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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 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 2013, 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 (NH_3 Bunkered) and total emissions from bunkering and storage (NH_3 Emissions):

$$\mathrm{NH_3\ Bunkered_{2050}} = \mathrm{HFO\ Bunkered_{2020}} * \frac{\mathrm{ED_{HFO}}}{\mathrm{ED_{NH_3}}} \tag{1}$$

$$\mathrm{NH_3\ Emissions_{2050}} = \mathrm{NH_3\ Bunkered_{2050}} * \mathrm{EF_{scenario}}. \tag{2}$$

In these equations, $\mathrm{NH_3\ Bunkered_{2050}}$ is the mass of bunkered ammonia in Singapore in 2050 in Mt; $\mathrm{HFO\ Bunkered_{2020}}$ is the present-day bunkered HFO in Singapore in Mt; $\mathrm{ED_{HFO}}$ and $\mathrm{ED_{NH_3}}$ are the gravimetric energy density of HFO and ammonia, respectively, in MJ kg^{-1}; NH_3 Emissions is the amount of ammonia leaked into the atmosphere from storage and bunkering processes in kt yr^{-1}; and $\mathrm{EF_{scenario}}$ 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 NO_x-free (with the potential exception of flaring as an abasement measure), its combustion may produce NO_x 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 km^2) compared to the scale of the GAINS model grid (100 km^2), 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 $PM_{2.5}$, but the contribution of HFO ($\sim$0.4 μg m^{-3} in 2050) is removed before the health calculations are performed. While the GAINS scheme is fairly linear, not removing the HFO emissions layer during the simulation of $PM_{2.5}$ can introduce 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 ($\text{Mortalities}_{\text{PM2.5 NH}_3}$), we compare the deaths in each scenario ($\text{Mortalities}_{\text{PM2.5 NH}_3\text{ Case}}$) to those in the *baseline* scenario ($\text{Mortalities}_{\text{PM2.5 Baseline Case}}$):

$$\text{Mortalities}_{\text{PM}_{2.5}\text{ NH}_3} = \text{Mortalities}_{\text{PM}_{2.5}\text{ NH}_3\text{ Case}} - \text{Mortalities}_{\text{PM}_{2.5}\text{ Baseline Case}}. \quad (3)$$

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

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.

	Emissions	Abatement[a]	Ammonia emissions (kt yr^{-1})	Contribution to ambient $PM_{2.5}$ ($\mu g\ m^{-3}$)[d]	Contribution to premature mortalities (deaths yr^{-1})[d]
Baseline	Other anthropogenic (i.e., non-shipping)	MFR[b]	30	5.52	670
	HFO	MFR (80% compared to 2020)	—	0.42	80
Leak	Medium leak	Unabated (0%)	50	1.30	210
	Medium leak	Storage only (50%)	25	0.65	115
	Medium leak	Storage and bunkering (75%)	12.5	0.33	65
	High leak[c]	Unabated (0%)	100	2.92	460
	High leak[c]	Storage only (50%)	50	1.30	210
	High leak[c]	Storage and bunkering (75%)	25	0.65	115

[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.

(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 and Bicer 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

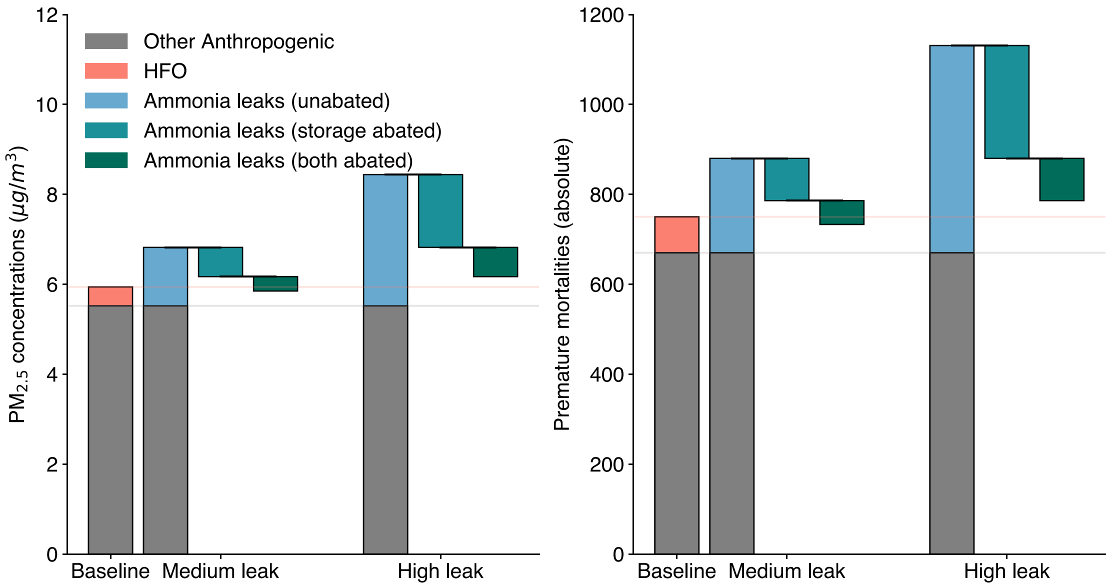

Figure 1. Waterfall plots of the average $PM_{2.5}$ concentration (μg m^{-3}) (a) and premature mortality (absolute) (b) in the *baseline*, *medium leak* (*unabated*), and *high leak* (*unabated*) scenarios. Also shown are the mitigation potential (in terms of air quality and premature mortality) due to the application of abatement measures in ammonia storage at ports and both storage and bunkering, respectively. *Baseline* is the IEA SDS with the GAINS maximum feasible reduction abatement strategy and where shipping fuel demand is met by HFO. *Medium leak* and *high leak* correspond to the baseline plus ammonia emissions from storage and bunkering at the Singapore port minus the contribution from HFO.

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 1130 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_2O), 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 $PM_{2.5}$. 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 $PM_{2.5}$ 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 *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^{-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^{-1} of ammonia are estimated to emit approximately 50–100 kt yr^{-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 $PM_{2.5}$ 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 $PM_{2.5}$ 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 $PM_{2.5}$ 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 *et al* 2021). I_2f 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 $PM_{2.5}$ 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 $PM_{2.5}$ 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 *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, $PM_{2.5}$ 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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