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Air quality and health effects of a transition to ammonia–fueled shipping in Singapore

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Abstract

Ammonia has been proposed to replace heavy fuel oil (HFO) in the shipping industry by 2050. When produced with low-carbon electricity, ammonia can reduce greenhouse gas emissions. However, ammonia emissions also contribute to local air pollution via the formation of secondary particulate matter. We estimate the potential ammonia emissions from storage and bunkering operations for shipping in Singapore, a port that accounts for 20% of global bunker fuel sales, and their impacts on air quality and health. Fuel storage and bunkering can increase total gaseous ammonia emissions in Singapore by up to a factor of four and contribute to a 25%–50% increase in ambient PM$_{2.5}$ concentration compared to a baseline scenario with HFO, leading to an estimated 210–460 premature mortalities in Singapore (30%–70% higher than the baseline). Proper abatement on storage and bunkering can reduce these emissions and even improve ambient PM$_{2.5}$ concentrations compared to the baseline. Overall, while an energy transition from HFO to ammonia in the shipping industry could reduce global greenhouse gas and air pollutant burdens, local policies will be important to avoid negative impacts on the communities living near its supply chain.

1. Introduction

The shipping industry has set a target to reach net zero greenhouse gas emissions by 2050 (IMO 2023). Shipping accounts for 85% of international trade per year by weight (United Nations Conference on Trade and Development 2018) and contributes 2.5% of global anthropogenic carbon dioxide (CO$_2$) emissions by burning 250 million tons (Mt) of heavy fuel oil (HFO) and diesel in engines (Corbett and Koehler 2003, Bows-Larkin et al 2015). The combustion of HFO and diesel also leads to emissions of particulate matter (PM) and its precursor gases. The primary and secondary particles smaller than 2.5 µm in diameter (‘PM$_{2.5}$’) emitted from domestic and international shipping or formed in the atmosphere via chemical reactions are estimated to directly contribute 1%–25% of PM$_{2.5}$, SO$_2$, and NO$_x$ in most port areas (Contini and Merico 2021) and lead to over 80 000 premature deaths per year globally (Bilsback et al 2020). Moreover, these shipping-related emissions and hence their impacts are unevenly distributed because port cities and regions along major shipping lanes get a disproportionately larger share of the burden.

A variety of low-carbon and low-air-pollution fuels are being explored to mitigate the shipping industry’s climate impacts (McKinlay et al 2021). Among these fuels, ammonia (NH$_3$) is proposed as the dominant option (IEA 2021). The International Energy Agency (IEA) projects ammonia to supply over 60% of the global shipping industry’s energy demand by 2050 in their Net Zero Emissions scenario. For scale, this
ammonia demand for shipping (∼200 Mt) would be similar to the total current global ammonia production of 180 Mt (Rouwenhorst et al. 2022). However, ammonia production, storage, and transport can also lead to ammonia leaks in liquid and gaseous forms (Al-Breiki and Bicer 2020a), which are toxic to both humans and the ecosystem. Incomplete ammonia combustion also leads to the formation of nitrous oxide, which has a global warming potential of 273 compared to carbon dioxide (Niki 2021). While the greenhouse gas emissions and aquatic toxicity impacts of ammonia as a maritime fuel are estimated to be lower than HFO (Bicer and Dincer 2018, Chalaris et al. 2022), the air quality impacts are not yet well characterized.

Concerns about the air quality impacts of the shipping industry are particularly acute in port cities. Previous work has investigated the air quality impacts of HFO combustion in ports and proposed various technology and policy solutions (Bilsback et al. 2020). Leakage from fueling/refueling (also known as ‘bunkering’) and fuel storage poses more limited air quality concerns for HFO but could play a more significant role with ammonia. The shipping industry’s bunkering and storage operations are even more concentrated than shipping activity, with 16 ports supplying approximately 60% of the global maritime fuel in 2020, mainly as HFO and diesel (IMO 2021). Among these, Singapore supplied approximately 50 Mt or 20% of the total global HFO for ships in 2021 (IMO 2021, Singapore MPA 2022a). The Singapore government has been responsive to the International Maritime Organization’s environmental directives and has enforced a sulfur cap on their bunkering operations (Singapore MPA 2022a). Moreover, the Maritime and Port Authority of Singapore has outlined incentives (e.g., up to a 100% rebate on the annual tonnage tax) for ships using green fuels such as ammonia (Singapore MPA 2022b).

