Air quality implications of coal-ammonia co-firing

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CREA is an independent research organisation focused on revealing the trends, causes, and health impacts, as well as the solutions to air pollution.

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Key findings

- Fine Particles ($PM_{2.5}$) are an atmospheric pollutant that are responsible for thousands of premature deaths in Japan each year, and millions worldwide.
- We estimated total emissions of $PM_{2.5}$ and precursor gases at Unit 4 of Hekinan Thermal Power Station, where 0 %, 20 % and 50 % of the energy demand is met by NH_3 (and the remaining energy demand is met by coal).
- We found that total emissions of $PM_{2.5}$ and precursor gases increase by 67 % when NH_3 displaces 20 % of the energy demand, and by 167 % when NH_3 displaces 50 % of the energy demand.
- These large increases in total emissions are due to the emissions of the $PM_{2.5}$ precursor gas NH_3, which are released during the shipping and combustion of this fuel.
- The increased total emission will likely lead to increased $PM_{2.5}$ concentrations and an even larger public health burden of this pollutant.

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Impacts of coal on air pollution and climate

The combustion of coal is a major source of electricity. However, burning this fuel also leads to the formation of air pollutants, which are detrimental to human health, and to the emissions of greenhouse gases, which are contributing to climate change.

Exposure to Fine Particles ($PM_{2.5}$) leads to a variety of respiratory and cardiovascular illnesses, including chronic obstructive pulmonary disease, ischemic heart disease, lung cancer, lower respiratory infections, and diabetes (Burnett et al., 2014; Di et al., 2017). Globally, $PM_{2.5}$ contributes to 4–8 million premature deaths each year (Lelieveld et al., 2015; Burnett et al., 2018). These premature deaths, combined with other non-fatal health illnesses caused by $PM_{2.5}$, cost the global economy USD 8 trillion, which is equivalent to 6.1 % of the global gross domestic product (World Bank, 2022). In Japan, $PM_{2.5}$ leads to ~43,000 premature deaths each year (State of Global Air, 2022).

Coal combustion is a major source of $PM_{2.5}$. Globally, coal combustion is responsible for 14 % (560,000) of the annual $PM_{2.5}$-related premature mortalities (McDuffie et al., 2021). Japan is the 4th highest producer of coal-fired electricity in the world (Ember, 2021), and this energy source accounts for 28 % of the nation's electricity (Our World in Data, 2023). Because of this, coal combustion accounts for a significant fraction (12 %) of the $PM_{2.5}$ concentration in Japan (McDuffie et al., 2021). In addition to $PM_{2.5}$, coal combustion also contributes to climate change, through emissions of greenhouse gases.

As an alternative fuel to coal, ammonia (NH_3) can also be burnt in power stations to generate electricity, however, this process does not emit greenhouse gases. Ammonia is a corrosive chemical and exposure to high concentrations of it can cause immediate damage (severe irritation and burns) to the eyes, skin, and mucous membranes of the oral cavity and respiratory tract. In contrast to other energy carriers, such as hydrogen (H_2), the transport of ammonia is relatively easier, cheaper, and safer. Therefore, NH_3 could be a green alternative to coal combustion (MacFarlane et al., 2020; Xue et al., 2019).

Fueling a power plant with ammonia

The Hekinan Thermal Power Station is Japan's largest coal-fired power plant and is owned by JERA, which is Japan's largest electricity producer. Over the past few years, Unit 4 of this power station has undergone technological developments to allow combustion of both coal and ammonia ('co-firing'). Figure A1 in Appendix A - Supplemental information (SI) shows how the site will accommodate this new fuel source. In 2023, JERA will meet 20 % of the energy demand at this unit through combusting 500,000 tons of ammonia (JERA, 2022c). If successful, they plan to further increase the ammonia co-firing rate to 50 % at this station by 2050, and to 100 % for all their supercritical plants after 2050 (IHI, 2022 c).

