Switching from MGO to LNG: An Assessment of Potential Emissions from Marine Fuels in the Inland Rivers

Edward W. Carr*
ecarr@udel.edu
207-518-8662
School of Marine Science and Policy
College of Earth, Ocean, and Environment
University of Delaware, Newark, DE

James J. Corbett
jcorbett@udel.edu
302-831-0768
School of Marine Science and Policy
College of Earth, Ocean, and Environment
University of Delaware, Newark, DE

*Corresponding Author

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ABSTRACT

An abundance of natural gas and increasingly stringent air quality regulations have led the marine transportation industry to investigate the use of liquefied natural gas as a marine fuel. This paper focuses on the projected change in emissions associated with a shift from marine distillate fuels to liquefied natural gas for vessels operating on the inland waterways in the United States. This paper focuses on the eastern Ohio River and its tributaries. Results show a greater than 90% reduction in emissions of nitrogen oxides, sulphur oxides, and particulate matter with the adoption of liquefied natural gas over marine distillates. Greenhouse gas emissions are unchanged due to higher emissions of methane during the total fuel life cycle of liquefied natural gas.
INTRODUCTION

Scope and Purpose
This work investigates end use and life-cycle contexts for the introduction of alternative fuels in an inland maritime commercial navigation fleet. This paper characterizes fleet technology and informs longer term technology-policy decisions regarding regional transportation innovation. This paper focuses on the Mid-Atlantic Transportation Sustainability University Transportation Center (MATS UTC) Region 3, but include adjacent waterborne freight corridors that connect with other regions.

UTC Region 3 covers a domain that includes domestic inland river shipping in West Virginia, Pennsylvania, Virginia, Maryland, and Delaware. This paper investigates domestic fuel infrastructure and shallow water navigation technologies in the region and assesses the emissions reductions associated with a transition to natural gas propulsion for the inland river fleet.

The study focus mainly addresses natural gas in liquefied (LNG) contexts, but the infrastructure and vessel activity analysis can be applied to compressed natural gas (CNG) by the region’s vessels. Discussion of a fleet switch over to natural gas products is currently focused on LNG and motivated by the high volume of natural gas being produced from Marcellus Shale deposits within UTC region 3.

This study characterizes the inland river fleet in UTC region 3 (henceforth referred to as Region 3), primarily on the Ohio, Allegheny, Monongahela, Kanawha, and Big Sandy Rivers. Based on the existing fleet composition, this paper considers technology performance comparisons for vessels to switch from traditional marine bunker fuels (marine gas oil/MGO) to natural gas fuels (LNG).

BACKGROUND AND LITERATURE

This analysis focuses on vessel activity on the Region 3 rivers shown in FIGURE 1 (DOT 2014; MATS 2015). The region of study includes Ohio and Kentucky, as these states share borders with important rivers, such as the Ohio and Big Sandy Rivers, and thus the study area includes vessel traffic that crosses from Region 3 into these states. Vessel activity is derived from AIS (Automatic Identification System) data from the USCG Zone 17, which provides coverage for all river segments east of the Ohio/Indiana state border (NOAA 2015).

MATS UTC Region 3 Overview
The recent boom in natural gas extraction in the Marcellus Shale region, located primarily in West Virginia and Pennsylvania, has led to an abundance of natural gas. Production continues to grow, reaching 15 billion cubic feet per day through July 2015 and accounting for almost 40% of US shale gas production (EIA 2015a). As production has increased, prices in the northeast region have fallen relative to the Henry Hub price. This source of relatively inexpensive fuel, coupled with tighter controls on vessel emissions has led the industry to investigate the use of natural gas products, such as liquefied natural gas (LNG) as marine fuels (Pospiech 2013; Banawan, El Gohary, and Sadek 2010; Wang and Notteboom 2014).
LNG is a cryogenic liquid, formed by cooling natural gas (methane, CH₄) down to -162°C at atmospheric pressure (Balon, Lowell, and Curry 2012). Consequently, LNG can be distributed, stored, and dispensed like other liquid fuels, provided the temperature of the liquid remains below -162°C. If LNG rises above this temperature, a fraction of the liquid will be lost due to “boil-off”, i.e. change from the liquid phase to the gas phase. This boil-off is one potential source of greenhouse gases (GHGs), as methane has a warming potential 30 times greater than that of CO₂ (Myhre et al. 2013).