Ammonia already leads to substantial air quality and health impacts globally. It is the dominant cationic species in the atmosphere and reacts with sulfates and nitrates to form secondary PM. By this secondary PM formation mechanism, ammonia contributes to over 20% of total ambient PM$_{2.5}$ concentrations in many rural areas and cities (Gu et al. 2021, Park et al. 2021, Chen et al. 2022). While the agricultural sector (via fertilizer application) emits approximately 90% of the anthropogenic atmospheric ammonia, sources such as vehicular emissions and power plant combustion dominate ammonia emissions in cities (McDuffie et al. 2020, Kawashima et al. 2022). Due to ammonia’s contribution to secondary PM$_{2.5}$, ammonia reduction is also seen as a potential mitigation step toward reducing the overall PM$_{2.5}$ concentration in urban areas (Gu et al. 2021). Secondary PM$_{2.5}$ formation in Singapore is currently likely ammonia-limited due to the higher observed molar concentrations of sulfate than ammonia in Singapore’s atmosphere (Weagle et al. 2018). Singapore currently emits and receives PM$_{2.5}$ and gaseous emissions from the shipping sector, a variety of other activities, and nearby countries such as Malaysia and Indonesia (Balasubramanian et al. 2003, Sheldon and Sankaran 2017).

In this study, we investigate the potential impacts on air quality and public health in Singapore resulting from replacing HFO with ammonia in the shipping sector. Our primary objective is to assess and quantify the range of potential consequences associated with this energy transition. To estimate the quantity of ammonia required in Singapore, we employ energy equivalency calculations, while emissions from storage and bunkering operations are estimated using a range of possible leak rates and abatement measures. Subsequently, we employ a reduced-complexity air quality model to evaluate the potential effects of ammonia shipping on PM$_{2.5}$ concentrations and premature mortality in Singapore. This research expands upon a substantial body of literature investigating the impact of energy transitions on health and air quality (e.g., Pye et al. 2020, Rathod et al. 2022) and specifically emphasizes the supply-side emissions resulting from the use of ammonia as a shipping fuel. These effects have not been extensively explored, and our work aims to provide an initial estimation of the potential magnitude of air quality and health effects to inform ongoing policy discussions in the shipping sector (e.g., GCMD 2022).

2. Methods

2.1. Ammonia emissions from storage and bunkering

To estimate ammonia emissions storage and bunkering, we first estimate the amount of ammonia that would be stored/bunkered in Singapore in the year 2050 if all demand for shipping fuels were met by ammonia. We assume no net change in the shipping industry’s annual energy demand between 2020 and 2050 based on IEA’s Sustainable Development Scenario (SDS) (10.7 EJ in 2020 to 10.5 EJ in 2050) and Net Zero Scenario (10.7 EJ in 2020 to 10 EJ in 2050). We thus multiply the current HFO bunker volume for Singapore with the gravimetric energy density ratios of HFO and ammonia. HFO here means all marine gas oil plus diesel that was bunkered in Singapore in 2020. The 2020 bunkered HFO values are sourced from the Singapore maritime agency (Singapore MPA 2022a), and energy densities (42 and 23 MJ kg$^{-1}$ for HFO and ammonia, respectively) are sourced from a recent study (McKinlay et al. 2021). While current ammonia-fueled marine
engines have thermal efficiency that are 30%-50% lower than those fueled by HFO (McKinlay et al 2021), we assume that by 2050 these efficiencies will be similar, and hence the fuel consumption will be directly proportional to the ratio of gravimetric energy densities (Wolfram et al 2022).