To satisfy this huge demand for ammonia, JERA has signed Memorandums of Understanding (MOUs) with the world's biggest producers and transporters of ammonia (JERA, 2022d; JERA, 2022h; JERA, 2022b). Using ammonia to supply 20 % of the energy demand of Unit 4 of Hekinan Thermal Power Station will double Japan's current consumption of this chemical. Because of this, JERA has been conducting international competitive bidding for ammonia supply (Nikkei, 2023). As a result, JERA have now signed MOUs on the supply of ammonia with Yara and CF Industries, who have key production sites in, for example, USA (CF Industries, 2023), Australia (Yara, 2023), and Norway (Yara, 2022). In anticipation of importing these large quantities of ammonia from distant regions, JERA have also signed MOUs with distribution companies to help import the fuel via ships, which will also themselves be powered by the fuel (JERA, 2022b). While it is uncertain exactly where the ammonia will be produced, JERA evidently expects to import it from distant locations and using ships that are also powered by this fuel.

Uncertain climate impacts

The use of ammonia as an alternative to coal has been widely scrutinised by the press (Reuters, 2022 a; Reuters, 2022 b; Service, 2018) and scientific community (Hughes et al., 2022; MacFarlane et al., 2020), as the overall impacts of this energy transition on climate change are uncertain. Climate is affected by coal and ammonia, as these fuels can lead to the emission of carbon dioxide, which is a potent greenhouse gas. Carbon dioxide is emitted from coal when the fuel is burnt in the power station. In contrast, carbon dioxide is not emitted when ammonia is burnt, however it can be emitted during its chemical production.

There are multiple different methods for producing ammonia, which are distinguished by their source of energy and whether any emitted carbon dioxide is captured. NH_3 is produced from the combination of hydrogen (H_2) and nitrogen (N_2), with hydrogen being produced from water, and nitrogen being produced from air. These chemical processes require large quantities of energy. In the traditional method for creating ammonia, which is sometimes referred to as 'grey' or 'brown', the energy demand is met by burning fossil fuels, which leads to the emissions of carbon dioxide. In blue ammonia production, fossil fuels are still used as the energy source, but Carbon Capture and Storage (CCS) is used to remove the emitted carbon dioxide from the atmosphere. In green NH_3 production, renewable energy is used as the energy source, and no carbon dioxide is emitted. Clean NH_3 refers to a combination of blue and green NH_3 production. However, clean methods for ammonia production suffer from methodological constraints, which have prevented its widespread use.

Currently, ammonia production is a significant source of greenhouse gas emissions, as the majority of ammonia is produced from the grey/brown method. NH_3 production leads to the emission of 500 million tonnes of carbon dioxide each year, which is equivalent to 2 % of global carbon dioxide emissions (The Royal Society, 2020).

Scientific research demonstrates that the climate benefits of using ammonia in coal power plants are highly dependent on the method of ammonia production. If clean ammonia is used to displace 20 % of all coal-fired power plants in Japan, carbon dioxide emissions are estimated to reduce by 40 million metric tons per year (Stocks et al., 2022). However, if the ammonia is produced via the grey/brown method, total emissions of carbon dioxide will not change, as the reduced carbon dioxide emissions at power plants in Japan will be entirely offset by increased carbon dioxide emissions outside of Japan where the ammonia is produced (Stocks et al., 2022). Hence, without major changes in the global chemical production sector, displacing coal with ammonia in the Japanese energy sector will not lead to any benefits on climate.

Unexplored pollution impacts

Displacing coal with ammonia also has the potential to affect $PM_{2.5}$ (Lu et al., 2017). The production, transport, and combustion of both coal and ammonia have the potential to affect $PM_{2.5}$ through the emissions of various species. $PM_{2.5}$ is both directly emitted into the atmosphere and formed in the atmosphere from precursor species, nitrogen oxides (NO_x), sulphur dioxide (SO_2), and NH_3 (see Figure A2 for schematic diagram).