LNG fuels emit lower levels of criteria pollutants such as nitrogen oxides (NOₓ), sulphur oxides (SOₓ), and particulate matter (PM₁₀ and PM₂.₅) (Afon and Ervin 2008; Bengtsson, Andersson, and Fridell 2011; Corbett, Thomson, and Winebrake 2014; Thomson, Corbett, and Winebrake 2015). LNG is not without its challenges as a fuel, however. Land-based studies of electricity generation estimate that leakage during the upstream, liquefaction, and shipping stages of exported LNG are up to 37gCO₂eq/MJ (Abrahams et al. 2015). The biggest technological challenge facing the adoption of LNG as a marine fuel is the requirement for larger fuel tanks and fuel systems, resulting in the entire system taking up three to four times as much space as conventional HFO/MGO engines and thus reducing available cargo space (Wang and Notteboom 2014).

International Maritime Organisation (IMO) regulations state that vessels operating within the US exclusive economic zone (EEZ) must reduce the sulphur content of marine bunker fuels such that they do not exceed 0.1% sulphur as of January 1, 2015 (IMO 2014). Prior to these rules going into effect vessels were burning either heavy fuel oil (HFO) or marine gas oil (MGO), which have sulphur contents of 3.5% and 0.1% respectively. In response to these emission controls vessel operators are looking for avenues of compliance, with LNG fuel switching a potential alternative to exhaust gas scrubbers (Wang and Notteboom 2014). Inland vessels in the US are within this sulphur control zone, but are unaffected by recent rule changes as inland vessels are already required to use low sulphur fuels (EPA 2015a).

For the most part, LNG vessel interest has focused on oceangoing and coastal fleets. To date there are over 100 non-LNG carrier vessels operating on LNG fuels, operating primarily in Norwegian coastal waters (DNV GL 2014). Estimates of LNG
vessel build costs and retrofits are scarce due to the emerging nature of the technology and the relative paucity of LNG vessels in operation. Balon et al. (2012) provide a rough estimate of vessel conversion costs at $7.2 million, with the fuel system accounting for $6.0 million. Balon et al. (2012) further estimate that over a ten-year period a typical tug could save almost $7 million in fuel costs after converting to LNG from HFO or MGO. Parsons et al. (2013) estimate that the cost to convert a 7000kW, 30,000 ton, Great Lakes Steamship would be much greater, at $15.5-17.5 million. Parsons et al. (2013) predict that annual fuel cost savings of $2.3-2.5 million, compared to current steam technology, would partially offset high initial capital costs.

Modernization and infrastructure development may be needed on inland rivers in the United States. The Inland Waterway Network (IWN) is aging. The average age of lock and dam infrastructure on the waterways is 61 years according to USACE statistics (USACE 2014a) and the average age of towboats is 40.1 years (USACE 2014b). The IWN (FIGURE 1) is a network of rivers providing a water arterial for the movement of freight including coal and farm goods around the American mid-west and ultimately internationally via the Mississippi River.

While compressed natural gas may be a ready source of alternative marine fuel, better fuel storage densities favor liquefaction, and motivate study of the potential use of LNG as a marine fuel in inland waterway transport. Also motivating the study are local-scale studies conducted in Pittsburgh (Port of Pittsburgh Commission 2015), the shifting marine fuels industry, and the abundance of relatively inexpensive LNG fuel. Coupled with a need for infrastructure upgrades on the IWN and stricter marine emission regulations changing conditions on the IWN present an opportunity for research into the modernization of the aging Region 3 fleet.

US Army Corps of Engineers (USACE) data were used to identify and describe the fleet of tug and towboats operating on the IWN in Region 3 using and AIS data provided by the US Coast Guard (USCG) was used to describe vessel activity. Total emissions of greenhouse gases (GHGs) and criteria pollutants (NOx, SOx, PM10, CO) in the region were estimated based on AIS activity from 2013. Using the same vessel activity from 2013, this paper employs an LNG retrofit scenario, which assumes that all vessels are retrofitted to run on LNG and natural gas liquefaction facilities are available. GHGs and criteria pollutants are estimated for an LNG fleet as well as estimates of fuel consumption for current and LNG technologies. Opportunities for LNG infrastructure development and capital costs are briefly discussed.