Ammonia emissions, mainly as boil-off gas leaks, occur in two key phases of the supply chain at ports: storage and bunkering (Al-Breiki and Bicer 2020a, 2021). We estimate these emissions at the Singapore port by multiplying the bunkered ammonia volume by a leak emission factor of 0.052% (or 0.52 g per kg fuel stored/bunkered) from Al-Breiki and Bicer (2020a, 2020b) (equation (2)). We refer to this estimate as the medium leak scenario. This emission factor is lower than the emission factors for liquefied natural gas (0.3%) and liquid hydrogen (0.18%) storage and bunkering used in maritime fuel feasibility studies (Lowell, Georgeff 2020). For a potential upper bound or high leak scenario, we assume the emission factor is a factor of two higher based on the uncertainty in ammonia emission factors from fertilizer storage (Beusen et al 2008). We also simulate abatement scenarios in which we apply 100% abatement to storage and 50% to bunkering based on plausible best-available technologies (i.e., recapture and/or flaring for storage leaks and advanced repair and process improvements for bunkering leaks). This results in a total of six leakage scenarios (see table 1).

Equations (1) and (2) summarize our calculation of total bunkered ammonia in 2050 (NH₃ Bunkered) and total emissions from bunkering and storage (NH₃ Emissions):

\[ \text{NH₃ Bunkered}_{2050} = \text{HFO Bunkered}_{2020} \times \frac{\text{ED}_{\text{HFO}}}{\text{ED}_{\text{NH₃}}} \]  

\[ \text{NH₃ Emissions}_{2050} = \text{NH₃ Bunkered}_{2050} \times \text{EF}_{\text{scenario}} \]  

In these equations, NH₃ Bunkered₂₀₅₀ is the mass of bunkered ammonia in Singapore in 2050 in Mt; HFO Bunkered₂₀₂₀ is the present-day bunkered HFO in Singapore in Mt; EDₜₜ is the gravimetric energy density of HFO and ammonia, respectively, in MJ kg⁻¹; NH₃ Emissions is the amount of ammonia leaked into the atmosphere from storage and bunkering processes in kt yr⁻¹; and EFscenario is the combined emission factor for ammonia bunkering and storage, in units kt ammonia emitted per Mt ammonia stored/bunkered, for a given leakage scenario.

Our study focuses on ammonia emissions from bunkering and storage, and thus we exclude other potential emissions changes from a transition to ammonia fuels. First, for a small country like Singapore, we assume they will acquire, rather than produce, ammonia and thus exclude ammonia emissions from production. Second, we do not include combustion-related emissions of ammonia at ports. While bunkering and storage are expected to be NOₓ-free (with the potential exception of flaring as an abatement measure), its combustion may produce NOₓ emissions. While ships spend a relatively shorter time at ports (~20 of over 500 h per ship in the open sea, Nguyen et al 2022), they also operate engines less efficiently, potentially leading to disproportionately high emissions. However, data on these emissions for ammonia fuels is currently limited, and our reduced complexity air quality model does not include this emission source. We acknowledge that the relative air quality impacts of ammonia and HFO fuels from combustion at ports may differ (e.g. Nguyen et al 2022). Mitigation approaches such as using shore power could reduce these emissions (Wan et al 2019).

### 2.2. Atmospheric modeling for secondary PM$_{2.5}$

We estimate the potential PM$_{2.5}$ change in the ambient air of Singapore due to a transition to ammonia fuels for shipping using the Greenhouse Gas Air Pollution Interaction Synergies (GAINS) model. GAINS estimates ambient PM$_{2.5}$ concentrations by using source–receptor relationships obtained using perturbed simulations in the European Monitoring and Evaluation Program (EMEP) atmospheric chemistry-transport model (Amann et al 2020). GAINS has a variable model resolution, with 0.1° by 0.1° resolution in urban areas and 0.5° by 0.5° elsewhere. It is important to note that the GAINS model’s representation of the conversion of precursor gases to PM$_{2.5}$ uses a linear form that has primarily been modeled for small changes (5%-50%) in emissions (Kiesewetter et al 2015a, 2015b). Thus, the response in PM$_{2.5}$ change due to a large increase in ammonia emissions might have large uncertainties in the GAINS model (Kiesewetter et al 2015b).