The emissions from coal and how they contribute to $PM_{2.5}$ are relatively well understood. Coal contributes to the formation of $PM_{2.5}$ through emissions of $PM_{2.5}$ during the mining of coal, and through emissions of $PM_{2.5}$, nitrogen dioxide and sulphur dioxide during the burning of coal. Coal power plants, including Unit 4 of Hekinan Thermal Power Station, provide measurements of these emissions each year. During the production of ammonia, 0.001 % is unintentionally emitted into the atmosphere (European Environment Agency, 2021). To the best of our knowledge, emissions of ammonia during its transport have not been quantified. However, scientific research shows that during the shipping of liquid methane from a round trip from USA to Belgium, 0.1 % of the methane was emitted into the atmosphere, due to being directed vented into the atmosphere to avoid unstable pressures and used as a fuel to propel the ship (Balcome et al., 2022). The combustion of ammonia leads to the emissions of unreacted ammonia (otherwise known as 'ammonia slip'), and nitrogen dioxide. The Japanese government reported that co-firing with coal and ammonia had no impact on emissions of nitrogen dioxide, as compared to when firing with coal only (Agency for Natural Resources and Energy, 2021). The amount of ammonia which is left unreacted and emitted into the atmosphere is, however, highly uncertain and is dependent on multiple different factors, with estimates ranging anywhere from 0.1 to 25 % (Balcome et al., 2022; DieselNet, 2023).

Overall, displacing coal with ammonia will affect emissions of multiple different species ($PM_{2.5}$, SO_2, NO_2, NH_3) from multiple different activities (production, transport, combustion). If changes in total emissions are large enough, they have the potential to affect atmospheric concentrations of $PM_{2.5}$ and human health.

Methodology for calculating pollutant emissions from the trial

In this study, we explored the air quality implications of co-firing Unit 4 of Hekinan Thermal Power Station with coal and ammonia. To achieve this, we quantified emissions of $PM_{2.5}$ and the precursor species under multiple coal:NH_3 fuel mix scenarios of (100:0, 80:20, and 50:50), whilst keeping the total energy demand constant. We accounted for emissions from each aspect of the fuel lifecycles (mining, industrial production, transport, and combustion).

We used a variety of different methods to calculate emissions, depending on the activity, fuel mix scenario, and species, and this is shown in Table 1. As JERA currently operates under the 100:0 fuel scenario, and they already report emissions of $PM_{2.5}$, nitrogen oxides, and sulphur oxides from combustion (Koplitz et al., 2017); we directly use these values (Table 1). For the remaining scenarios for these activities, we assume emissions of $PM_{2.5}$ and sulphur dioxide decrease proportionally to the reduction in coal, and no change in emissions of nitrogen oxides. For the remaining activities, species, and scenarios, we combine underlying activity data (coal production, ammonia production, ammonia transport, ammonia combustion) with measured emission factors from the scientific literature. Note, for ammonia combustion, we assume an emission factor of 0.1 %, which is at the lower end of the range of estimates (0.1 - 30 %), and therefore provides a conservative estimate.

Table 1 - Methods and data used to calculate emissions from the coal:NH_3 trial				
Activity	Species	100:0	80:20	50:50
Coal Mining[a]	$PM_{2.5}$	coal production x emission-factor		
NH_3 production[a]	NH_3	NH_3 production x emission-factor		
NH_3 transport[b]	NH_3	NH_3 transport x emission-factor		
Combustion[d]	$PM_{2.5}$	Reported	Reported x 0.8	Reported x 0.5
Combustion[d]	SO_2	Reported	Reported x 0.8	Reported x 0.5
Combustion[d]	NO_2	Reported	Reported	Reported
Combustion[c]	NH_3	NH_3 burnt x emission-factor		

Source: Emission factors for coal mining[a] and NH_3 production[a] are taken from the European Environment Agency (2021), for NH3 production[b] are taken from Balcome et al. (2022), and for combustion[c] of NH_3 are from Balcome et al (2022) and DieselNet (2023). Reported emissions of combustion[d] of coal are taken from Koplitz et al. (2017).

