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A review of liquefied natural gas refueling station designs

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ABSTRACT

The majority of operational liquefied natural gas (LNG) refueling stations in the world have no boil-off gas (BOG) management and rely on regular LNG delivery to condense the BOG. To reduce the pressure of LNG tanks onboard vehicles prior to filling, the BOG is vented to the atmosphere, is collapsed in the tank, or is returned to the refueling station. In this study, different onboard LNG tank architectures are discussed, and the design strategies for LNG conditioning and BOG management technologies employed in LNG refueling stations are analyzed. The critical analysis of different designs of LNG refueling stations indicates that 44% of designs have no BOG management, 28% of designs rely on liquid nitrogen condenser or a liquefier to condense the BOG, and 28% of designs compress the BOG to produce compressed natural gas. Our research shows that in China and the U.S., where stations with BOG management are rare, the number of LNG refueling stations has increased by 32 and 3 times, respectively, between 2010 and 2015. This study highlights the fact that as heavy fuel oil and diesel are replaced by LNG, it is critical to pay proper attention to the design of the LNG supply chain and LNG refueling stations to minimize or eliminate BOG venting and reduce greenhouse gas emissions.

1. Introduction

Climate change is one of the main concerns of the 21st century [1], and eliminating the greenhouse gas (GHG) emissions from industrial and transportation processes is one of the most pressing challenges [2,3]. For many years, natural gas (NG) has been proposed as a transitional, low-carbon fuel [4]. More recently, renewable natural gas [5–10] has emerged as a potential link between existing distribution infrastructure and renewable energy sources. The benefits associated with NG use have been reported by several authors focused on economic and market growth [4,9–19]. However, and despite this significant body of work, the overall benefits associated with NG use remain uncertain.

The announcements at the 21st Conference of Parties (COP) in Paris indicate that reaching the 2 °C scenario targets would require immediate and significant changes over the next three decades (as opposed to changes occurring over centuries) [20]. The relative impact of methane (the main component in NG) compared to CO_2 may have to be revised to accommodate these more aggressive targets. More importantly, the reduction in CO_2 emissions from NG use must be compared to the impact of the corresponding methane emissions. We illustrate the importance of these considerations by reviewing the state-of-the-art in liquefied natural gas (LNG) refueling stations. Without reliable data on the actual deployment technologies, most of the models and analyses comparing widespread NG use to the existing energy options will remain incomplete.

NG is composed of methane (83–99.7%), ethane, propane, butane, and nitrogen [21], and has the lowest carbon-content compared to petroleum fuels, such as diesel and gasoline [22]. During combustion, NG emits less CO_2 and lower levels of criteria pollutants than diesel. Fig. 1 shows that the replacement of diesel with NG can potentially reduce CO_2 and NOx emissions up to 20% [23,24] and 90% [25,26], respectively, and SOx and particular matter emissions by almost 100% [24]. By regulation in Europe and North America [27,28], ultra-low-sulphur diesel (ULSD) was phased in for on-road vehicles between 2006 and 2010. This regulation came into effect in North America for off-road, rail, and inland waterway marine applications between 2007 and 2014 [28].

NG is delivered in two forms to consumers who are not connected to gas pipelines: compressed natural gas (CNG) and LNG. LNG is about 600 times denser than gaseous NG at atmospheric pressure, and as a result, LNG is the most efficient way of transporting NG across long distances when pipelines are not available. The volumetric energy density of LNG at −162 °C and 90 kPa is 22.2 MJ/L which is about 60% that of diesel and 2.45 times higher than that of CNG at 25 MPa (3,600 psig) [6]. This makes LNG an attractive fuel for heavy-duty trucks [29–31], trains [22,32,33], and ships [25,34], where fuels with high energy densities are required.

LNG is a cryogenic liquid stored at temperatures as low as −162 °C. Heat transfer from the environment to the LNG causes the evaporation

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Nomenclature

BOG	Boil-off gas
CNG	Compressed natural gas
GHG	Greenhous gas
GWP	Global warming potential
LCNG	Liquefied-compressed natural gas
LNG	Liquefied natural gas
LN_2	Liquid nitrogen
NG	Natural gas
MAWP	Maximum allowable working pressure
ULSD	Ultra-low-sulphur diesel

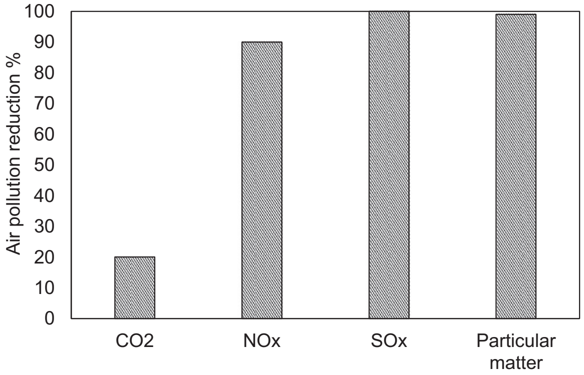

Fig. 1. Air pollution reduction% by combusting NG instead of diesel.