#### 2.2.1. Ammonia emissions

We represent the estimated ammonia emissions from bunkering and storage in Singapore by modifying the GAINS emission inventory model to include this new emissions source (Kiesewetter et al 2015b, Klimont et al 2017, Rafaj et al 2018, Amann et al 2020). We explicitly specify the total mass of ammonia emitted from bunkering and storage in the ‘Other_Industrial_Process’ category. Emissions in this category are spatially distributed equally over the industrial areas of Singapore and are assumed to be emitted constantly (in other
words, they do not have seasonality). Given that current HFO bunkering in Singapore has no seasonality (Singapore MPA 2022a), the GAINS assumption of constant emissions is reasonable for our analysis. The assumption of uniform spatial distribution across industrial zones may lead to a misallocation of emissions to locations farther from the port area and either underestimate or overestimate impacts in densely populated regions. However, due to Singapore’s relatively small size (730 km²) compared to the scale of the GAINS model grid (100 km²), we believe the effects of this misallocation will be small. Additional uncertainties linked to the resolution of the GAINS model are discussed in section 3.4.

2.2.2. Other emissions
Ammonia primarily reacts with other anionic atmospheric species such as sulfates and nitrates to form PM (Gu et al 2021). Emissions of these other species are expected to change under the climate policies that would likely coincide with an ammonia transition in the shipping sector. We set emissions from other sectors to follow the IEA’s SDS (Rafaj et al 2018), which roughly represents the Shared Socioeconomic Pathway-1 with a 2.6 W m⁻² end-of-century radiative forcing. We also use the standard GAINS maximum feasible reduction (MFR) abatement strategy (Klimont et al 2017, Rafaj et al 2018), where the best available abatement measures are adopted starting from 2020 and peaking by 2040. We specify shipping emissions for our baseline scenario using the ECLIPSE_V6a_MFR inventory, in which the PM_{2.5} emissions from the shipping sector are reduced to 20% in 2050 compared to 2020 levels (Klimont et al 2017). GAINS does not simulate natural sources such as dust and sea salt; instead, their concentrations are prescribed using the EMEP’s air quality model simulations (Amann et al 2020).

We then run the following scenarios using the GAINS model for the year 2050: (a) baseline, where HFO fuels continue to be used in shipping but with reduced emissions due to abatement policies (see above), (b) medium leak (unabated), (c) medium leak (storage abated), (d) medium leak (both abated), (e) high leak (unabated), (f) high leak (storage abated), and (g) high leak (both abated) (see table 1). Due to the scenario development workflow in GAINS, structurally removing the HFO emissions layer from the model in our ammonia scenarios was not feasible; thus, the leak scenarios have baseline HFO emissions included. To remove the effect of these HFO emissions, we simulate a scenario with HFO emissions removed and then retroactively subtract this HFO contribution from each of the leak scenarios. This process allows us to assess the effects of the various leakage scenarios. This subtraction occurs after the model simulates PM_{2.5} emissions from the shipping sector are reduced to 20% in 2050 compared to 2020 levels (Klimont et al 2017). GAINS does not simulate bias in the modeled concentration.

2.3. Health effects
We estimate the impact on public health by calculating the additional premature deaths among adults older than 25 years due to elevated PM_{2.5} levels from ammonia emissions using the global exposure mortality model (GEMM, developed by Burnett et al 2018). The concentration–response parameters for GEMM were established for five main causes of death linked to air pollution: ischemic heart disease, stroke, chronic obstructive pulmonary disease, lung cancer, and lower respiratory infections. GEMM relies on three inputs: population data, cause-specific baseline mortality rate, and PM_{2.5} concentrations. Following Burnett et al (2018), we assume the health impacts of PM_{2.5} are consistent across compositions, implying that ammonia–heavy aerosols do not differ in health effects from combustion or sea salt aerosols. For our study, we use the 2019 figures from the Global Burden of Disease 2019 report, available at https://ghdx.healthdata.org/gbd-2019 (Vos et al 2020). We assume the 2050 population and baseline mortality rates remain unchanged from 2019, which may affect the absolute results but not the relative comparisons across our scenarios. To determine the added premature deaths (Mortalities_{PM_{2.5} NH_1}), we compare the deaths in each scenario (Mortalities_{PM_{2.5} NH_1 Case}) to those in the baseline scenario (Mortalities_{PM_{2.5} Baseline Case}):

\[
\text{Mortalities}_{PM_{2.5} \text{ NH}_1} = \text{Mortalities}_{PM_{2.5} \text{ NH}_1 \text{ Case}} - \text{Mortalities}_{PM_{2.5} \text{ Baseline Case}}. \tag{3}
\]