Increased pollutant emissions

Figure 1 shows emissions under the various fuel mix scenarios at Unit 4 of Hekinan Thermal Power Station. When coal is the only fuel source (100:0 scenario), total emissions across all species ($PM_{2.5}$ + SO_2, + NO_2 + NH_3) and activities (production + transport + combustion) are 1,348 tons. The largest contributions to total emissions under this scenario are NO_2 (800 tons) and SO_2 (529 tons). Contrastingly, $PM_{2.5}$ emissions are negligible (19 tons) and there are no emissions of NH_3.

Displacing coal with ammonia leads to substantial increases in total pollutant emissions. Total emissions increase by 67 % (from 1,348 to 2,249 tons) when the energy demand of NH_3 is increased from 0 % (100:0 scenario) to 20 % (80:20 scenario). Worse still, total emissions increase by 167 % (from 1,348 to 3,602 tons) when the energy demand of NH_3 is increased from 0 % (100:0 scenario) to 50 % (50:50 scenario). These large increases in total pollutant emissions are driven by emissions of NH_3. When 20 % (80:20 scenario) and 50 % (50:50 scenario) of the energy demand is met by ammonia, emissions of NH_3 increase by 1,011 and 2,528 tons, respectively. In contrast, emissions reduce only marginally for $PM_{2.5}$ (4-9 tons) and SO_2 (106-265 tons), and emissions do not change at all for NO_2. Therefore, displacing coal with ammonia leads to large increases in emissions of ammonia, which entirely offsets the negligible reductions in emissions of other species ($PM_{2.5}$, SO_2).

Geographically, the increased pollutant emissions will be distributed both at Hekinan Thermal Power Station and internationally. The increased emissions of NH_3 due to replacing coal with this fuel are driven by emissions from the transport of this fuel (50 %) and the combustion of this fuel (50 %). Because of this, the increase in total emissions due to replacing coal with NH_3 are distributed at both Hekinan Power station and along the route of the ship transporting the fuel. Using coal as the only energy source (100:0 scenario), total pollutant emissions at Hekinan Thermal Power Station are 1,348 tons (see Figure 1, black star). When 20 % (80:20 scenario) and 50 % (50:50 scenario) of the energy demand is met by ammonia, total emissions at Hekinan Thermal Power Station increase to 1,738 tons (+30 %) and 2,339 tons (+75 %), respectively (see Figure 1, black star).