**METHODS AND DATA**

First, vessels operating in Region 3 were characterized based on operational characteristics such as age, vessel type, and installed horsepower. Second, vessel activity was analyzed, including speed, number of voyages/trips, estimated emissions, and estimated fuel consumption.

**Vessel technology evaluation**

We use data from the United States Army Corps of Engineers to describe the fleet characteristics, and AIS data from the National Oceanic and Atmospheric Administration (NOAA) and the United States Coast Guard (USCG) to characterize vessel activity in Region 3.
Summary of age characterization

The USACE lists a total of 2,332 towboats as registered in the inland waterway network. Of these, 797 are registered to cities within states in, or directly adjacent to (Ohio and Kentucky), UTC Region 3.

Towboats

The mean age of towboats in Region 3 and adjacent states of the inland river system is 40.1 years, including retrofitted vessels. Vessels aged 40 and above comprise 48.9% of all towboats. The majority of vessels in Region 3 are more than 30 years old (80%), with 110 vessels (13.8%) less than 20 years old.

Horsepower

The distribution of vessel horsepower for towboats on the inland rivers is positively skewed, with 68.6% of all towboats registering horsepower below the mean value of 1,982 horsepower (1 hp = 746 watts (W)) (EIA 2015b). In general, Region 3 towboats are low powered and ageing. The geospatial location for each towboat home berth was obtained by geocoding the “Base1” variable in the USACE “towb13.txt” file available at http://www.navigationdatacenter.us/db/wtlus/data/, which describes the operation headquarters for each vessel in the USACE registry. Estimated average horsepower by river segment was based on vessels registered within that river segment. The mean horsepower of all Region 3 towboats was applied in cases where no towboats were registered in a river segment.

Analysis of Vessel Activity

AIS data provided by the United States Coast Guard (USCG) http://marinecadastre.gov/ais/) was used to analyze vessel activity on the inland rivers in Region 3. AIS data are continuously collected using land, sea, and satellite-based receivers and provide vessel information such as unique vessel identifier, location, ship type, speed, length, and course. Vessel identifiers are encrypted in the data provided by USCG and so it is not possible to directly link the USCG AIS data to the USACE list of registered vessels described in the previous section.

USCG AIS data are provided in ESRI file geodatabase point format, which provides geospatial information for each vessel observation point. The geodatabase was clipped to only include inland river data points, leaving 14.5 million AIS data points describing all of UTM Zone 17 for the year 2013. These AIS data were then used to estimate vessel operations on Region 3 Rivers.

AIS data can be used in a number of ways to explain vessel movements in a given region. It is possible, yet computationally intensive, to link each data point in a vessel track using a common “VoyageID” identifier. In order to reduce computational overhead, a modified technique was applied, whereby AIS data such as speed and number of voyages were aggregated by river segment, thus providing mean transit statistics for each river segment in 2013.

Speed

Vessel speed is encoded in the AIS files as Speed Over Ground (SOG), given in knots (kt). All SOG values below 0.2kts were removed from the dataset, under the assumption
that speeds from 0 - 0.2kts correspond with berthed/anchored vessels and observed fluctuations in the data for some vessels while at berth, but still includes most maneuvering vessels. SOG values in Zone 17 had a mean and standard deviation of 4.24 and 2.35 respectively. The mean SOG was then calculated for each river segment in the USACE inland waterway network.

**Voyages**

The USCG AIS data set links individual vessel observation points with specified voyages. Each point corresponding with a given vessel on a given voyage has a unique “VoyageID” identifier from which the number of vessels transiting a given river segment was estimated. For each unique “VoyageID” observed in a given river segment, it was assumed that the vessel transited the entirety of the river segment. A total of 1,813 voyages were observed in Region 3 rivers in 2013. Voyage counts per river segment are shown in (FIGURE 4).

**Vessels**

Although identifying information is scrubbed from the AIS dataset, a unique, encrypted, Maritime Mobile Service Identity (MMSI) is provided for each vessel observed. MMSI was used to count the number of vessels operating in Region 3 rivers, as well as the vessel types. In total, 334 vessels completed 1,813 voyages in 2013. 86% of voyages were completed by towboats and tugs, with an additional 11% of voyages performed by tows longer than 200m in length. (http://www.navcen.uscg.gov/pdf/AIS/AIS_Special_Notice_and_AIS_Encoding_Guide_2012.pdf)