3. Results

3.1. Ammonia emissions from storage and bunkering
Assuming a complete transition from HFO to ammonia, we estimate that Singapore could potentially be supplying approximately 90 Mt of ammonia annually by 2050. For context, this amount is equivalent to roughly 50% of the current global ammonia production (Rouwenhorst et al 2022). When estimating the ammonia emissions from storage and bunkering activities at the port, we use various scenarios for leak rates and abatement levels. With medium leak rates, estimated annual emissions are approximately 50 kilotons.
With high leak rates, the projected annual emissions reach 100 kt yr\(^{-1}\) (kt), 25 kt, and 12.5 kt per year for the unabated, storage abated, and both abated cases, respectively (table 1). With high leak rates, the projected annual emissions reach 100 kt yr\(^{-1}\) if unabated. For comparison, the cumulative ammonia emissions from other human-driven sources in Singapore such as agricultural and industrial activities are projected to total around 30 kt yr\(^{-1}\) in 2050 (using the SDS-MFR scenario in GAINS). These findings highlight the importance of addressing storage and bunkering-related ammonia emissions. If left unabated, these emissions could contribute to the amplification of Singapore’s ammonia emissions by 100%–300%. Implementation of targeted abatement policies has the potential to significantly mitigate this impact, potentially reducing it by roughly 50%–75%.

Since ammonia bunkering is a new concept, there is still a large gap in the literature about the processes that contribute to its emissions via leaks and the effectiveness of various abatement strategies. We use the most complete study of ammonia emissions from shipping, which estimates leaks as boil-off-gas (Al-Breiki et al, 2020a). They find that bunkering and storage together contribute 40% of leaks (12% from storage and 28% from bunkering) in the ammonia supply chain for ships (excluding production). The remainder of the leaks come from ammonia delivery to ports (28%) or leaks on ships (20%), which are outside the scope of our study. Operators may release the boil-off gas from storage, recapture it, or flare it. Current industrial processes have large regional and technological heterogeneity (Thompson and Carnegie, 1989, Stevens and Desai, 2010, Wijayanta et al, 2019), and how these practices may be applied in the shipping sector is uncertain. Additionally, research in other leaky systems such as natural gas suggests technically feasible leak reductions can be difficult to achieve in practice (Alvarez et al, 2012, Edwards et al, 2021). We thus include a range of abatement levels in our study. Our assessment does not consider other potential sources of ammonia emissions, such as small and persistent pipeline leaks and accidental releases, as these have not been adequately characterized for bunkering operations.

### 3.2. Ambient PM\(_{2.5}\) concentrations in Singapore

An energy transition to ammonia fuels in the shipping sector can lead to a large increase in PM\(_{2.5}\) concentrations around major ports such as Singapore (see figure 1(a)). The baseline PM\(_{2.5}\) concentration in Singapore in 2050, where HFO continues to be the dominant shipping fuel and the best available abatement measures are adopted, is projected to be 5.5 \(\mu g\) m\(^{-3}\) in 2050, compared to approximately 11 \(\mu g\) m\(^{-3}\) today (Rafaj et al, 2018, Amann et al, 2020). HFO contributes and additional of 0.4 \(\mu g\) m\(^{-3}\) to this total in 2050. However, with a transition to ammonia fuels under a medium leak (unabated) or high leak (unabated) scenario, the ambient PM\(_{2.5}\) concentrations are estimated to reach 6.8 or 8.4 \(\mu g\) m\(^{-3}\), respectively, an increase of 25%–50% compared to the baseline (without HFO). Various abatement strategies could reduce the air

### Table 1. Health and air quality effects of a transition to ammonia fuels in the shipping sector in Singapore. We present results for ammonia emissions from bunkering and storage, ambient PM\(_{2.5}\) concentrations, and health effects (i.e. premature mortalities) in 2050 for different leak scenarios (medium and high) and abatement measures (unabated, storage only, and storage and bunkering), compared to a baseline scenario where HFO continues to be used and best available abatement measures are adopted.