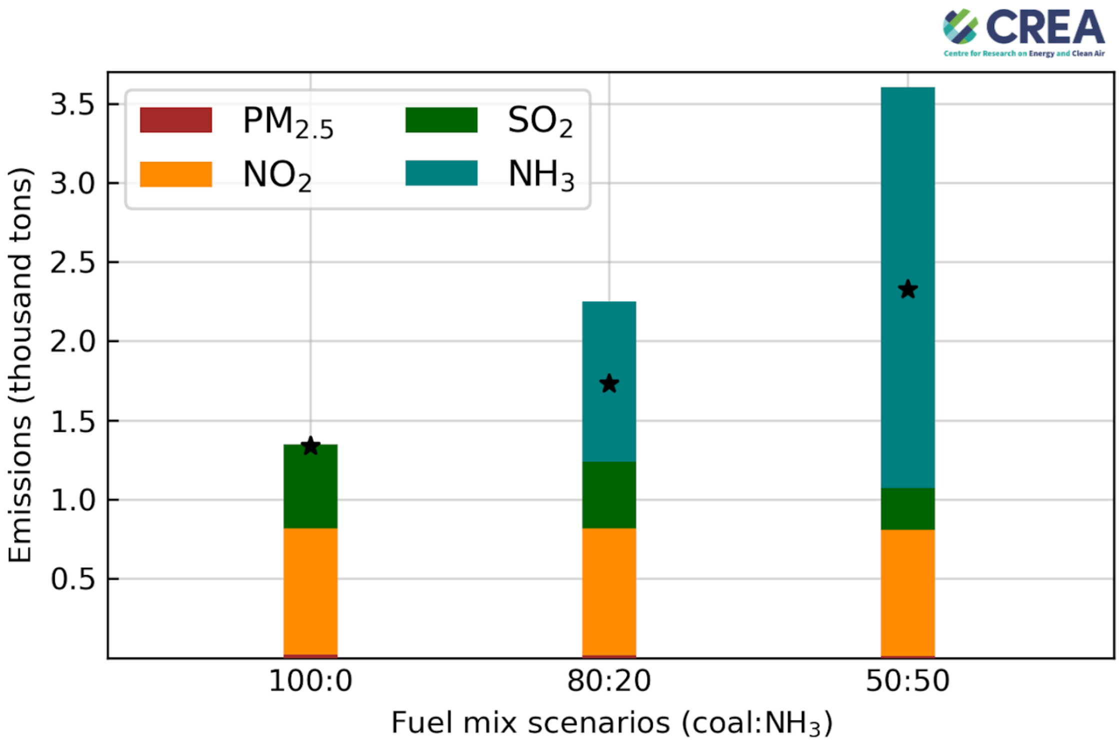

Figure 1 - Emissions of $PM_{2.5}$ and its precursor species (NO_2, SO_2, and NH_3) at Unit 4 of the Hekinan Thermal Power Station

Note: For each of the three fuel mix scenarios, we show emissions of $PM_{2.5}$ (red bar) SO_2 (green bar), NO_2 (orange bar), NH_3 (blue bar) from all activities (production + transport, + combustion), and total pollutant emissions ($PM_{2.5}$ + SO_2 + NO_2 + NH_3) from combustion only (black star).

Sources: Data used to create this figure is taken from Koplitz et al. (2017), European Environment Agency (2021), Balcome et al (2022) and DieselNet (2023).

Implications for regional public health

The increased emissions at Unit 4 of Hekinan Thermal Power Station could have far-reaching consequences for human health, as (i) the increased total emissions are substantial and include emissions from a particularly important species, (ii) $PM_{2.5}$ undergoes long-range transport in the atmosphere, (iii) even small increases in $PM_{2.5}$ concentrations can lead to large increases in human mortality risk. The increased emissions at Unit 4 of Hekinan Thermal Power Station will likely increase atmospheric concentrations of $PM_{2.5}$ as the magnitude of emission increases are substantial (30-75 %), and as it includes increases in emissions of ammonia, which is an especially strong precursor of $PM_{2.5}$ (Gu et al, 2021). The increased atmospheric concentrations of $PM_{2.5}$ will likely be distributed over a large region, as $PM_{2.5}$ can persist in the atmosphere for several weeks, and undergo long range transport. For example, $PM_{2.5}$ concentrations in Japan can be affected by emissions that originate thousands of kilometres away, such as from China (Aikawa et al., 2010). Therefore, it is highly likely that the emissions from Hekinan power station could affect $PM_{2.5}$ concentrations in nearby cities, such as Nagoya, which is only 50 km away and has a population of ~2 million. The increased atmospheric concentrations of $PM_{2.5}$ will likely lead to a large increase in the public health burden, as even small changes in $PM_{2.5}$ concentrations can yield large increases in mortality risk (Vonodos et al., 2018).

Implications for ecosystem health

The increased emissions have the potential to affect environmental health, through increased nitrogen deposition. The health of organisms are, in part, determined by the delicate balance in nutrients, including nitrogen, iron, and phosphorus. Changes in the nutrient balance can lead to eutrophication, which is the excessive growth of plants and algae. Increased nitrogen deposition due to human activity has altered the balance in nutrients so much that it has led to eutrophication in coastal ecosystems (Malone et al., 2020), degradation in marine ecosystem health (Kim et a., 2014 a; Kim et al., 2014 b; Ren et al., 2017), and biodiversity loss in Japan (Lin et al., 2021). The NH_3 emitted into the atmosphere during both the ship cruise and combustion will eventually be deposited into marine and terrestrial ecosystems, and further worsen this environmental issue.