of LNG, generation of boil-off gas (BOG), and consequently, an increase in pressure [35]. To maintain the LNG at low temperatures and pressures, LNG carriers release the BOG to atmosphere [36], re-liquefy it, or consume it in their engines [37]. In small LNG facilities, such as LNG refueling stations, the BOG gradually increases the pressure of the storage system. By regularly delivering “unsaturated” LNG to these refueling stations, the BOG is condensed and the storage tank pressure reduces before reaching its maximum allowable working pressure (MAWP) [38]. Unsaturated LNG refers to the LNG at a less than −143 °C and 0.34 MPa (35 psig) [39]. The MAWP of LNG storage tanks is set at 1.3 MPa (175 psig) [38]. In LNG refueling stations with low fuel delivery rates, the BOG generation causes the pressure of LNG storage tanks to rise and the chance of BOG release rate to the atmosphere increases [38].

CO_2 and methane emissions account for 92% of global GHG emissions [2]. Methane is the main constituent of NG [21]. Recent studies [30,40] showed that the well-to-wheels methane emissions from NG value chain (including LNG) had up to 72 times more impact on climate change than CO_2 in a 20-year period due to higher radiative forcing of methane. Delgado and Muncrief [30] used the concept of global warming potential (GWP) and the data available from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model 2014 to compare well-to-wheels GHG emissions of NG and diesel. With total emissions of 1.12% and 1.19% for conventional NG and shale gas, respectively, their analysis indicated that switching from diesel to NG reduced the GHG emissions by 4–5% over a 100-year period. However, in a 20-year time horizon, NG emissions corresponded to 19–24% increase in the GHG emissions compared to diesel.

In 2015, Burnham et al. [41] analyzed and compared the methane leakage in four links across the NG value chain (Table 1). They used the GREET model 2015 for their analysis.

Table 1 shows that, on average, 8.40 to 8.68 g methane/ m^3 NG is emitted to the atmosphere across the NG value chain. This is equivalent to emissions of about 605 to 625 g $CO_{2\ \mathrm{equivalent}}$/ m^3 NG in a 20-year horizon [42]. Table 1 also indicates that the transmission and storage sector contributes to 33–35% of methane emissions, and the distribution sector, which includes refueling stations, fueling process, and onboard LNG tanks, contributes to 28% of methane emissions. This shows that the transmission, storage, and distribution sectors are the largest contributors to the methane emissions in the production and distribution chain. As a result, preventing heat transfer to LNG and controlling BOG release will significantly reduce the GHG emissions from these sectors.

A survey of the available literature shows that the BOG release rate from different designs of LNG refueling stations had not been quantified accurately. Powars [38] reported that the average methane venting from stations was about 1 vol% per delivery of unsaturated LNG to the stations. Using a lumped-body model, Powars showed that a 15,000 gal capacity LNG station with a 1,000 gal LNG/day dispensing during a 4-hr window remained under the MAWP of 1.3 MPa (175 psig), whereas the same capacity station with a 500 gal LNG/ day dispensing during a 2-hr window reached the MAWP within 15 days. In 2015, Hailer [44] measured the methane emissions from two LNG refueling stations. Hailer reported that one of the operating LNG stations had a methane emissions of 0.1% to 1.5% of fuel dispensed to vehicles and the second station had a methane emissions of 0.9% to 5.3%. Hailer also pointed out that the methane emissions from LNG refueling stations were not necessarily due to the heat transfer to the LNG storage tanks. The BOG returned from vehicles to the station also caused a sudden pressure rise in the LNG storage tank and pressure relief valves were activated.

Prior work has highlighted the importance of mitigating the release of methane along the supply chain [7]. However, there have been limited studies on the technological aspects of methane abatement in the NG delivery chain. The main focus of this study is therefore on the technological aspects of LNG refueling stations and fuel supply systems of LNG-fueled vehicles, and how these technologies contribute to reducing methane emissions from the natural gas supply chain. In this

Table 1
Methane emissions across different sectors.

Sector	g methane/ m^3 NG (vol%) GREET Model 2015 [41]		g $CO_{2\ \mathrm{equivalent}}$/ m^3 NG Global Warming Potential [42,43]			
	Conventional NG	Shale gas	Conventional NG		Shale gas	
			20-year horizon	100-year horizon	20-year horizon	100-year horizon
Gas field	2.16 (0.30)	2.44 (0.34)	156	54	176	61
Processing	0.92 (0.13)	0.92 (0.13)	66	23	66	23
Transmission and storage	2.93 (0.41)	2.93 (0.41)	211	73	211	73
Distribution (station pathway)	2.39 (0.34)	2.39 (0.34)	172	60	172	60
Total emission	8.40 (1.18)	8.68 (1.22)	605	210	625	217

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