<table>
<thead>
<tr>
<th>Leak Scenario</th>
<th>Abatement</th>
<th>Ammonia Emissions (kt yr(^{-1}))</th>
<th>Contribution to Ambient PM(_{2.5}) ((\mu g) m(^{-3})) (^d)</th>
<th>Contribution to Premature Mortalities (Deaths yr(^{-1})) (^d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>MFR (^b)</td>
<td>30</td>
<td>5.52</td>
<td>670</td>
</tr>
<tr>
<td>Medium leak</td>
<td>Unabated (0%)</td>
<td>50</td>
<td>1.30</td>
<td>210</td>
</tr>
<tr>
<td>Medium leak</td>
<td>Storage only (50%)</td>
<td>25</td>
<td>0.65</td>
<td>115</td>
</tr>
<tr>
<td>Medium leak</td>
<td>Storage and bunkering (75%)</td>
<td>12.5</td>
<td>0.33</td>
<td>65</td>
</tr>
<tr>
<td>High leak (^c)</td>
<td>Unabated (0%)</td>
<td>100</td>
<td>2.92</td>
<td>460</td>
</tr>
<tr>
<td>High leak (^c)</td>
<td>Storage only (50%)</td>
<td>50</td>
<td>1.30</td>
<td>210</td>
</tr>
<tr>
<td>High leak (^c)</td>
<td>Storage and bunkering (75%)</td>
<td>25</td>
<td>0.65</td>
<td>115</td>
</tr>
</tbody>
</table>

\(^a\)Values in parentheses represent the total abatement of combined storage and bunkering emissions.

\(^b\)MFR refers to the maximum feasible reduction abatement case in the GAINS model.

\(^c\)The emissions factor in the high leak scenario is two times that in the medium leak scenario.

\(^d\)Values for HFO and ammonia scenarios are additional to values from other anthropogenic emissions.
quality impacts of ammonia storage and bunkering but are not likely to reduce them below the baseline. Ambient PM$_{2.5}$ concentration in the medium leak (storage abated) and medium leak (both abated) scenarios is 6%–12% higher compared to the baseline (without HFO) and 50%–75% lower compared to the unabated scenario. In the high leak (storage abated) and high leak (both abated) scenarios, ambient concentrations are 11%–23% higher compared to the baseline.

3.3. Health effects

The increases in PM$_{2.5}$ concentrations in Singapore due to an ammonia transition in the shipping sector can lead to a variety of health effects. We focus here on premature mortality (see figure 1(b)). Under our baseline scenario (where HFO remains the dominant fuel), air-quality–related premature mortality in Singapore in 2050 is estimated to be 750 deaths (with 80 deaths due to HFO), compared to 1,500 deaths in 2020. These baseline results illustrate the benefits of implementing the best available abatement measures. Under the medium leak (unabated) and high leak (unabated) scenarios, premature mortalities are estimated to increase to a total of 880 and 1,130 deaths, respectively, an increase of 30%–70% compared to the baseline. However, proper abatement measures can reduce premature mortalities. Under the abatement scenarios, the additional premature mortalities are 9%–17% higher than the baseline in the medium leak scenario and 17%–31% higher in the high leak scenario. We note that the relationship between PM$_{2.5}$ concentration and health effects is nonlinear after a certain threshold (Cohen et al 2017), and a small increase in PM$_{2.5}$ can cause relatively higher health effects. However, because the PM$_{2.5}$ concentrations in all scenarios are relatively low (<10 µg m$^{-3}$), our results follow the super-linear relationship (for example, a 50% increase in PM$_{2.5}$ relative to our 2050 baseline scenario causes a 70% increase in premature mortalities).

Since the changes in PM$_{2.5}$ were small, we did not observe any noticeable premature mortality changes in neighboring countries. However, similar to ambient PM$_{2.5}$, these health effects could change rapidly if PM$_{2.5}$ concentrations increase if ammonia is produced in nearby regions. The interdependency of ambient concentrations and health effects between regions to facilitate ammonia supply chains calls for better coordination between regions on ensuring proper abatement measures are applied.