Given that well over 85% of all voyages were by towboats, emissions estimates by assume that all voyages are by tugs/towboats. Over 90% of tugs/towboats are category 1 vessels, and given the horsepower profile (> 1000kW) and aging nature of the fleet we assume that all vessels are Tier 0 vessels (EPA 2009). There are four kinds of distillate fuels in marine service, DMX, DMA, DMB, and DMC. DMA, which contains no traces of residual fuel and is also referred to as MGO, is used primarily in Category 1 engines (EPA 2008). The carbon content of these four distillate fuels is largely the same, thus CO₂ emissions assuming MGO provides a robust estimate, even if some vessels use other marine distillates. Based on information from EPA, all vessels in Region 3 are currently assumed to be burning MGO/DMA.

**Emissions**

River segment estimates of speed, horsepower, and voyages can be used to estimate towboat emissions using Equation 1.

**Equation 1: Emission estimation methodology**

\[
\text{Emissions} = \text{Power} \times \text{Activity} \times \text{Load Factor} \times \text{Emission Factor} \times n\text{Voyages}
\]

Where emissions (g/kWh) are a function of the number of voyages and installed vessel power (kW), hours of vessel activity (h), load factor (the fraction of main engine load used for propulsion), and the emission factor (g/kWh). Emission factors for Marine
Distillate Fuels (MGO) and liquefied natural gas (LNG) fuels are shown in TABLE 1. Emission factor describes the amount of a given pollutant emitted per kilowatt-hour of engine activity. Emission factors are typically calculated by empirical observation of a representative sample of engines. Bengtsson et al. (2011) compiled LNG emission factors using data from EPA and Wartsila, a major manufacturer of ship engines. Bengtsson et al. compiled MGO emission factors from data from the Swedish Environmental Protection Agency, which closely agree with values used by EPA (EPA 2009) and in Europe (Campling et al. 2013).

TABLE 1 Emission Factors (g/kWh) for towboats using MGO and LNG fuels (Bengtsson et al., 2011)

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>MGO (g/kWh)</th>
<th>LNG (g/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSFC</td>
<td>217</td>
<td>183</td>
</tr>
<tr>
<td>CO₂</td>
<td>266</td>
<td>205.2</td>
</tr>
<tr>
<td>NOₓ</td>
<td>5.4</td>
<td>0.61</td>
</tr>
<tr>
<td>SO₂</td>
<td>0.18</td>
<td>0</td>
</tr>
<tr>
<td>PM₁₀</td>
<td>0.12</td>
<td>0.03</td>
</tr>
<tr>
<td>CO</td>
<td>0.47</td>
<td>1.01</td>
</tr>
<tr>
<td>N₂O</td>
<td>0.014</td>
<td>-</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.0018</td>
<td>1.01</td>
</tr>
</tbody>
</table>

(BSFC: Brake Specific Fuel Consumption)

A load factor of 69% was used to estimate towboat emissions, as suggested by Koerber et al. (2007) and employed by Comer et al. (2011) to estimate emissions from marine vessels in the Great Lakes and portions of the inland waterway system. Upstream emissions are accounted for using results from Corbett, Thomson, and Winebrake (2014).

Fuel Consumption

Fuel consumption is estimated using the same formula as for emissions, shown in Equation 1, and using the MGO and LNG BSFC for the emissions factor for criteria or greenhouse gas pollutants. Brake Specific Fuel Consumption (BSFC) describes the amount of fuel used to produce 1kWh.

RESULTS

The base case presents results for the existing MGO fleet, while the LNG scenario estimates emissions and fuel use for a fleet-wide switch to LNG.

Base Case: Existing fleet

Base Case: Fuel Consumption

Our results show that total fuel consumption in Region 3 and adjacent states was 35,434,000 gallons, or 113,000 metric tons, in 2013 (1 metric ton MGO = 7.64 barrels (EIA 2015c); 1 barrel = 42 gallons). The results from our analysis using AIS data are validated using fuel tax data (Dager 2014) collected for the inland waterways, as shown in TABLE 2. Our estimated fuel consumption results all undercount compared to fuel tax
Our results likely provide conservative estimates of fuel consumption as they do not account for fuel burned in auxiliary engines, and by main engines when waiting at dams and shoals in the river. Note that the Ohio River segment in the fuel tax data describes the length of the Ohio River, from Pittsburgh to its confluence with the Mississippi, and thus our modeled estimates are notably lower as our study area only captures segments east of the Ohio-Indiana state line. The entire length of the Ohio River is listed as 864.7 miles in the USACE IWWN shapefile. This study only estimates emissions over the 445.8 river miles downriver of Pittsburgh at the confluence of the Ohio, Monongahela, and Allegheny Rivers, equivalent to 51.6% of miles on the Ohio River. Assuming a uniform distribution of fuel consumption over the length of the Ohio River, applying this distance ratio to the fuel tax data yields expected fuel consumption of about 180,000 tons. Thus our estimate is on the same order of magnitude, and appears reasonable without additional processing of AIS data for the western reaches of the Ohio River (planned for future work).

