuel tank), bunkering losses, availability of bunkering ports, and high upfront vessel added cost (Eise Fokkema et al., 2017).

Methane leakage during bunkering might potentially offset the overall environmental advantages of LNG; in Corbett et al. (2015) it was reported that a 1% methane leakage increases the net GHG emissions of the vessel by 8.2–10% and in Chryssakis et al. (2015) that, on a WTW basis, a 5.5% methane leakage would result in zero GHG emissions reduction advantage over diesel fuel.

Jafarzadeh et al. (2017) showed that the price gap (between LNG and MGO) and tax level on NO_X and SOx are important factors in the conversion of marine gas oil (MGO) fishing vessels into LNG vessels and for the improvement of the environmental profile of the fishing industry at large. In addition, the level of presence in ECA areas, price gap (MGO/LNG), and vessels' fuel consumption are critical for the profitability of LNG vessels over conventional vessels (Eise Fokkema et al., 2017).

Due to computational and modelling framework limitations, techno-economic modelling of alternative technologies lacks the ability to capture the energy consumption and GHG and air pollutant emissions associated with the production of alternative fuels. Several of the studies related to the evaluation of energy and environmental performance of alternative technologies in transportation and stationery service demands demonstrated that TTW analysis alone would not be enough to characterise and understand the true environmental and energy values of alternative technologies. This strongly suggests that a detailed WTW analysis is essential in fully understanding the energy and environmental impact of alternative technologies, and for consistent comparison between alternative technologies. In addition, most prior WTW studies focused on macro-level analysis, and a detailed and site-specific analysis would be of interest in the light of the importance of the local energy infrastructure and context, as it is plausible that it could capture details that would otherwise be usually ignored. Thus, the aim of this study is to analyse the WTW energy consumption, GHG emissions, and air pollutant emissions of selected compressed/liquefied renewable natural gas (CRNG/LRNG) and CNG/LNG fuel supply pathways[3]

[1] Emission control areas (ECAs) are: the Baltic Sea (only for SOx), the Northern Sea (only for SOx), the North America area (SOx, NOx, and PM), and the United States-Caribbean Sea (SOx, NOx, and PM).

[2] The Norwegian government imposed a tax on NOx emission (about 2 €/kg NOx from ships, fishing vessels, and other industries) and allocated the NOx fund for reducing measures. LNG-fuelled ships are eligible for 25 €/kg annual NOx emission reduction support, with a maximum amount equivalent to 75% of the additional investment costs of LNG propulsion.

[3] Pathway refers to a specific predetermined route designed to supply fuel to vehicles. Throughout the paper, we used the prefix 'selected' because we selected few pathways out of many gas supply possibilities; based on resource availability, infrastructure development or readiness, and other factors that related to Denmark.