3.4. Caveats

Several assumptions in this study impact our results and may lead to an under– or overestimate of the impacts of a transition to ammonia fuels in the shipping sector on air quality and health in Singapore. Ammonia leaks depend on the quantity of fuel bunkered and stored, which may change if demand for shipping changes in the future or if ammonia engines do not have the same efficiency as HFO engines. Ammonia is a novel shipping fuel, and thus the level of leakage that may result from a large-scale...
transition—and adoption of various abatement measures—is also highly uncertain. The range of scenarios we present aims to capture many potential outcomes but may underestimate the upper and lower bounds. Additionally, different storage and bunkering approaches not represented here (e.g., flaring, ship-to-ship transfer, etc.) may lead to higher or lower emissions. Emissions from incomplete combustion in ships were also not evaluated in this study but could substantially impact air quality near ports and marine biogeochemistry. Furthermore, nitrous oxide (N\textsubscript{2}O), a potent greenhouse gas formed from photochemical reactions of leaked and incompletely combusted ammonia, could contribute to climate warming. Finally, it is important to compare ammonia fuels not only with HFO but also with other alternatives such as natural gas and methanol, which are also anticipated to play an important role in the shipping industry.

Our assessment of air pollution and health impacts is also limited by several features of the GAINS model. Most critically, the simplified chemistry in GAINS limits its precision in scenarios with significant species changes, such as ammonia converting to PM\textsubscript{2.5}. Complex atmospheric processes, chemistry, and meteorology can affect pollutant formation and distribution. While GAINS is useful for broad assessments, it may miss nuanced pollutant transformation pathways, and thus the conversion of ammonia to PM\textsubscript{2.5} should be considered an initial scoping estimate. To improve understanding, especially in species-variable cases, pairing GAINS with advanced atmospheric transport models that consider emissions, meteorology, chemistry, and deposition for comprehensive pollutant simulation is crucial. Incorporating an atmospheric transport model alongside high-resolution gridding can also contribute to refining the spatial attribution of emissions and the corresponding impacts. The GAINS grid resolution is relatively coarse, particularly when applied to a small nation like Singapore. Sub-grid processes and impacts, especially over densely populated regions, remain insufficiently characterized, leading to potential underestimation of impacts compared to when higher resolution models are used (e.g. Bilsback \textit{et al} 2020).

4. Conclusion and policy implications

A transition to alternative fuels is key to reaching net zero emissions in the shipping sector but may have a variety of impacts on human health and the environment. We analyze the air quality impacts of a fuel switch from HFO to ammonia in the shipping industry in Singapore in 2050. Assuming that Singapore retains its dominance as a global hub for bunkering and sees a complete transition from HFO to ammonia, we estimate that 90 Mt yr\textsuperscript{-1} of ammonia (equivalent to half of current global ammonia production) could be bunkered and stored in Singapore in 2050. Storage and bunkering of 90 Mt yr\textsuperscript{-1} of ammonia are estimated to emit approximately 50–100 kt yr\textsuperscript{-1} of ammonia into the atmosphere of the Singapore port area under medium and high leak scenarios with no abatement. These unabated emissions are a factor of two to three higher than the projected total anthropogenic ammonia emissions in Singapore outside the shipping sector. These additional emissions could lead to a 25%–50% increase in PM\textsubscript{2.5} in Singapore compared to a 2050 baseline and result in an additional 210–460 premature mortalities per year (an increase of 30%–70%). Strong abatement measures could reduce these impacts and even potentially lead to lower impacts than an HFO baseline coupled with the best available abatement measures.

While our study focuses on Singapore, a transition to ammonia fuels in the shipping industry could have broader global impacts. Given the relatively short atmospheric lifetimes of ammonia and its gaseous and particulate form of only a few hours and days, respectively, we did not observe a considerable PM\textsubscript{2.5} increase in Singapore's neighboring countries. However, if ammonia is produced in nearby regions, the overall supply chain of ammonia for shipping could cause noticeable enhancements in ambient PM\textsubscript{2.5} concentrations in regions that are ammonia-limited. The interplay of abundant ammonia with other atmospheric species could have unexpected, non-linear outcomes and thus calls for a detailed study using chemistry-refined modeling (Clappier \textit{et al} 2021). If other anthropogenic sources of sulfur dioxide and nitrogen oxides from Singapore or its neighboring countries continue emitting at higher amounts than the MFR abatement modeled in this work, they could lead to higher secondary PM\textsubscript{2.5} formation. Similarly, if only a fraction of the ports and ships switch to ammonia initially, the overlapping shipping lanes and ports could also see higher ambient PM\textsubscript{2.5} concentrations than in the case where the fuel source is either entirely HFO or entirely ammonia.