Plans to scale up the energy transition

After using 0.5 million tons of ammonia to fuel Unit 4 of Hekinan Thermal Power Station, there are several plans to scale up the displacement of coal with ammonia in other power stations. Scaling up this technology to the rest of the coal-fired power plant fleet across Japan, the national government expects the annual ammonia demand to increase to 3 million tons per year by 2023, and to 30 million tons by 2050 (METI, 2022). JERA has signed MOUs to explore co-firing at other power stations across Japan (JERA, 2022g), Malaysia, (JERA, 2022a), and Singapore (JERA, 2022f), as well as the scaling up of the international production (JERA, 2022d; JERA, 2022h) and shipping (JERA, 2022b) of NH_3. Other Japanese companies, such as Mitsubishi Heavy Industries (MHI) and IHI Corporation, have also signed MOUs on the exploration of co-firing coal and NH_3 in Indonesia (MHI, 2022; IHI, 2022b), Singapore (MHI, 2022 a), Taiwan (MHI, 2022d), Thailand (MHI, 2023), India (IHI, 2022a) and Chile (MHI, 2022c). This is of particular importance for Indonesia, where $PM_{2.5}$ already contributes to a staggering 94,000 premature deaths each year, with around 13 % due to coal (McDuffie et al., 2021). Moreover, some of these projects intend to use high ammonia co-firing percentages, reaching 30 % (MHI, 2022c) and 100 % (JERA, 2022f). Therefore, upon completion of the trial, it is very likely that the negative air quality impacts will not be confined only to Japan, but also translated to multiple different countries outside of Japan.

Comparisons with previous research

In our research, we have found that ammonia co-firing at Unit 4 of Hekinan Thermal Power Station could increase $PM_{2.5}$, which is corroborated by independent research (Lu et al., 2017). We have reached our conclusion by using data from peer-reviewed scientific research to estimate the emissions from the long-term (1 year) ammonia co-firing (20-50 %) at this unit which has a thermal capacity of 1000 MW, and have considered all aspects of the fuel lifecycles (mining, production, transport, and combustion).

In contrast, previous research by Japanese power companies implies that (Hara, 2019; Fujimori, 2019), under certain conditions, the impacts of ammonia co-firing on $PM_{2.5}$ can be minimised. However, in contrast to our methodology, their research uses data from their own experiments, which have not been independently reviewed. For instance, several of their experiments only assess low ammonia co-firing rates (6–20 %) to meet low thermal inputs (10 MW) over short time scales, and none of their experiments consider emission during the international shipping of ammonia — which we find be one of the dominant drivers for increased atmospheric emissions of ammonia from co-firing. Hence, it is highly uncertain if the results from their experiments are representative of operational conditions. Indeed, the authors of the research performed by the power companies conclude that

> "…evaluation of combustion characteristics on an actual scale and evaluation of various coal types and combustion conditions assumed for operation are insufficient, and further technical studies are desired in the future prior to commercialization. In addition, many aspects of the combustion phenomenon when mixing coal, which is a solid fuel, and ammonia, which is a gaseous fuel, are

still unknown. To this end, it is necessary to continue working to elucidate the underlying phenomena."[1]

Conclusions and recommendations

Air quality in Japan has improved significantly due to decades of scientific research, environmental policy, and investments in air pollution mitigation technologies (Wakamatsu et al., 2013). For instance, the Japanese-average $PM_{2.5}$ concentration has decreased by ~30 % between 2010 and 2018 (Ito et al., 2021). However, $PM_{2.5}$ concentrations in Japan still exceed the guideline value suggested by the World Health Organization (WHO) and this pollutant is the 8th leading risk factor for premature mortality and disability (State of Global Air, 2022). Our results indicate that Japanese improvements in air quality could be undermined, or even offset, by replacing coal with NH_3.