Our estimates report fuel consumption on the Monongahela River to be 23% of the fuel use expected from the fuel tax data. This discrepancy might be explained by the fact that vessels may purchase fuel in one river segment, but then travel to adjacent segments. The AIS data show vessel traffic as constrained to the first 32 miles of the Monongahela from its confluence with the Allegheny and Ohio Rivers. It is conceivable that vessels operating in this region might purchase fuel at locations along the Monongahela, but spend much of their time operating along reaches of the Ohio River.

**Base Case: Emissions and GHG profiles**

Vessel activity on the inland rivers in Region 3 resulted in the regional emissions of 3,000 tons of NO\(_x\), 100 tons of SO\(_x\), 70 tons of PM\(_{10}\), and 260 tons of CO in 2013, as shown in FIGURE 2.

Inland river vessels in Region 3 emitted 148,400 tons of CO\(_2\) in 2013, along with 1 ton of CH\(_4\) and 8 tons of N2O, resulting in a total CO\(_2\) equivalent of 150,600 metric tons. Our results employ global warming potential estimates from Myhre et al. (2013) where CH\(_4\) = 30, N2O = 265. For reference, EPA estimates are CH\(_4\) = 25, N2O = 298 (EPA 2015b).
TABLE 2  Comparison of modeled fuel consumption (gallons) with fuel tax data for the inland rivers and projected LNG fuel consumption in Region 3

<table>
<thead>
<tr>
<th>WTWY</th>
<th>River Name</th>
<th>MGO Modeled</th>
<th>Fuel Tax Data</th>
<th>LNG</th>
</tr>
</thead>
<tbody>
<tr>
<td>2027</td>
<td>Kanawha River, WV</td>
<td>5,800</td>
<td>11,956</td>
<td>5,300</td>
</tr>
<tr>
<td>2028</td>
<td>Elk River, WV</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>2077</td>
<td>Monongahela River, PA and WV</td>
<td>2,200</td>
<td>9,546</td>
<td>2,000</td>
</tr>
<tr>
<td>2078</td>
<td>Ohio River</td>
<td>104,400</td>
<td>345,054</td>
<td>94,100</td>
</tr>
<tr>
<td>2345</td>
<td>Big Sandy River, KY and WV</td>
<td>400</td>
<td>-</td>
<td>400</td>
</tr>
<tr>
<td>2346</td>
<td>Little Kanawha River, WV</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>2347</td>
<td>Muskingum River, OH</td>
<td>100</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>6529</td>
<td>Allegheny River PA</td>
<td>100</td>
<td>612</td>
<td>100</td>
</tr>
</tbody>
</table>

Sum
Boil-off
Total

LNG Scenario: Fleet-wide switch to LNG

LNG Scenario: Fuel Consumption
Fuel consumption would be an estimated 102,000 metric tons of LNG if all vessel operations for 2013 were switched to LNG fuel. The difference in fuel consumption is because the BSFC per kWh is lower for LNG than MGO, as described by Bengtsson et al (2011) (TABLE 1). This value represents the quantity of fuel used by vessel for propulsion, not accounting for boil off. Assuming a boil-off rate of 0.15% per day (Hasan, Zheng, and Karimi 2009), the total annual LNG fuel required, including boil-off, would be 102,200 metric tons as shown in TABLE 2 (1 metric ton of LNG = 10.4 barrels (EIA 2015c))

LNG Scenario: Fleet Emissions and GHG profiles
A Region 3 inland river fleet using LNG would emit an estimated 340 tons of NOx, near zero tons of SOx, 20 tons of PM10, and 560 tons of CO as shown in XXX, which also shows differences in emissions between MGO and LNG. Switching to LNG results in a 90% reduction in NOx, a near complete reduction in SOx, a 97% reduction in PM10, and a 215% increase in CO.
Fleet wide downstream CO₂ emissions from LNG vessels are estimated at 114,300 tons based on 2013 activity. LNG vessels will emit an estimated additional 780 tons of CH₄ through combustion, and 20 tons of CH₄ from boil-off, resulting in a total CO₂ equivalent of 137,500 metric tons, a 8.6% reduction in GHG emissions from fuel combustion compared with MGO during the in-use phase.