While climate policies promise overwhelming global benefits for health and air quality, our results highlight the potential for adverse effects in particular locations. The combustion of HFO sold at the port in Singapore is responsible for approximately 20% of premature deaths (16 000 out of a global total of 80 000) attributed to shipping emissions (Mao \textit{et al} 2022). Shifting from HFO to ammonia as the fuel source in Singapore's port holds the potential to significantly decrease these impacts globally but, if ammonia leaks are not controlled, could worsen air quality in Singapore. We show that proper abatement on storage and bunkering operations can reduce emissions, PM\textsubscript{2.5} formation, and health impacts by over 50% and may even reduce local impacts to below levels expected under a scenario with continued HFO use. This range of potential future impacts highlights the inherent uncertainties in evaluating technologies and systems that
have yet to see large-scale adoption and underscores the essential role of public policy in mitigating adverse side effects of energy transitions. International standards can facilitate global consensus on standards and optimal practices to ensure equitable environmental and health advantages across various ports and regions. As more work is being undertaken to assess ammonia as a maritime fuel (GCMD 2022), we find that its air quality impacts could be substantial and should be considered as part of a holistic impact assessment.

Data availability statement

Data supporting the main findings can be found in the online version of GAINS (https://gains.iiasa.ac.at/gains/GOD/index.login?logout=1&switch_version=v0) under ‘RATHOD_NH3_SDS_MFR_LEAKS’ scenario that describes ammonia emissions from storage and bunkering leaks in the SDS with MFR.

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References

Al-Breiki M and Bicer Y 2020a Investigating the technical feasibility of various energy carriers for alternative and sustainable overseas energy transport scenarios Energy Convers. Manage. 209 112652
Al-Breiki M and Bicer Y 2021 Comparative life cycle assessment of sustainable energy carriers including production, storage, overseas transport and utilization J. Clean. Prod. 279 123481
Amann M et al 2020 Reducing global air pollution: the scope for future policy interventions Phil. Trans. R. Soc. A 378 20190331
Balasubramanian R, Qian W-B, Decesari S, Facchini M C and Fuzzi S 2003 Comprehensive characterization of PM$_{2.5}$ aerosols in Singapore J. Geophys. Res. Atmos. 108
Beusen A H W, Bouwman A F, Heuberger P S C, Van Drecht G and Van Der Hoek K W 2008 Bottom-up uncertainty estimates of global ammonia emissions from global agricultural production systems Atmos. Environ. 42 6067–77
Chalakis I, Jeong B and Jang H 2022 Application of parametric trend life cycle assessment for investigating the carbon footprint of ammonia as marine fuel Int. J. Life Cycle Assess. 27 1145–63
Chen Z et al 2022 Non-agricultural source dominates the ammonium aerosol in the largest city of South China based on the vertical S$_{IN}$ measurements Sci. Total. Environ. 848 157750
Contini D and Merico E 2021 Recent advances in studying air quality and health effects of shipping emissions Atmosphere 12 1
Gu B et al 2021 Abating ammonia is more cost-effective than nitrogen oxides for mitigating PM$_{2.5}$ air pollution Science 374 758–62

8


Kiesewetter G, Schöpp W, Heyes C and Amann M 2015b Modelling PM_{2.5} impact indicators in Europe: health effects and legal compliance Environ. Model. Softw. 74 201–11


McKinlay C J, Turnock S R and Hudson D A 2021 Route to zero emission shipping: hydrogen, ammonia or methanol Int. J. Hydrog. Energy 46 28282–97


Park J, Kim E, Oh S, Kim H, Kim S, Kim Y P and Song M 2021 Contributions of ammonia to high concentrations of PM_{2.5} in an urban area Atmosphere 12 12


Seldon T I. and Sankaran C 2017 The impact of Indonesian forest fires on Singaporean pollution and health Am. Econ. Rev. 107 526–9


Stevens R and Desai U R 2010 Self-supported flare-stack vibrations in ammonia plant Process Saf. Prog. 29 254–63

Thompson J R and Carnegie R N 1989 Building a high-integrity ammonia storage tank—1988 Plant/Oper. Prog. 8 92–95


Weagle C L et al 2018 Global sources of fine particulate matter: interpretation of PM_{2.5} chemical composition observed by SPARTAN using a global chemical transport model Environ. Sci. Technol. 52 11670–81