Our results suggest that displacing coal with NH_3 could increase concentrations of $PM_{2.5}$ due to large increases in emissions of NH_3, which is a major precursor to $PM_{2.5}$. Therefore, before the health of humans is risked by further expanding implementation of this technology, we recommend the following;

- Research into how the emissions change associated with displacing coal with ammonia at Unit 4 of Hekinan Thermal Power Station will affect $PM_{2.5}$ concentrations. Our research shows large increases in emissions of NH_3, through both the transport and combustion of NH_3, which suggest an increase in concentrations and health impacts of $PM_{2.5}$.
- Research into the emissions and air quality changes caused by scaling up co-firing at other power stations across Japan and internationally, and using higher ammonia co-firing ratios.

Overall, co-firing coal and ammonia in Japanese coal-fired power plants to meet the nation's energy demand will lead to a huge increase in the demand for ammonia. We

[1] This is a generated translation of an extract from the original report that was written in Japanese ("ただし、実機規模での燃焼特性評価や、運用上想定される様々な炭種、燃焼条件に対しての評価は不十分であり、実用化に先立って今後のさらなる技術的検討が望まれる"; Hara, Central Research Institute of Electric Power Industry, 2019, p.68-69; translated by DeepL Translator).

conclude that quenching this increased thirst for ammonia could lead to huge increases in atmospheric emissions of ammonia, which would have devastating effects on human health, ecosystem health, and the economy.

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Appendix A - Supplemental information (SI)

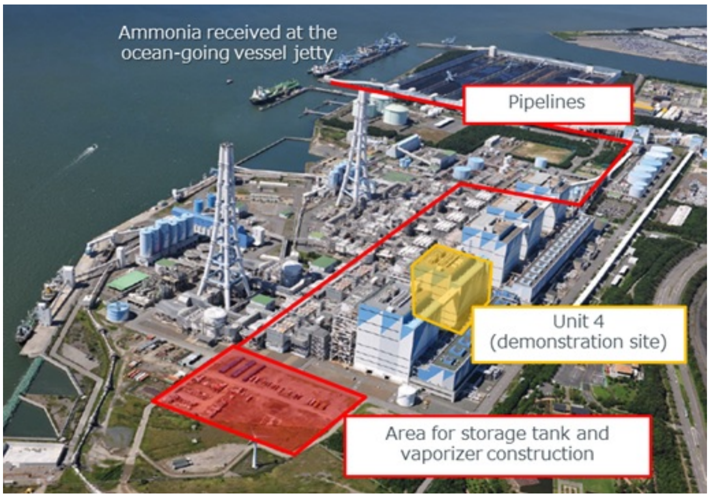

Figure A1 - Planned usage of ammonia at Heikanan Thermal Power Station (JERA, 2023 c)

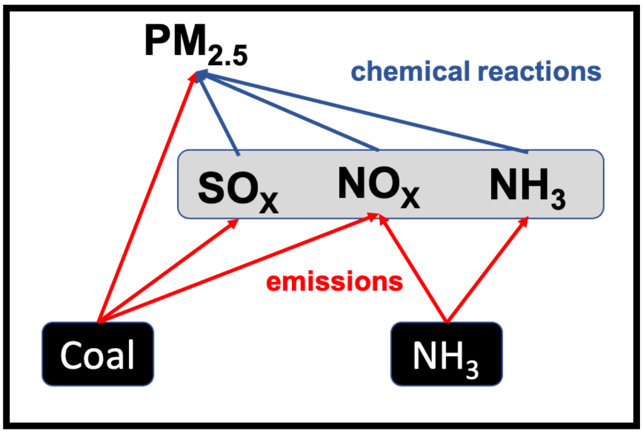

Figure A2 - Schematic diagram of how coal and ammonia can lead to $PM_{2.5}$ formation