*Life Cycle Emissions*

As mentioned previously, upstream leakage of natural gas can occur during the extraction, liquefaction, transportation, and regasification phases. Total lifecycle analysis uses estimates of emissions at all stages of the fuel cycle, from the “well-to-hull,” thus providing a more accurate picture of the GHGs emitted compared to analysis GHGs from fuel combustion alone. A report for the US Maritime Administration (MARAD) estimates that for vessels burning MGO, for every 170g of CO₂eq emitted during the downstream combustion phase, 45g are emitted during the upstream distribution and feedstock phases (Corbett, Thomson, and Winebrake 2014). MGO vessels emitted an estimated 150,600 tons CO₂eq during the downstream phase, thus using the ratio of 170:45, upstream MGO emissions result in an additional 40,000 tons of CO₂eq, bringing the total GHG emissions from MGO vessels up to 190,400 tons CO₂eq.

Corbett et al., (2014) estimate that for every 180g of CO₂eq emitted by an inland river towboat during the downstream LNG combustion phase, 65g of CO₂eq are released during the fuel transfer and feedstock stages. The LNG combustion phase emitted 137,500 tons CO₂eq. Using the ratio above, 180:65, to estimate the additional upstream GHG emissions associated with LNG use results in an estimated 50,000 tons CO₂eq emitted during the upstream stages. Thus the total GHG emissions are estimated to be 187,200 tons CO₂eq, or a 1.7% reduction compared with MGO (FIGURE 3). Given the approximate nature of calculations at this scale, this result should be interpreted as near GHG parity between MGO and LNG.
DISCUSSION

Potential benefits for GHGs and air quality
A fleet-wide switch to LNG would result in a 1.7% reduction in GHGs from vessels operating in Region 3 when considering the total fuel life cycle. Given the inherent imprecision of inputs to activity estimates, which could vary by more than 2%, this small difference likely represents GHG parity between LNG and MGO fuels for vessels in inland river service. However, our results find substantial reductions in air pollutants. With the exception of CO which yields a 215% increase, a fleet-wide switch to LNG would result in an over 90% reduction in NO\textsubscript{x}, SO\textsubscript{x}, and PM\textsubscript{10}.

Opportunities within Region 3
FIGURE 4 shows the density of natural gas processing facilities in Region 3 along with the number of voyages per river segment. The Ohio River and tributaries flow through a network of natural gas processing facilities, with a number of facilities in close proximity to the IWWN.

It is important to note that these facilities do not produce LNG through liquefaction or perform LNG peak shaving, and that there are currently not any liquefaction facilities in close proximity to Region 3 rivers (DOT 2015). Natural gas processing plants are included as a proxy for natural gas processing activity, with the potential for LNG facilities in the region. All natural gas processing facilities shown are well within the typical 250-mile drayage radius for transporting natural gas products (Stewart et al. 2014; Neandross et al. 2014) indicating the possibility for joint liquefaction/natural gas processing facilities. Despite the availability of natural gas processing facilities in the region, major infrastructure upgrades would be required to support LNG as a fuel on the inland rivers.

The highest number of voyages per river segment occur along the Ohio River west of the Big Sandy River, and between the Little Kanawha and Big Sandy Rivers,
meaning any LNG bunkering facilities installed along these reaches would be highly
transited and accessible. Note that no data are shown for reaches of the Ohio River in
western Ohio and Indiana as the AIS region changes from Zone 17 to Zone 16.

FIGURE 4 Number of voyages per river segment and density gradient showing
clustering of LNG processing facilities in region 3 near parts of Region 3 waterways
(EIA 2015d)

FIGURE 5 shows fuel use by river segment along with ports listed as offering
bunkering services in the USACE port and waterway facilities database (USACE 2015). USACE lists a single facility, located on the Ohio River just west of the confluence with the Big Sandy River, as offering “gas” bunkering services. All fueling facilities listed in Region 3 offer either petroleum products or are listed generally as offering “fuel” bunkering services.

The highest MGO fuel consumption occurs along the Ohio River west of the confluence with the Big Sandy River, with fuel use declining slightly up to the confluence with the Little Kanawha River.

FIGURE 5 Fuel use by river segment and bunkering facilities by fuel type (USACE 2015)
The mean vessel age is highest in the reaches around Pittsburgh, at the confluence of the Allegheny, Monongahela, and Ohio Rivers with the average age in three reaches being above 50. The Kanawha and Big Sandy Rivers are home to vessels with a mean age greater than 39.5. Only in 7 reaches in Region 3 is the mean vessel age below 32, further demonstrating the aging nature of the IWWN fleet of tug and towboats.

CO₂ emissions are greatest along the Ohio River downstream of the Little Kanawha River (FIGURE 6). Driven by a high number of voyages along this river, CO₂ emissions far exceed IWWN emissions in the eastern Ohio River corridor around Pittsburgh. CO₂ emissions also serve as a proxy for criteria pollutant emissions, which follow the same pattern of intensity and distribution as CO₂ emissions. Population density is low along most reaches of the eastern Ohio River in our study region, with the exception of Pittsburgh at the confluence of the Allegheny, Monongahela, and Ohio Rivers.

Given high fuel consumption, number of voyages, CO₂ and criteria pollutant emissions, and average vessel ages along the Ohio River downstream of the Little Kanawha River, this area merits further study as a potential region for investment in LNG infrastructure.

FIGURE 6 CO₂ emissions from IWWN vessel activity in 2013 and 2010 Census population density

CONCLUSIONS
The average age of all towboats registered in Region 3 is 40.1 years. Vessels ages are above the regional average in the reaches around Pittsburgh as well as the Kanawha and Big Sandy Rivers in West Virginia. While likelihood of retrofitting vessels in such an old fleet may be low, vessel operators may have an opportunity to phase in new, LNG, vessels as they retire vessels at the end of their operational life.

In total, towboats in Region 3 consumed 113,000 metric tons (45,434,000 gallons) of marine distillate fuel in 2013. Of this total, 104,400 tons were consumed along the Ohio River. Switching to LNG would result in a drop in fuel consumption to 102,200 metric tons (9.5% change). Vessel activity is high in regions close to natural gas.
processing facilities, aiding connection with existing natural gas infrastructure by either truck or pipeline.

LNG bunkers would reduce criteria pollutants by 90% for NO$_x$, ~100% for SO$_x$, and 97% for PM$_{10}$. CO emissions would increase by 215%. Vessels operating on Region 3 waterways emitted GHGs totaling 190,400 tons CO$_2$eq in 2013. If the entire fleet were to switch over to LNG and maintain similar operations, factoring in upstream leakage, GHG emissions would be nearly on par with MGO use. Emissions of CO$_2$eq and criteria pollutants are greatest along the Ohio River from the Little Kanawha downstream into Kentucky, thus any reduction in criteria pollutants from an LNG fuel switch would have the greatest impact in these regions.

This fleet of inland vessels operates most voyages occurring along the Ohio and Kanawha Rivers in West Virginia. Vessels operating around Pittsburgh are older, with average age more than 50 years; however, relatively few voyages occur in this region. CO$_2$ and criteria pollutant emissions are greatest along the Ohio River in West Virginia and Kentucky.

West Virginia merits more study as an available option for investment in LNG infrastructure in Region 3 based on analysis of vessel activity and emissions. However, the fleet investment challenge in this region must be considered along with infrastructure. We assume LNG availability in the region; however, further work is required to study the LNG fuel supply market, as well as better characterization of the costs associated with a switch from MGO to LNG. Rivers in West Virginia are highly used, resulting in high fuel consumption and GHG and criteria pollutant emissions. Additionally towboats registered in the region are among the oldest, on average, in Region 3 and thus apparent opportunities for capital investment need to be studied further. Waterways in West Virginia are close to natural gas processing facilities and IWWN ports offering bunkering services, offering an opportunity for LNG facilities to link the two. Further studies are required to estimate the magnitude of the health benefits associated with a switch to LNG fuels. While all of Region 3 would benefit from air quality improvements associated with a switch to LNG, the magnitude of reductions, in terms of tons of pollutant abated, would be greatest in West Virginia.
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